Title: Misalignment between national mangrove monitoring capacities and policy ambition

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Misalignments between national mangrove monitoring capacities and climate policy targets

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Abstract

Ambitious global targets for mangrove conservation have advanced rapidly in recent years, yet the implementation of these commitments depends largely on national monitoring systems and policy processes. Despite widespread reliance on country-reported data for setting and evaluating targets, little is known about how national mangrove statistics are generated or how they interact with climate policy frameworks. Here, we assess national capacities for monitoring mangroves and evaluate them within the context of Nationally Determined Contributions (NDCs) and Greenhouse Gas National Inventory Reports (NIRs) submitted under the Paris Agreement. We extracted information on mangrove extent and biomass, as well as their underlying data sources, using country reports within the Global Forest Resources Assessments (FRA) for 2005, 2010, 2015, 2020, and 2025. We then compared these country-reported estimates (from 2005-2020) against independently produced time series of mangrove extent commonly used by the scientific and practitioner communities. We used these data to assess how national mangrove monitoring capacities have improved over the past two decades. We then examined how these capacities relate to inclusion of mangroves in NDCs and NIRs. Our results show highly variable estimates of mangrove extent, yet strong improvements in capacities for monitoring mangroves over the last twenty years. We did not find that countries with greater integration of mangroves into national policy had stronger monitoring capacities; rather we observed that many countries with strong monitoring capacities lack commensurate policy ambition. Our findings show where targeted investment, better data standards, and stronger links between monitoring and policy could help countries meet their mangrove related commitments.

Keywords: blue carbon; climate change mitigation; Nationally Determined Contributions; Earth Observation; climate policy; ecosystem mapping; wetland inventories; national forest inventories

Introduction

Mangroves—the vegetated wetlands that exist along many tropical, subtropical, and warm temperate coastlines—are critical ecosystems that jointly contribute to climate change mitigation and adaptation (Macreadie et al. 2021; Chow 2018; Sidik et al. 2018). As the international community strives to meet global targets for tackling climate change and halting biodiversity loss, increased calls for natural climate solutions (i.e., conservation, restoration, and improved management; Griscom et al. 2017) have helped drive adoption of mangrove conservation and restoration targets within national-scale policy and commitments (Arkema et al. 2023; Ofori et al. 2025; Friess 2023). For example, targets for mangrove conservation and restoration are increasingly integrated into Nationally Determined Contributions (NDCs) to the 2015 Paris Agreement, with 45 countries including blue carbon ecosystems (i.e., mangroves, salt marshes, and seagrasses) as mitigation components within their new or updated NDCs (Lecerf et al. 2021; Arkema et al. 2023). While establishing evidence-based policy targets is important, successfully achieving and reporting on them will depend heavily upon actual field implementation and monitoring processes—including through space-based earth observation—and spatial planning (Hegglin et al. 2022; Ofori et al. 2025).

Monitoring of land cover change in forests or vegetated wetlands is typically done through two avenues: i) analysis of remotely sensed imagery and ii) field-based inventories (Kauffman and Donato 2012; Pham et al. 2019; Arnold et al. 2023). While the former provides wall-to-wall data on extent and vegetation structure, the latter provides data on a broader suite of variables, such as species composition, vegetation structure, or soil carbon. Mangroves have well-established challenges for both remote sensing (e.g., signal saturation, persistent cloud cover and tidal fluctuation which complicates use of optical imagery) and field inventories (e.g., tidal flooding, soft soils & aerial roots, and remote locations), which have prompted global modeling approaches to help fill key data gaps (Sanderman et al. 2018; Simard et al. 2019; Bukoski et al. 2020; Rovai et al. 2021). These advancements can directly support commitments for mangrove conservation and restoration, yet we lack understanding of the degree to which they are currently being used by national governments. Policy targets, such as those set in NDCs, are ideally based on current conditions, and accurate monitoring data is therefore key for setting realistic goals (Sexton et al. 2016).

International processes that collate statistics on forest extent and condition can provide valuable insight into the status of national-level forest monitoring (Nesha et al. 2021), including for mangroves. These periodic reporting frameworks prompt countries to submit official statistics on their forest resources, often distinguishing between different forest types or ecosystems. The resulting reports, compiled at regular intervals, provide insights into forest extent and condition while also revealing the strength and evolution of national forest monitoring capacities (e.g., extent, vegetation condition, carbon stocks, and governance capacity). Analyses of these submissions—examining the data sources, methodologies, and their changes over time—have demonstrated that country-level capacities for forest inventory and monitoring have improved greatly in recent decades (Romijn et al. 2015; Nesha et al. 2021). However, it is currently unclear whether these strengthened capacities similarly translate to the unique conditions of mangroves, despite their increasing adoption within NDCs. Understanding how countries generate mangrove data, how these data have evolved over time, and how they connect to national climate policy is therefore essential for aligning mangrove stewardship with global climate ambitions.

To support the adoption and achievement of ambitious targets for mangrove conservation, this study assesses national-level capacities for monitoring change in mangrove extent and condition (such as canopy structure, biomass/carbon stocks, and disturbance/health indicators) within the context of national policy ambition. Our objectives were three-fold: i) to develop an understanding of the data sources and methods that underpin national statistics of mangrove extent and condition, ii) to assess how country-level capacities for monitoring changes in mangroves have developed through time, and iii) to relate these capacities to mangrove-specific policy targets and mechanisms, as proxied by NDCs and National Greenhouse Gas Inventory Reports (NIRs). Our analysis identifies opportunities for how the global scientific mangrove community can further develop international capacity for successful monitoring of these critical ecosystems, including where additional investment in tools, datasets, and capacity building could support nations in achieving their mangrove-related goals.

Methods

We assessed national mangrove monitoring capacity and its relationship to climate reporting by analyzing (i) country submissions to the Global Forest Resources Assessment (FRA) from 2005–2025, and (ii) the extent to which mangroves are incorporated into NDCs and NIRs. We compared country-reported mangrove extent with three independent global time-series datasets to evaluate consistency and change through time.

We focused on the United Nation's Global Forest Resources Assessment (FRA) country reports as a means of evaluating changes in national capacities for mangrove monitoring for three reasons: i) the FRA has been running since 2005, providing 20 years of consistent reporting, ii) the FRA has requested information on mangroves (deemed a "special forest category") within all reports, and iii) FRA reports have been similarly used to evaluate forest monitoring capacity by others (Nesha et al. 2021; Romijn et al. 2015). We therefore adopted a framework to evaluate the capacities for monitoring mangroves, as indicated in the FRA country reports, and how they have changed over time. We then extended this framework to assess how countries have incorporated mangroves into their NDCs and GHG NIRs over time, and how the inclusion of mangroves in policy targets and reporting compares to national-level capacities for monitoring. We provide details of each of these analyses in the following sections.

Compilation and assessment of country-level monitoring capacity and policy ambition

First, we compiled the FRA country reports for all mangrove-holding countries for 2005, 2010, 2015, 2020, and 2025. Using the reports, we then collected quantitative and qualitative data on how each country was tracking mangrove extent and biomass/carbon stocks. Quantitative data primarily consisted of estimates of mangrove extent for all years reported within each of the FRA reports, whereas qualitative data typified the sources and methods used to produce them. For example, extent estimates reported in FRA reports are typically based on original data (e.g., based on published estimates, classification of satellite imagery, or derived from forest inventories), estimations (i.e., gap-filling time series based on linear trends), or fore-/hindcasting (i.e., using linear trends from multiple estimates to project an extent for the desired year).

We reviewed all NDCs submitted between 2015 and June 2025 using the United Nations Framework Convention on Climate Change (UNFCCC) reports portal (Bhargava Gajre et al. *In prep*). Countries received one point for each NDC in which mangroves appeared as a distinct component of mitigation, adaptation, or biodiversity strategy (maximum capped at 4, consistent with the FRA scoring scale). For NIRs, countries were assigned one point per report in which mangroves were listed as a separate land category, rather than aggregated within "forest" or "wetlands."

Scoring of monitoring capacity & inclusion of mangroves in national policy documents

Using indicators adapted from Nesha et al. (2021), we assigned scores (0–4; Table 1) reflecting the use of remote sensing for mangrove area estimation; and integration of mangroves into national forest inventories (NFIs). The scores primarily indicate i) whether original data are used within the reports, ii) whether these data are produced internally (i.e., by government agencies) or externally (e.g., international consultants), iii) how many original estimates exist and whether they are consistently produced through time, and iv) the recency of the data. A higher score represents stronger, more repeatable national monitoring systems.

To score a country's integration of mangroves into its policy ambition and mechanisms, we established indicators for inclusion of mangroves in a country's NDCs and NIRs (Table 1). We were primarily interested in identifying countries that have consistently integrated mangroves into their policy targets and commitments for climate change mitigation. For both NDCs and NIRs, we scored countries by assigning one point for each report in which a country included a mangrove-specific target/inventory category but capped these scores at four to align with the FRA scores. For example, Australia, which has included mangroves in all seven NIRs, was scored a four—indicating very consistent inclusion of mangroves in its NIRs.

Table 1: Indicators used to assess data sources, data quality, and change in both mangrove monitoring capacity (using remote sensing and national forest inventories) and policy ambition (as evidenced by their NDCs and GHG NIRs).

Indicators	Indicator Criteria	Indicator Value	Code
Use of remote sensing for forest area monitoring	No forest cover map	Low	0
	One forest cover map (externally produced)	Limited	1
	Multiple forest cover maps (externally produced); typically not following consistent methodologies	Intermediate	2
	One or more forest cover map(s) (produced in-country); most recent produced before 2000 for 2005 assessment, before 2005 for 2010 assessment, before 2010 for 2015 assessment, before 2015 for 2020 assessment; before 2020 for 2025 assessment.	Good	3
	Multiple forest cover maps (produced in-country); most recent produced after 2000 for 2005 assessment, after 2005 for 2010 assessment, after 2010 for 2015 assessment, after 2015 for 2020 assessment; after 2020 for 2025 assessment.	Very good	4
Use of national forest inventories for forest monitoring	No forest inventory	Low	0
	One forest inventory (externally produced)	Limited	1
	Multiple forest inventories (externally produced); or in-country, but no full cover for all forests	Intermediate	2
	One or more forest inventories (produced in-country); most recent before 2000 for 2005 assessment, before 2005 for 2010 Assessment, before 2010 for 2015 assessment, before 2015 for 2020 assessment; before 2020 for 2025 assessment.	Good	3
	Multiple forest inventories (produced in-country); most recent produced after 2000 for 2005 assessment, after 2005 for 2010 assessment, after 2010 for 2015 assessment, after 2015 for 2020 assessment; after 2020 for 2025 assessment.	Very good	4

Inclusion of mangroves in Nationally Determined Contributions (NDCs)	We assigned 1 point for each NDC in which mangroves are mentioned in relation to biodiversity conservation or adaptation to or mitigation of climate change. The total score is therefore the number of NDCs in which mangroves are explicitly mentioned, providing a measure of their consistent inclusion within national policy targets. We capped the score at 4, although some countries have included mangroves more times than this.	Low Limited Intermediate Good Very Good	0 1 2 3 4
Inclusion of mangroves in Greenhouse Gas National Inventory Reports (NIRs)	We assigned 1 point for each NIR in which data for mangroves are explicitly reported. The total score is therefore the number of NIRs in which mangroves are assessed, providing a measure of their consistent inclusion within national greenhouse gas inventories. We capped the score at 4, although some countries have included mangroves more times than this.	Low Limited Intermediate Good Very good	0 1 2 3 4

Comparing alternative independently produced maps of mangrove extent

We then sought to understand how nationally produced estimates of mangrove extent compared against global maps that have been developed by the mangrove scientific community. Mangroves have been extensive mapped over the past 25 years given the fundamental importance of maps for monitoring changes in mangrove extent, carbon stocks, and biogeography (see Ximenes et al. 2023 for a review of prominent mangrove extent maps). A handful of (at their time, groundbreaking) maps have been produced for distinct years (e.g., 2000), which employ a mix of compiling national or regional maps, unsupervised classification of satellite imagery, and advanced geospatial mapping techniques such as object-based image analysis and use of higher resolution imagery (Spalding et al. 2010; Giri et al. 2011; Jia et al. 2023). Despite the early importance of these maps, they do not directly address changes in mangroves extent. Thus, more recent work has focused on development of time-series of mangrove extent, which explicitly map changes through time (Bunting et al. 2018; Hamilton and Casey 2016; Hamilton and Presotto 2024; Zhang et al. 2025; Bunting et al. 2022; Goldberg et al. 2020).

Given our objective was to compare independent mangrove extent estimates against country-reported values through time, we used three mangrove time series in our analyses. We chose to exclude the Goldberg et al. time series given their dataset only spans 2000-2016. Each time series provides binary presence/absence of mangrove extent at roughly 30m spatial resolution; however, they vary in the underlying satellite imagery, and methods employed (Table 2). For example, the Global Mangrove Watch

(GMW) dataset uses synthetic aperture radar (SAR) data that is sensitive to forest structure and presence of water (important for mapping mangroves), whereas the Continuous Global Mangrove Dynamics (CGMD) dataset employs optical imagery but an improved change detection algorithm to better account for gains in mangrove extent. In comparing the three time-series datasets against country-reported estimates, we do not intend to identify a "best" dataset or make any assumptions that one type of data is more accurate than another. Rather, we compare the datasets solely as an informative process to better understand their strengths and limitations. Each time series dataset provides maps that span the 2005-2020 period (with CGMD spanning 1984-2023), which aligns with the primary reporting years of the FRA reports. However, they do not cover the FRA estimates reported this year (2025), and we consequently excluded this year from our comparisons.

In addition to the global maps mentioned here, several countries have detailed national land cover maps (e.g., Indonesia's One Map, the U.S.'s National Land Cover Database) that often include mangrove extent. We did not collate and assess each of these national scale maps given the challenges of identifying, accessing, and evaluating these maps for the full set of countries we examined. However, in assessing the data sources within the FRA reports, we identify where and when national level maps (such as Indonesia's One Map) are incorporated into country-level reporting as part of the FRA.

Table 2 | Technical summary of independently produced time series of global mangrove extent used in this study. The three time series are compared against nationally reported estimates of mangrove extent compiled by this study.

Dataset	**Description**	**Resolution (m)**	**Available Years**	**Reference**
Global Mangrove Watch v. 3.0 (GMW)	**Approach:** Extremely randomized tree classification of Landsat 5 TM, Landsat 7 ETM+ and ALOS PALSAR L-band dual polarization (HH + HV) satellite imagery.	25	1996, 2007-2010, 2015-2020	(Bunting et al. 2022)
Global Mangrove Cover for the 21st Century (GMC-21)	**Approach:** Integration of multiple maps of mangrove extent in ~2000 to establish a baseline followed by application of annual tree cover loss & gain to determine annual extent. The dataset provides mangrove extent using two separate approaches: binary presence/absence for each pixel, and a continuous metric in which extent is adjusted using percent canopy cover.	27.5	Annually 2000-2020	(Hamilton and Presotto 2024; Hamilton and Casey 2016)

Continuous Global Mangrove Dynamics (CGMD)	**Approach:** Random Forest classification for three baseline years (the 1980s, 2010, and 2023), followed by a change-detection algorithm to identify change and produce the intermediate annual maps.	30	Annually 1984-2023	(Zhang et al. 2025)

Evaluating changes in monitoring capacity through time

We evaluated how capacities for monitoring mangroves have changed through time using two approaches: i) testing for convergence in the country-reported and independent estimates of mangrove extent, and ii) assessing changes in the country-level remote sensing and forest inventory scores. The first operates under the hypothesis that as mapping methods have improved over the last 20 years, we expected national and global estimates to converge over successive generations. The second approach uses our qualitative data from the FRA reports to examine whether countries are adopting best practices (i.e., use of mapping technology) and standards (i.e., internally produced, consistent, repeatable, and updated) for reporting mangrove extent.

To test whether differences between the country-reported and independent estimates were larger in the 2005 reports relative to those from 2020, we calculated normalized differences between the estimates and examined whether these reduced through time. We compared the country-reported estimates for 2005, 2010, 2015, and 2020 against corresponding estimates from all three time series datasets (GMW, GMC-21, and CGMD). The one exception was GMW, which does not estimate mangrove cover in 2005; we therefore substituted GMW's estimate from 2007. We then normalized the country-reported estimates using each time series dataset (see Eq 1) and compared the trends in normalized differences through time. A trend towards 0 was interpreted as evidence of convergence between the national and independent mangrove extent estimates and suggestive of improved monitoring capacity by national actors.

Eq 1. $$Normalized\ Difference = \frac{(FRA_{ha} - Independent\ Estimate_{ha})}{Independent\ Estimate_{ha}}$$

Second, we examined how country-level scores for remote sensing and forest inventories have changed over the last 20 years. We assigned scores to each report for all countries using the indicators in Table 1. We then averaged the scores across all countries for each reporting year and plotted the scores through time. An increase in the scores indicated increased autonomy in monitoring, consistency in reported data, and recency of the data. We understood each of these criteria to suggest improvement in monitoring capacities.

Comparison of mangrove monitoring capacities and policy targets for mangroves

Finally, we cross-referenced our indicator scores for mangrove monitoring and incorporation of mangroves within NDCs and NIRs. We sought to understand whether those countries that have consistently included mangroves within their NDCs and NIRs are also the countries with the strongest capacities for monitoring. Conversely, we were also interested in identifying countries that have consistently integrated mangroves into their climate policy and commitments, but with limited monitoring capacities. To examine these, we mapped all two-way combinations of remote sensing capacity, NFI capacity, NDC integration, and NIR integration. All analyses and figures were produced using Program R (v 2025.05.1+513).

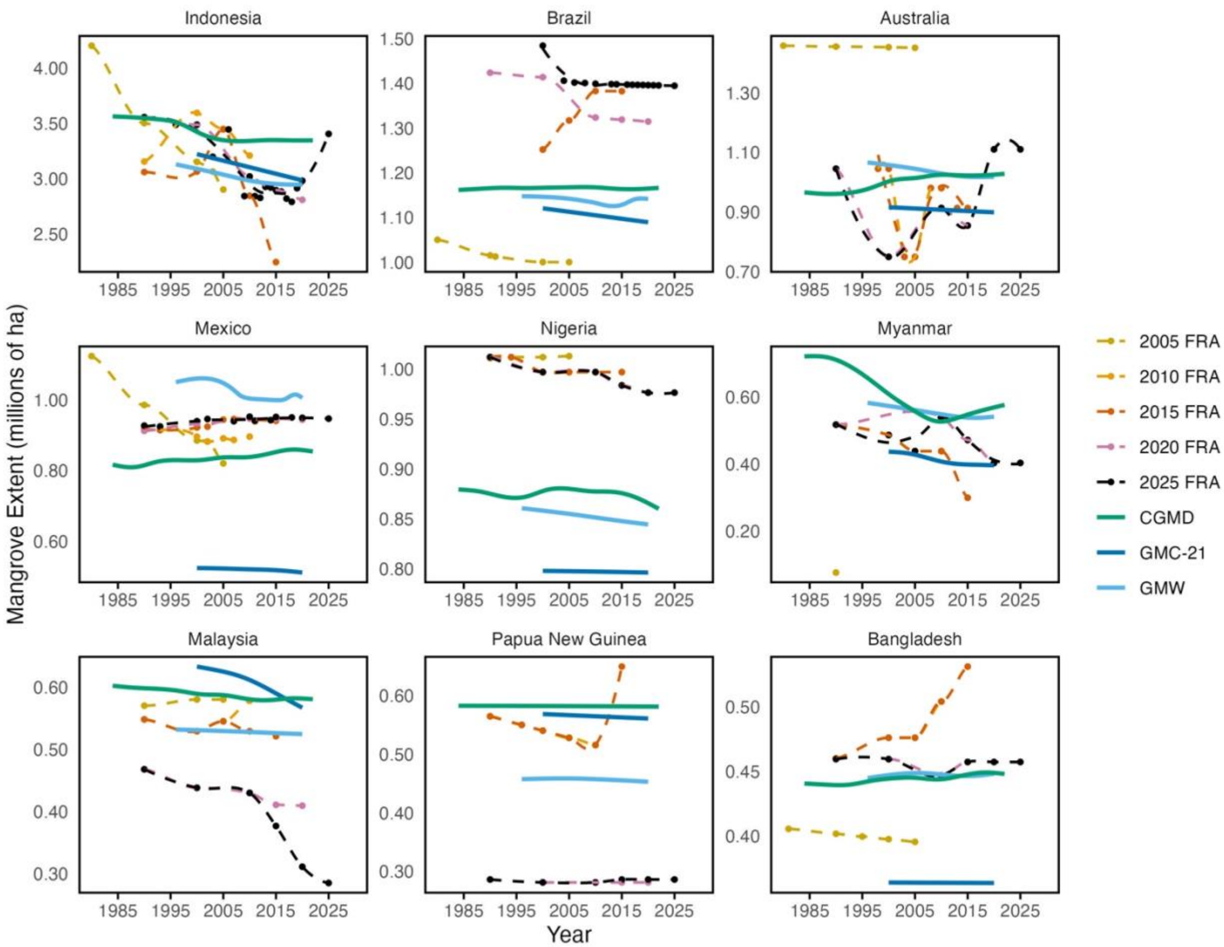
Results

Comparison of country-reported and independently produced mangrove extents

The country-reported mangrove extents were highly variable across the five report years. Figure 1 shows country-reported extents and their comparable estimates from the time series datasets for the top nine mangrove holding countries (representing ~61% of global mangrove cover). No consistent patterns (e.g., over or under-estimation of country-reported estimates relative to the time series estimates) emerge from the data. For example, some countries (e.g., Indonesia, Myanmar, and Australia) reported data that aligned closely with independent estimates in recent reporting years, whereas others report substantially higher (Brazil & Nigeria) or lower (Malaysia and Papua New Guinea) estimates. However, we did observe systematic differences in the time-series datasets as a function of how "forests" are defined. For example, extent estimates by GMC-21 are almost always lower than GMW and CGMD due to the GMC-21 being based on the Hansen Global Forest Cover Change dataset, which removes trees less than 5m in height. Mangroves in Indonesia, Malaysia, and Papua New Guinea tend to be tall, and so we see a smaller discrepancy between GMC-21 and the other two datasets for these countries.

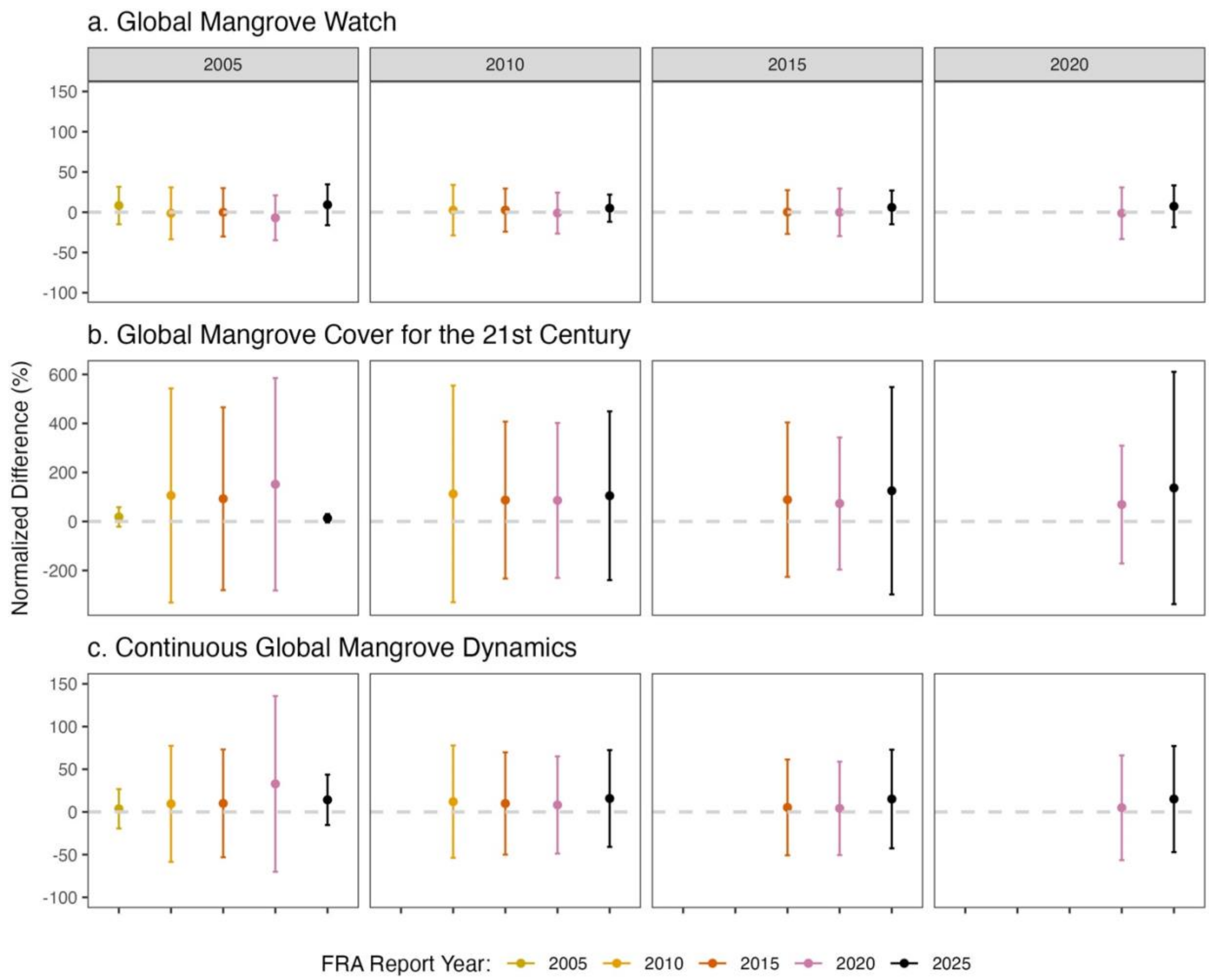
We also did not see strong evidence suggesting that country-reported and independent estimates are converging through time. For some countries, estimates from later reports tended to converge relative to estimates from 2005 (e.g., for Brazil, Australia, Myanmar, and Bangladesh). However, our monitoring scores indicated that, of these four countries, only Brazil and Bangladesh substantial improved their mapping capacities from 2005 to later years (Table S1) whereas Australia and Myanmar appeared to have strong capacities as early as 2005. Across the three time series datasets, we generally saw close alignment through time, except for GMC-21 reporting substantially lower values for Mexico and Bangladesh.

Figure 1 | Temporal trends in country-reported and independent estimates of mangrove extent. Comparison of country-reported mangrove extents and three continuous series of global mangrove extent (GMW, GMC-21, & CGMD). Data for the top nine mangrove holding countries are presented, representing ~61% of global mangrove extent in 2020 (per GMW data). The trend lines were fit using the Generalized Additive Model (GAM) function in R.



When we normalized the differences between the country-reported and the independent estimates for the top 40 mangrove holding countries (representing 96% of global mangrove cover), we also observed substantial variability in the differences through time (Figure 2). We did not observe any clear pattern of estimates from recent reports (e.g., the 2005 estimate provided in the 2025 report) aligning more closely with the time series estimates relative to earlier reports (2005 estimate from the 2005 report). However, we did see strong variation in normalized differences across the three time series datasets. Averaged across all report years, GMW had the smallest normalized difference (1.7 ± 1.4%; mean & standard deviation), followed by CGMD (9.9 ± 3.0%), and GMC-21 (94.8 ± 17.6%). The large, normalized difference between the country-reported estimates and the GMC-21 data was largely driven by the Bahamas and Pakistan. Excluding these two countries brought the average GMC-21 difference in line with the other two datasets (11.4 ± 2.4%). The Bahamas appears to have great variation across the three time-series datasets and scored poorly (0 across all five FRA reports) given its use of a single mangrove extent estimate from 2005-2025.

Figure 2 | Comparison of country-reported and independent mangrove extent estimates. Normalized differences between country-reported mangrove extent and independently produced time series data from a) Global Mangrove Watch, b) the Global Mangrove Cover for the 21st Century, and c) the Continuous Global Mangrove Dynamics for 2005, 2010, 2015, and 2020. The panels (i.e., columns) correspond to distinct timepoints for mangrove extent estimates, whereas the colors denote the FRA report year providing that estimate. Individual points are averaged normalized differences across all countries, and error bars are standard deviations of the means.



Analysis of country-level capacities for mangrove monitoring

Our scoring analysis of country-level capacities for mangrove monitoring also showed substantial variability in current capacities for monitoring mangroves (Figure 3). Of the top ten mangrove-holding countries (~63% of global mangrove extent), all scored at least a 3 for the use of remote sensing, except Nigeria (Table S1). However, only five of these top ten countries clearly had NFIs that allowed estimate of biomass/carbon stocks in a mangrove stratum, again indicating that field-based NFIs have been slower to incorporate mangroves compared to use of remote sensing. No clear geographic patterns in remote sensing and NFI capacity emerged (Figure 3).

Contrary to our comparison of country-reported and independent estimates, our scoring analysis shows clear improvements in country-level monitoring capacities over recent decades (Figure 4). We scored the FRA reports for 35 countries, which host ~95% of global mangrove cover. The average score for use of remote sensing to monitor mangroves increased from 2.09 in 2005 to 2.85 in 2025 (out of a maximum score of 4), representing a 36% improvement in the score over 20 years. Across all countries, the 2020 score dropped relative to 2015, which was primarily due to the “recency” component of the indicator, with many countries using extent estimates that predate 2015 for the 2020 FRA. The same pattern held in 2025 but was offset by a greater number of countries improving their score from intermediate (2) to good (3) capacities (Figure 4b).

Average scores for integration of mangroves into NFIs were consistently lower than our scores for use of remote sensing (ranging from 0.82 in 2005 to 1.58 in 2025). However, despite the generally lower integration of mangroves into NFIs, the percentage increase in the NFI score (93%) was nearly three times larger than that of remote sensing (36%). This reflects the recent movement of several nations, such as Suriname, towards establishing a national forest stratum for mangroves and monitoring it through permanently sampled forest plots. Most of the improvement occurred between 2005 and 2015, as NFI capacity scores plateaued in 2020 and 2025 (Figure 4a & 4c).

Figure 3 | Current capacities for monitoring mangroves. Country-level capacity for monitoring mangroves via use of (a) remote sensing (RS) approaches and (b) national forest inventories (NFI), as per data sources and methods from the 2025 Forest Resource Assessment country reports. Criteria for each of the scores are provided in Table 2.

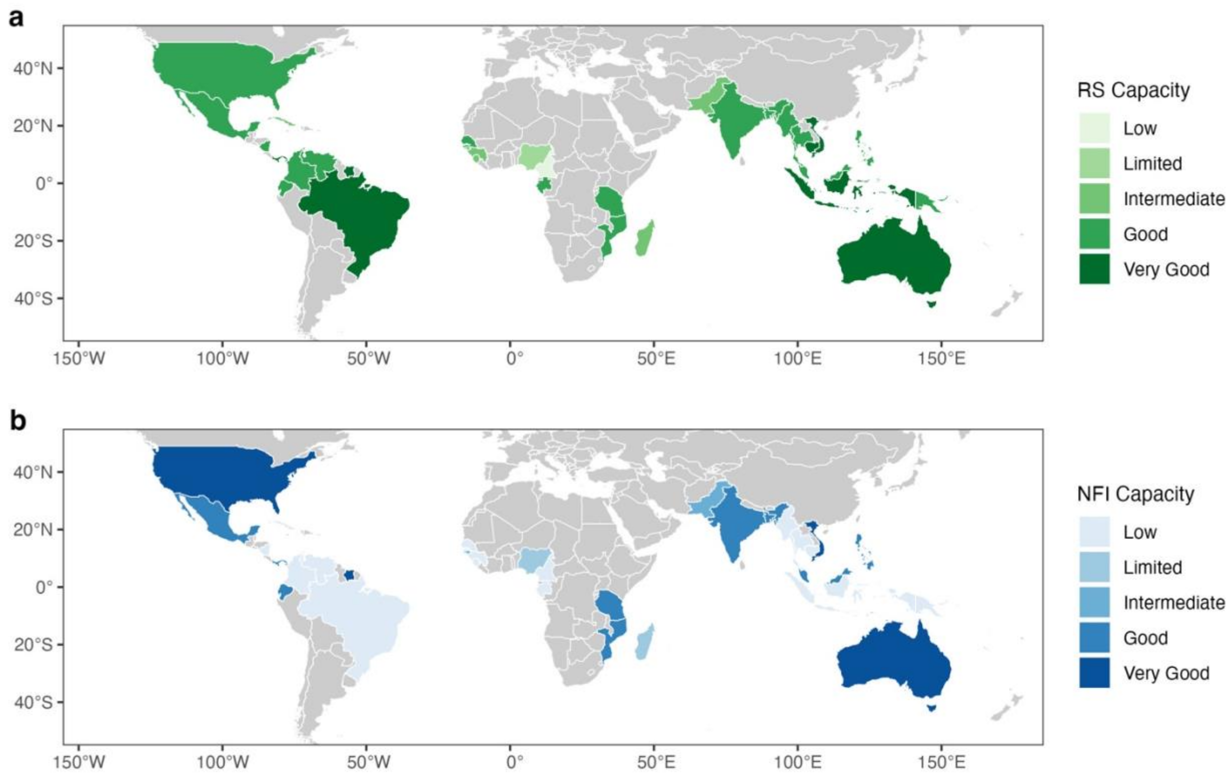
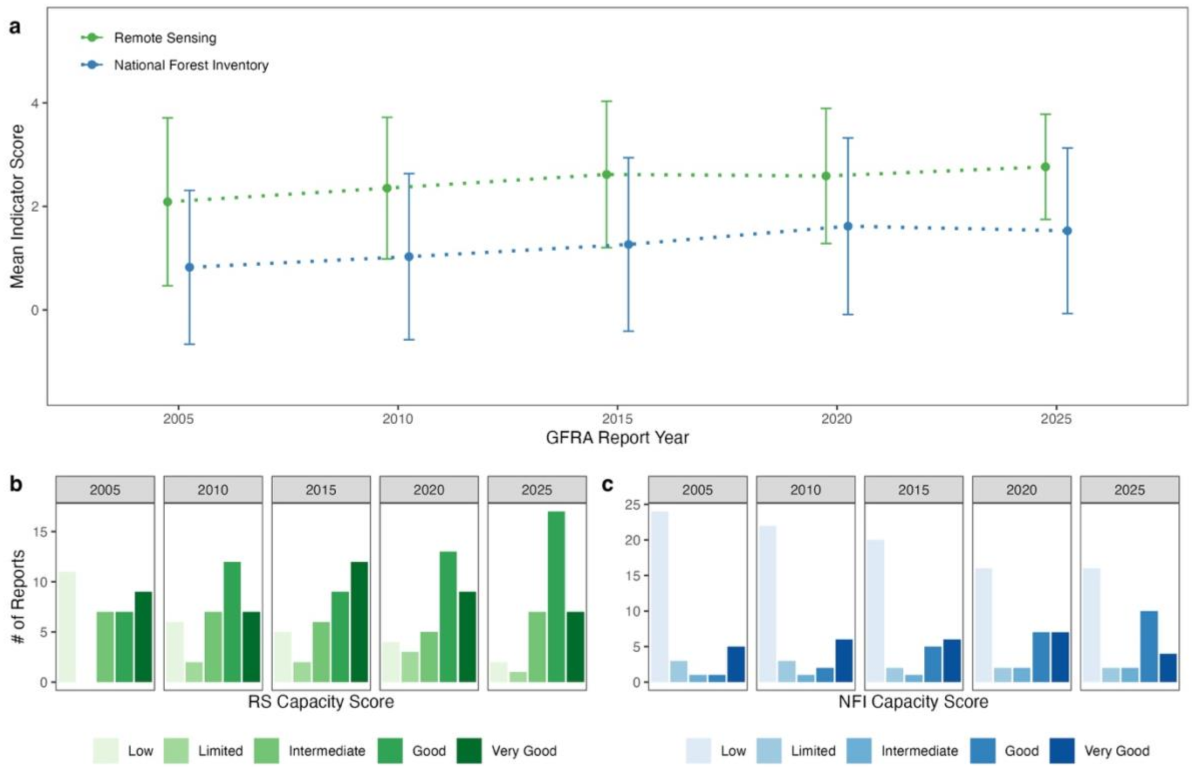


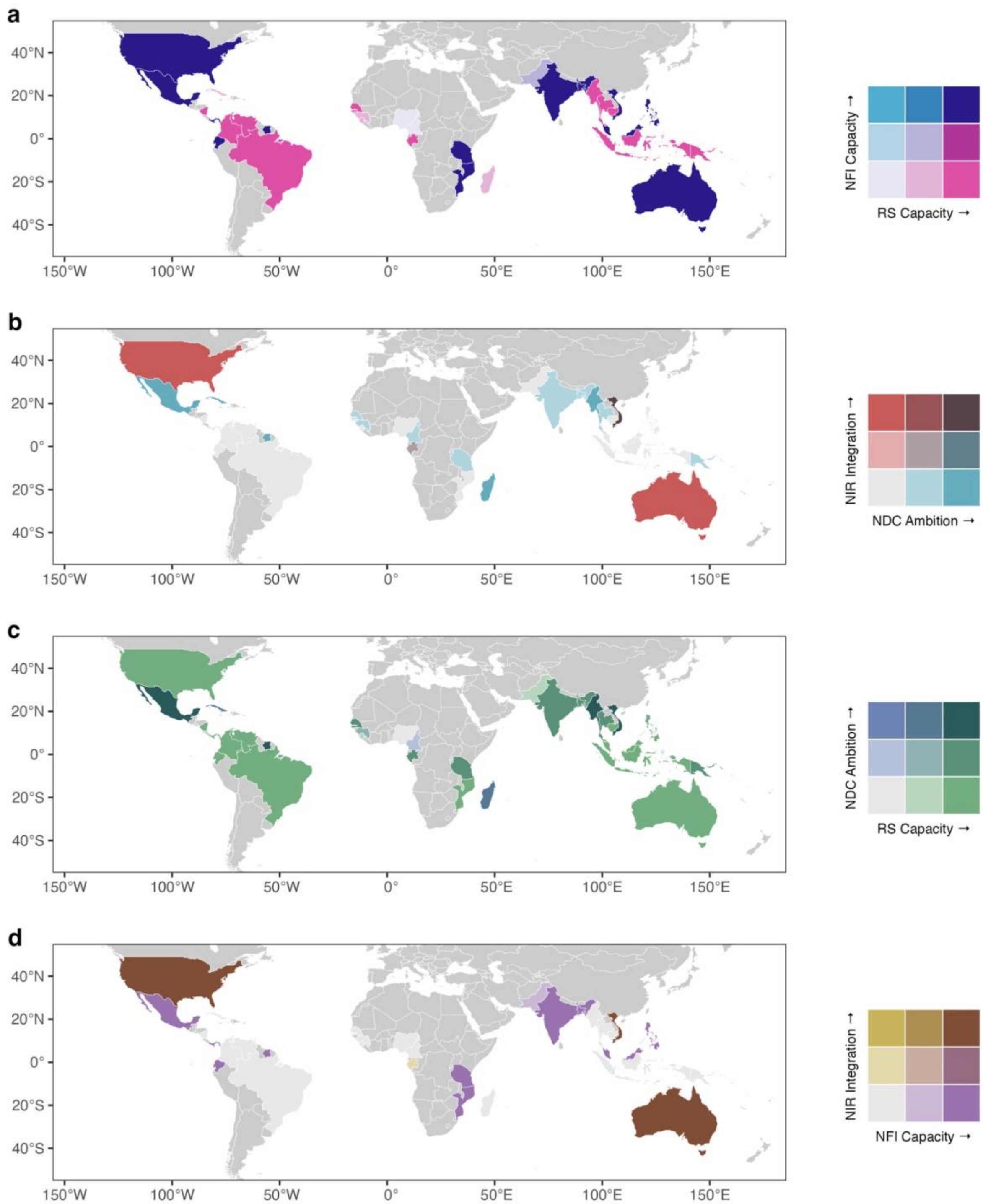
Figure 4 | Changes in national mangrove monitoring scores. Changes in a) average national capacities for monitoring mangroves through remote sensing (RS) and national forest inventory (NFI) approaches; b) distribution of scores for national RS capacity, and c) distribution of scores NFI capacities. Criteria for each of the scores are provided in Table 2, and the maximum score (for both RS and NFIs) that a country can receive is 4. In panel a, the points are mean values whereas the error bars are standard deviations.



Comparison of mangrove monitoring capacity with policy ambition

To understand how capacities for monitoring mangroves relate to national policy targets and emissions reporting, we compared the country-level scores on monitoring and policy. We had complete sets of scores for 33 countries, representing ~95% of global mangrove cover (Figure 5). Across this subset of countries, 26 had high national-level capacities for monitoring mangroves (RS score ≥ 3), but only 13 had comparably high NFI capacities (NFI score ≥ 3). Twenty-two countries included mangroves in their NDCs (with four countries scoring a 3 or higher), and just nine countries included mangroves in their NIRs. Only four countries (Australia and Vietnam) reported mangroves as a separate component of their NIRs more than once (although note that Costa Rica, which we did not assess here, also includes mangroves in its NIR). Across all four indicators, a handful of countries consistently scored highly (Australia, Mexico, Suriname, the United States, and Vietnam), whereas the lowest scoring countries featured the Bahamas and a handful of west African countries (Cameroon, Nigeria, Sierra Leone). Our two-way comparisons across the four criteria suggest that RS capacity scores tend to be higher than NFI capacities, and inclusion of mangroves in NDCs tends to outpace their integration within NIRs (Figure 5).

Figure 5 | Two-way comparisons of mangrove monitoring capacities and policy ambition. Comparison of a) capacity for use of remote sensing (RS) vs. inclusion of mangroves within national forest inventories (NFI); b) continuous inclusion of mangroves in Nationally Determined Contributions (NDCs) vs. integration within Greenhouse Gas National Inventory Reports (NIRs); c) capacity for use of RS vs. consistent inclusion of mangroves in NDCs; and d) inclusion of mangroves within NFIs vs. integration of mangroves within NIRs.



Discussion

Changes in mangrove monitoring capacities over the last 20 years

Our analyses identified a diversity of data sources and methods for reporting on national mangrove conditions within the FRA reports. Synthetic desk reviews, such as the United Nations Food and Agriculture Organization's "The World's Mangroves: 1980-2005" (Spalding et al. 2010; 1997; FAO 2007; Ruiz-Luna et al. 2008), featured prominently in the early 2000s. Mangrove extent estimates from these synthetic studies were widespread across FRA reports and were frequently carried forward or used to derive linear extrapolations for later years (e.g., Gabon, Sierra Leone, and Pakistan). More recently, many countries have adopted internal mapping approaches or engaged with international consultants (e.g., through the REDD+ readiness processes) to map their land cover, which have improved national estimates of mangrove cover. However, these consultant driven processes have not always translated to consistent and repeatable monitoring, as they sometimes result in single year maps that are employed similarly to the 2007 FAO reports (i.e., carried forward or used for linear extrapolation). In the most recent reports, we observed widespread improved capacities for use of remote sensing for mangrove monitoring (~70% of countries in the 2025 report with a score of 3 or higher; Figure 4b & Table S1). This finding likely reflects the increased accessibility of satellite data, spatial processing, and computing power (Islam et al. 2025), prioritization of mangroves as a target ecosystem for conservation, and broader engagement with structured inventory processes (e.g., Ramsar's National Wetland Inventory process).

Our comparison of the country-level estimates against the three time series datasets (GMW, GMC-21c, and CGMD) highlighted substantial variation within and across the mangrove extent estimates (Figure 1). Each of these time series is based on different underlying imagery sources and mapping methodologies, and thus we do not perceive one as outperforming the others. We also do not assume country-reported or independent estimates are systematically more accurate than the other. Rather, each data type plays an important role in different contexts. Global maps of mangroves are developed to reduce uncertainty at global scales and therefore may miss locally important areas or key characteristics of mangroves (Cissell et al. 2021; Canty et al. 2025). For instance, Belize and China are shown to have many small patches of short-stature mangroves, which are poorly captured by global mapping efforts that employ satellite imagery at 30m or coarser resolutions (Cissell et al. 2021; Hu et al. 2020). These mangroves often do not fall within national definitions of "forest" due to their low canopy height and may consequently be mapped and reported within a "wetlands" category. Locally calibrated maps are likely to be more accurate (e.g., by reflecting national definitions or adapting to urban conditions) than global maps in many instances (Sun et al. 2025; Reyes et al. 2024). However, for countries that use linear extrapolations or carry forward earlier estimates, updated independent maps may provide more recent and more accurate estimates. For countries with geospatial capacity but no structured mangrove mapping process, independent maps may also form an entry point for locating training data upon which to build locally calibrated models (Reyes et al. 2024). We observed some adoption of this in the most recent 2025

FRA report—both Colombia and Venezuela employed data from GMW to estimate national mangrove cover in recent years.

Formally integrating mangroves into NFIs appears to lag behind the use of remote sensing for monitoring, which mirrors trends in monitoring forests of all types (Nesha et al. 2021). We also observed a parallel trend in our analysis of NIRs, where mangroves were rarely separated out as their own land cover stratum. Mangroves are typically included in a general "forests" category (Figure 5d), which limits the ability to monitor changes in their condition and may miss important carbon pools (such as soil organic carbon), which is critical for maximizing benefits from blue carbon mechanisms. Establishing permanent plots in mangroves is challenging due to remote field conditions and difficult forest access, yet select countries–such as Australia, Bangladesh, India, Malaysia, Mexico, Mozambique, and the United States–have done so (Henry et al. 2021; Arnold et al. 2023). Other countries (such as Honduras and Guatemala) also have permanent plots in mangroves, but they do not appear to be formally integrated into NFIs or United Nations based reporting processes. Finally, countries such as Suriname have recently established mangrove strata within NFIs and are undertaking field data collection for international reporting structures.

Mangroves present challenges for NFIs beyond just field accessibility considerations. Given the often small, linear footprint of mangroves along coastlines, sample plot frequency typically needs to be intensified within mangroves to accurately estimate area and condition (Brown 2015). Moreover, as mentioned above, protocols for measurements might need to be adapted to accurately track key features of mangroves—such as deep soil organic carbon pools. Statistical techniques such as "small-area estimation" may also be promising for increasing the precision of inventory-based estimation without the need for establishing additional inventory plots (Wiener et al. 2021; Brown 2015). These techniques employ remotely sensed proxies or spatial models to improve the efficiency of inventories (Lister et al. 2020), and candidate proxies are abundant for mangroves (Sanderman et al. 2018; Simard et al. 2019). Additional work is needed to understand the degree to which mangroves are integrated into forest (or wetland) inventories, as relatively limited detail was provided through the FRA reports.

Linking mangrove monitoring capacity to policy ambition and reporting mechanisms

Our comparison of national-level monitoring capacities and the integration of mangroves into NDCs and NIRs suggests key areas where technical capacity and ambition for mangrove conservation can be improved. As countries move toward implementing their NDCs, they are required to monitor and report on their progress through the Enhanced Transparency Framework (ETF) (Weikmans et al. 2021). Countries must submit Biennial Transparency Reports every two years, including their NIRs and progress towards their NDCs. The Enhanced Transparency Framework purposefully allows flexibility in the data sources that underpin the Biennial Transparency Reports, and others have noted the importance of Earth Observation (i.e., remote sensing) data for meeting these objectives (Hegglin et al. 2022). Our results suggest that many countries may be well positioned to track changes in mangrove extent due to strong monitoring capacities, yet many countries (such as Australia, Ecuador, Malaysia, and the Philippines) have not formally integrated mangroves into their NDCs or NIRs. Conversely, twelve countries that include mangroves in their NDCs explicitly mentioned the need to improve mangrove monitoring and mapping processes. Thus, despite improvement over recent decades, opportunities exist to improve technical capacities for monitoring and better integration mangrove targets within national climate policy. We expect to see greater alignment between NDC, NIR and NFI data as countries transition from Paris Agreement-based reporting requirements to the ETF.

Mangroves and other coastal ecosystems frequently encounter challenges related to their classification (i.e., definition), which has major impacts on their reporting (Acosta-Velázquez et al. 2023). Mangroves may be classified as either forests or wetlands, and multiple agencies outside of those responsible for forests may be engaged in mangrove monitoring/policy. Although focusing on the FRA reports (which have required reporting on mangroves as a special category since 2005) gave us a consistent and globally applicable view of national mangrove monitoring, not all mangrove-related policy or data sources may be integrated into the FRAs. This is a notable limitation of our analysis that could be overcome in future investigations of national reporting mechanisms for wetlands. For example, National Wetland Inventories that seek to fine-tune inventory processes to the unique nature of wetland ecosystems are now being developed and promoted across many countries (Stephenson et al. 2025).

Reclassifying mangroves as wetlands is attractive for many countries, as wetlands are eligible for accounting of soil organic carbon under the IPCC's guidelines (i.e., soil carbon is typically excluded from "forests" per IPCC guidance), which can translate to increased conservation finance. However, reclassifying mangroves as wetlands is not without its challenges, as reclassification requires recalculation of National Greenhouse Gas Inventories along countries' entire reporting timelines (IPCC 2014; Raturi et al. 2024). When mangroves are reported within a "forests" classification, they may already be incorporated into results-based payment mechanisms such as REDD+, making reclassification administratively and financially unfeasible until the end of the corresponding crediting or payment period. However, doing so negates the disproportionate magnitude of carbon stores in mangrove soils that might be included in national accounting and reporting. Nevertheless, support for National Wetlands Inventories is increasingly available (Stephenson et al. 2025), and we anticipate more widespread classification of mangroves as wetlands in the future. Future work should assess and understand the impacts of such reclassifications, as changing definitions of mangroves are known to greatly influence statistics of mangrove extent and condition (Acosta-Velázquez et al. 2023; Canty et al. 2025).

Looking Forward

Our assessment highlights both progress and gaps in national monitoring capacities, target setting for climate change mitigation, and reporting mechanisms for mangroves. Ultimately, these three processes are interlinked—highlighting mangroves within NDCs might signal their prioritization, which may lead to enhanced monitoring and incorporation within reporting mechanisms. Conversely, strong monitoring processes and accurate data on shifts in mangrove extent and condition will enable countries to set achievable targets, which will facilitate their engagement in international climate mitigation processes. Our analyses highlight countries and regions that already have strong capacities for monitoring mangroves, as well as areas where enhanced capacity building and resources may drive more ambitious and more tractable targets. Greater adoption of remote sensing approaches promises an accessible and promising foundation for monitoring mechanisms that directly link to policy targets. However, integration of mangroves into field-based inventories is critical for tracking changes in the condition (e.g., biodiversity, carbon stocks, nutrient cycling, health) of these ecosystems—which more directly proxy the ecosystem services that national governments seek to protect. Despite our focus on climate policy mechanisms, enhanced policy ambition and monitoring will help support the broader array of mangrove ecosystem services that benefit vulnerable coastal communities across the globe.

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SUPPLEMENTARY TABLES & FIGURES

Table S1. Assessments of data sources for monitoring mangrove area using remote sensing and biomass stocks using national forest inventories. See Table 1 for an explanation of the remote sensing and national forest inventory indicator scores.

Country	Cumulative mangrove extent (%)	Use of remote sensing for monitoring mangrove extent					Integration of mangroves into national forest inventories				
		2005	2010	2015	2020	2025	2005	2010	2015	2020	2025
Indonesia	20	2	3	4	4	4	0	0	0	0	0
Brazil	28	2	3	4	3	4	0	0	0	0	0
Australia	35	4	4	4	4	4	4	4	4	4	4
Mexico	42	4	4	4	3	3	0	3	4	4	3
Nigeria	47	0	0	0	1	1	0	0	0	1	1
Myanmar	51	3	3	3	3	3	0	0	0	0	0
Malaysia	54	4	4	4	4	3	4	4	4	4	3
Papua New Guinea	58	3	3	4	3	3	0	0	0	0	0
Bangladesh	61	0	3	3	3	3	0	3	3	4	3
India	63	4	4	4	4	3	4	4	4	4	3
Cuba	66	0	0	0	0	2	0	0	0	0	0
Mozambique	68	3	2	2	3	3	3	3	3	4	3
Philippines	70	4	3	4	4	3	1	1	1	3	3
Venezuela	72	3	3	3	3	3	0	0	0	0	0
Colombia	74	3	3	3	0	3	0	0	0	0	0
Madagascar	75	0	1	1	1	2	3	3	3	3	1
Guinea-Bissau	77	2	2	2	2	2	2	2	2	2	2
Thailand	79	3	3	3	3	3	0	0	0	0	0
United States	81	0	2	4	4	3	4	4	4	4	4
Guinea	82	0	1	1	1	2	0	0	0	0	0
Cameroon	83	0	0	0	0	0	0	0	0	0	0
Vietnam	85	0	4	4	4	4	0	4	4	4	4
Gabon	86	0	0	0	2	3	0	0	0	0	0
Bahamas	87	0	0	0	0	0	0	0	0	0	0
Panama	88	4	4	4	3	4	1	1	3	3	3
Ecuador	89	4	3	3	4	3	0	0	3	3	3

Sierra Leone	90	2	2	2	2	2	0	0	0	0	0
Senegal	91	4	3	3	3	3	0	0	0	0	0
Tanzania	92	2	2	2	3	3	0	0	3	3	3
Pakistan	92	2	2	2	2	2	0	0	0	2	2
Suriname	93	2	2	2	3	4	0	0	0	3	4
Nicaragua	93	3	3	3	3	3	0	0	0	0	0
French Guiana	94	0	0	3	2	2	0	0	0	3	3
Cambodia	94	4	4	4	4	4	0	0	0	0	0