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Perspective

Harnessing Big Data to Support the Conservation and Rehabilitation of Mangrove Forests Globally

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Mangrove forests are found on sheltered coastlines in tropical, subtropical, and some warm temperate regions. These forests support unique biodiversity and provide a range of benefits to coastal communities, but as a result of large-scale conversion for aquaculture, agriculture, and urbanization, mangroves are considered increasingly threatened ecosystems. Scientific advances have led to accurate and comprehensive global datasets on mangrove extent, structure, and condition, and these can support evaluation of ecosystem services and stimulate greater conservation and rehabilitation efforts. To increase the utility and uptake of these products, in this Perspective we provide an overview of these recent and forthcoming global datasets and explore the challenges of translating these new analyses into policy action and on-the-ground conservation. We describe a new platform for visualizing and disseminating these datasets to the global science community, non-governmental organizations, government officials, and rehabilitation practitioners and highlight future directions and collaborations to increase the uptake and impact of large-scale mangrove research.

Introduction

Scientists, policymakers, and practitioners are increasingly looking for ways to harness big data to improve conservation outcomes.[1,2] Since the advent of satellite remote sensing (SRS) in the 1970s, global datasets have been instrumental for monitoring ecosystem change, identifying proximate drivers of environmental decline, estimating the value of ecosystem services, and tracking progress toward achieving conservation commitments.[3] This has led to the establishment of global initiatives that aim to coordinate the collection, processing, and dissemination of big data obtained directly or derived from SRS. In this data-rich age, non-governmental organizations (NGOs), government officials, and local practitioners can find it difficult to keep pace with and locate management-relevant information to inform conservation and rehabilitation efforts. Greater access to SRS data has stimulated a similar increase in the volume, velocity, variety, and veracity of mangrove datasets to that observed for other ecological systems.[2] However, even though mangroves were among the first ecosystems to be mapped globally at moderate spatial resolutions,[4] coordination between dataset developers has not yet been achieved. We postulate that coordination when developing and utilizing mangrove forest datasets—facilitated by simple open access and analysis tools—will greatly enhance effective conservation of these important ecosystems.

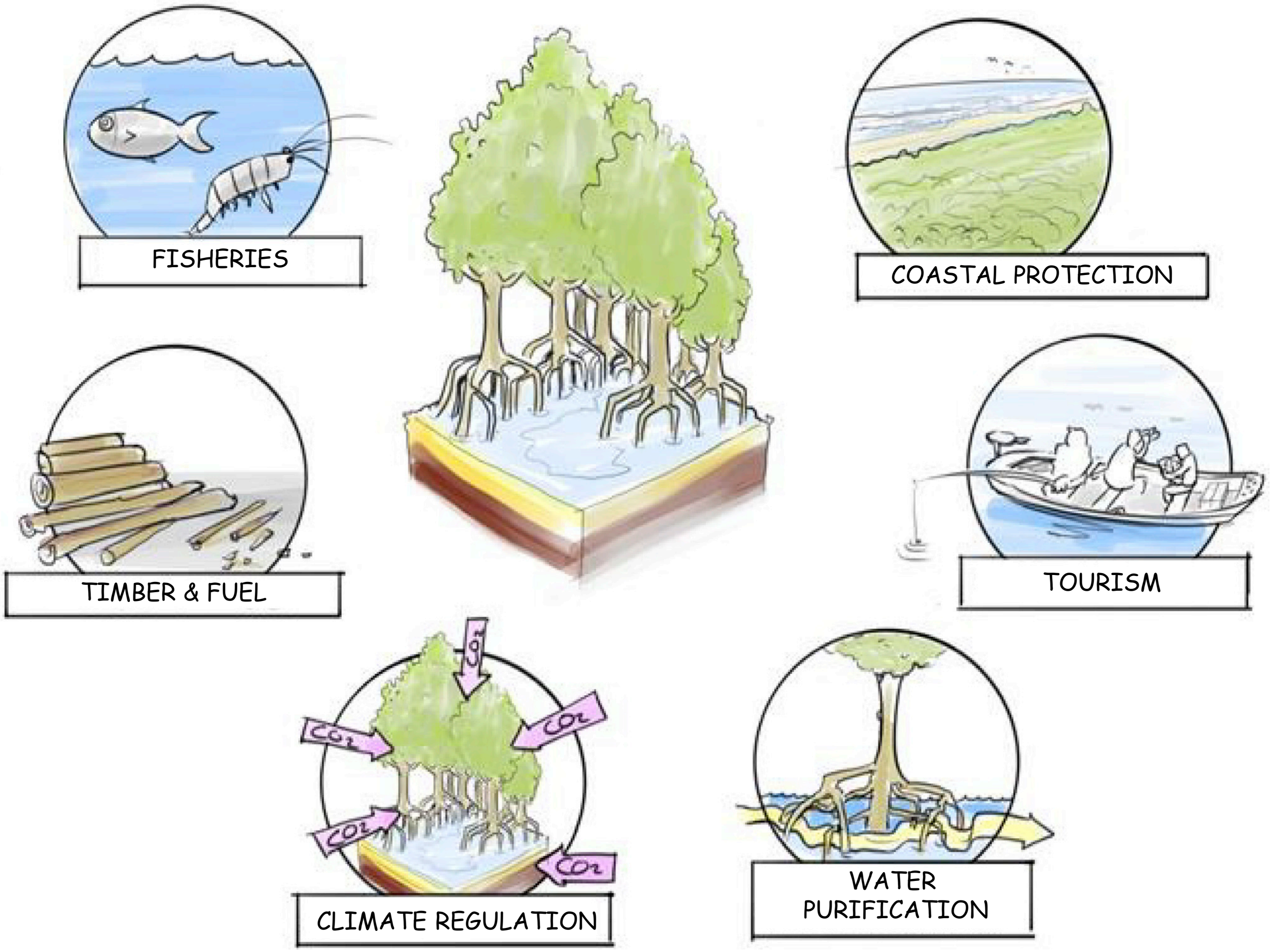

Figure 1. Ecosystem Services Provided by Mangrove Forests
Adapted from Spalding et al.[25]

Mangrove forests occur on sheltered intertidal zones in tropical, subtropical, and some warm temperate regions.[5] Historically, they are thought to have covered over 200,000 km^2 of the world's coastline, but they have suffered large-scale deforestation and degradation,[6] including particularly rapid losses (1%–2% of area per annum) in the second half of the 20th century.[7] Mangrove forests now cover an area of 137,600 km^2,[8] and despite a large decline in the rates of deforestation, they still face a range of pressures. Almost half of the world's population lives within 150 km of a coastline,[9] driving pressure for land and resources. The deforestation of mangroves has largely come from conversion to aquaculture, agriculture, and urbanization,[10,11] and additional areas have been degraded by the exploitation of resources and pollution.[12,13] The expansion of palm oil plantations[14] and mining in intertidal areas are among new and rapidly increasing drivers of mangrove degradation. These threats, coupled with the increased awareness of mangroves' value to people,[15–17] have stimulated growing management and policy interest in the conservation and rehabilitation of mangrove forests.

Mangroves are among Earth's most productive ecosystems[18,19] and support a wide range of biodiversity, including globally threatened plant species,[20] threatened animal species (e.g., the tiger [*Panthera tigris*] and pygmy three-toed sloth [*Bradypus pygmaeus*] [21]), marine megafauna,[22] and functionally important invertebrates.[23] Mangrove forests also provide people with many benefits (via ecosystem services), including timber and fuelwood provision, coastal protection, fishery enhancement, tourism, and climate regulation from decreased CO_2 due to carbon capture (Figure 1).[16,17,24]

Developing a one-size-fits-all management strategy for mangroves is inappropriate given the huge spatial variation in structure, species diversity, abiotic environment, and the threats that affect them. Mangroves exist across a range of climatic[26] and geomorphic[27,28] settings, all of which influence species diversity, forest structure,[29] and ecosystem service provision.[30] Proximate drivers of mangrove deforestation and degradation show substantial geographical variation[11] both within and between regions such that this variability in the root cause of deforestation produces distinct changes in ecosystem service loss.[31] Data on this variation are important because different geomorphic settings, mangrove types, and threats need different management and rehabilitation strategies.[32] A lack of robust and consistent

Table 1. Existing Global Mangrove Datasets

Dataset	Description	Nominal Year	Resolution	Mangrove Extent Used	Download or Viewer	Reference
Mangrove extent and change	composite extent map using remote-sensing and visual-interpretation approaches	1999–2003	–	–	https://data.unep-wcmc.org/datasets/5	Spalding et al.[5]
	first globally consistent remote-sensing-based map of mangrove extent	2000	30 m	–	https://data.unep-wcmc.org/datasets/4	Giri et al.[4]
	Giri et al.[4] dataset refined by the removal of areas above an elevation threshold	2000	–	Giri et al.[4]	–	Tang et al.[39]
	global analyses of mangrove deforestation based on the GFC dataset	annual 2000–2012	30 m	–	http://faculty.salisbury.edu/~sehamilton/mangroves/	Hamilton and Casey[40]
	most current global analysis of extent captures both losses and gains over a 20-year period	1996, 2007–2010, 2015, 2016	25 m	–	https://data.unep-wcmc.org/datasets/45	Bunting et al.[8]
Mangrove biomass	climate-driven model of potential mangrove AGB	–	–	Spalding et al.[5]	–	Hutchison et al.[41]
Mangrove height and biomass	canopy height maps based on a digital elevation model and lidar altimetry	2000	30 m	Giri et al.[4]	https://doi.org/10.3334/ORNLDAAC/1665	Simard et al.[29]
	canopy height maps based on a digital elevation model; biomass derived from global allometric model	2000	–	Giri et al.[4]	–	Tang et al.[39]
Freshwater and sediment impacts on mangrove condition	changes in mangrove extent are modeled against human alteration to free-flowing rivers	–	–	Bunting et al.[8]	–	Maynard et al.[42]
Mangrove fragmentation	global analyses of the change in fragmentation metrics over time	annual 2000–2012	0.2° × 0.2°	Hamilton and Casey[40]	–	Bryan-Brown et al.[43]

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Table 1. *Continued*

Dataset	Description	Nominal Year	Resolution	Mangrove Extent Used	Download or Viewer	Reference
Soil carbon	covariates of climate and location data modeled against measurements of soil carbon	–	∼10 km	Giri et al.[4]	–	Jardine and Siikamäki[44]
	assessment of how soil carbon stocks vary across latitude, hemispheres, and mangrove community composition	2014	–	Hamilton and Casey[40]	–	Atwood et al.[45]
	fine-scale three-dimensional variation in soil-carbon density as assessed by machine-learning approaches	2000	30 m	Giri et al.[4]	https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/OCYUIT	Sanderman et al.[46]
	variation in soil carbon examined in relation to coastal environmental settings via climate-geophysical models	–	∼25 km	Hamilton and Casey[40]	available from the corresponding author upon reasonable request	Rovai et al.[30]
	mangrove soil-carbon stocks across different classifications of coastal environmental settings	–	30 m	Hamilton and Casey[40]	–	Twilley et al.[47]
Aboveground and belowground carbon	field measurements modeled against latitude for estimating total biomass carbon	–	–	WRI and IIED[48]	–	Twilley et al.[49]
	mangrove AGB modeled against latitude; BGB assessed as a relative fraction of AGB	–	∼9 km	Giri et al.[4]	–	Siikamäki et al.[50]
Total carbon	annual assessment of total carbon stocks and losses from deforestation	annual 2000–2012	30 m	Hamilton and Casey[40]	https://dataverse.harvard.edu/dataverse/GMCSD	Hamilton and Friess[51]
Mangrove tourism	analysis of TripAdvisor website to identify mangrove attractions and their usage	up to 2015	–	–	https://maps.oceanwealth.org	Spalding and Parrett[52]

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Table 1. *Continued*

Dataset	Description	Nominal Year	Resolution	Mangrove Extent Used	Download or Viewer	Reference
Coastal protection	global valuation model of the role of mangroves in reducing annual coastal flood damages to people and property	2010	20 km	Giri et al.[4]	https://osf.io/ecs4p/	Losada et al.[53]
Conservation hotspots	conservation hotspots identified by the intersection of threatened megafauna distributions with areas of high mangrove loss	2016	~20 km	Hamilton and Casey[40]	https://megafauna.wetlands.app/	Sievers et al.[22]

Abbreviations are as follows: AGB, aboveground biomass; BGB, belowground biomass; GFC, Global Forest Cover.

large-scale spatial data on mangrove forests has significantly hampered national- and regional-scale policies and solutions for mangrove management and rehabilitation.

This Perspective provides the global conservation science community, NGOs, government officials, and rehabilitation practitioners with an overview of the latest scientific advances in the assimilation, coverage, and availability of global datasets of mangrove extent, environments, ecosystem services, and threats and the potential application of these new datasets and maps for future mangrove conservation and rehabilitation efforts. The paper is split into four sections. First, we provide an overview of existing and forthcoming global datasets relating to mangrove distribution, structure, ecosystem services, and threats to their persistence. Second, we present the challenges of translating these new analyses into policy action and on-the-ground conservation. Third, we outline the current development of a new platform for visualizing and disseminating these datasets in order to put scientific information in the hands of practitioners working at the forefront of mangrove conservation and rehabilitation. Fourth and finally, we highlight future directions and collaborations that are needed to increase the impact and utility of large-scale mangrove research.

Existing and Upcoming Global Mangrove Datasets

Despite being in the golden age of open data access and technological advancement,[33] achieving global conservation targets for coastal ecosystems has been hindered by the absence of globally consistent data on their current and historic extent and condition.[34] Access to resources such as the multidecadal Landsat Earth observation archive[35] and new higher-resolution (both temporal and spatial) satellites (e.g., Sentinels 1 and 2;[36] Planet Labs Dove satellites, https://www.planet.com/) allows analyses over long periods of time and at spatial resolutions capable of mapping linear and naturally fragmented ecosystems such as mangrove forests. Data availability is coupled with greater access to high-performance computing systems[37] and cloud-based geospatial platforms (e.g., Google Earth Engine), enabling rapid planetary-scale SRS data processing and analyses.[38] This combination has coincided with, and stimulated, a number of global-scale analyses (Tables 1 and 2), which together have the potential to answer critical questions related to mangrove conservation (Figure 2). These analyses can be broadly split into three types: (1) baseline products, (2) secondary datasets, and (3) ecosystem service and biodiversity analyses (Box 1).

Baseline Products

Mangrove Extent and Change. Analyses of mangrove extent at large spatial scales have, until recently, relied on temporally static maps from the beginning of the 21st century.[4,5,39] These efforts underpin our understanding of the geographical distribution of mangrove ecosystems globally circa 2000; however, they fail to capture areas of deforestation, degradation, or regeneration. Addressing this, Hamilton and Casey[40] used the Global Forest Cover (GFC) dataset[56] to provide an estimate of deforestation between 2000 and 2012. Although this dataset[40] provided the first globally consistent SRS-based analysis of mangrove losses, it contains limitations related to the definition of forest (e.g., vegetation > 5 m in height) that would potentially exclude short-stature mangroves and areas of mangrove regeneration and colonization (after 2000).

Table 2. Upcoming Global Mangrove Datasets

Dataset	Description	Nominal Year	Resolution	Mangrove Extent Used	Download or Viewer	Reference
Mangrove degradation	changes in the structural condition of mangroves as identified by vegetation index time series	triannual 1984–2018	30 m	Bunting et al.[8]	–	Worthington and Spalding[28]
Drivers of mangrove extent change	machine learning and decision trees used for classifying mangrove loss as commodities, human settlement, erosion, extreme climatic events, or non-productive conversion	2000–2005, 2005–2010, 2010–2016	30 m	Giri et al.[4]	–	Goldberg et al.[54]
	shoreline erosion and surface water change used for identifying erosion hotspots in mangrove forests	–	–	Bunting et al.[8]	–	Bhargava et al.[55]
Mangrove geomorphic typology	mangroves classified according to their geomorphic, deltaic, estuarine, lagoonal and open coast, and sedimentary settings	2016	25 m	Bunting et al.[8]	http://maps.oceanwealth.org/mangrove-restoration/	Worthington and Spalding[28]
Protected-area effectiveness for mangrove conservation	work ongoing	–	–	Bunting et al.[8]	–	–
Restoration potential	expert-driven model of the environmental conditions enabling mangrove restoration at the landscape scale	2016	–	Bunting et al.[8]	http://maps.oceanwealth.org/mangrove-restoration/	Worthington and Spalding[28]
Fishery enhancement	field measurements used for modeling mangrove dependency for invertebrate and finfish species	2016	1 km	Bunting et al.[8]	https://maps.oceanwealth.org	–

A recent initiative that aimed to create the first mangrove-specific global time-series dataset is the Global Mangrove Watch (GMW). GMW is an international scientific collaboration initiated in 2011 through the Kyoto & Carbon Initiative of the Japan Aerospace Exploration Agency (JAXA).[57] The GMW is a consortium of Aberystwyth University (https://www.aber.ac.uk/en), solo Earth Observation (soloEO, https://soloeo.com), Wetlands International (https://www.wetlands.org), the Institute for International Water Management, the Nature Conservancy, and the World Conservation Monitoring Centre (https://www.unep-wcmc.org) and is supported by JAXA through the provision of L-band synthetic aperture radar (SAR) data from JERS-1, ALOS PALSAR, and ALOS-2 PALSAR-2. The GMW aims to provide high-quality global mapping of mangrove extent on at least an annual basis. The GMW has mapped mangrove extent globally by using ALOS PALSAR and Landsat time series for the nominal year 2010, providing a new global baseline of mangrove extent.[8] In addition, the GMW initiative detects changes from the 2010 baseline by using JERS-1 SAR data with a nominal date of 1996; ALOS PALSAR data acquired in 2007, 2008, and 2009; and ALOS-2 PALSAR-2 data annually from 2015 onward at a spatial resolution of 25 m.

As with most global datasets, errors of omission and commission in the GMW maps are inevitable, but the ongoing work to refine and update this data layer is enabling a process of continual improvement. This global dataset is complemented by a large and growing number of national-scale monitoring programs and regional and local studies.[58,59] These smaller-scale datasets potentially provide more accurate measures of mangrove extent and change in response to local drivers and could therefore have greater relevance for on-the-ground management. Local and national datasets also play a crucial role in providing training data for global mapping approaches, contributing to improved accuracy and therefore greater usability. The challenge is that these more local-scale mapping exercises often differ in approach, resolution, and timescales and therefore limit comparison between studies in order to show robust trajectories of mangrove change. Opportunities exist for future research aimed at greater coordination and integration between global, national, and local datasets to leverage the full value of these different analyses.

Mangrove Degradation. Whereas the impact of mangrove loss has been long recognized as a threat to biodiversity and the ecosystem services that mangrove forests support, the role of degradation within extant mangroves has been less widely addressed.[7] In particular, mangrove loss is only one indicator of the conservation status of mangroves,[60] and a positive trajectory in mangrove area could hide substantial changes in habitat quality or ecosystem condition.[61,62] Worthington and Spalding[28] used the Landsat time series to assess change over time in a

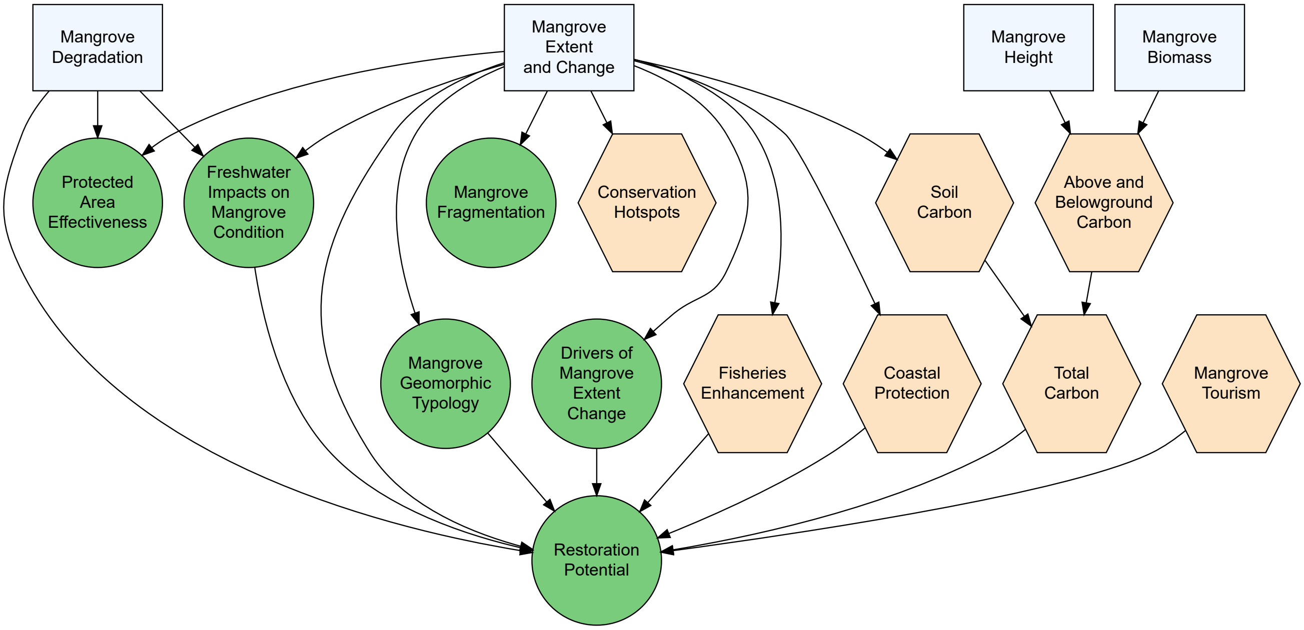


Figure 2. A Roadmap of the Interconnectedness between Global Mangrove Datasets

Pale-blue rectangles, baseline products; green circles, secondary datasets; beige hexagons, analyses of ecosystem services and biodiversity. Arrows represent the integration of products into new datasets rather than causal links between data.

range of vegetation indices (e.g., normalized difference vegetation index) to identify areas that are considered degraded within the most recent GMW extent (i.e., 2016). Such areas could have been affected by timber harvest, alterations due to drainage, or natural disturbances such as cyclones. The identification of such areas could present an opportunity for rapid and effective intervention, including conservation actions to prevent further impacts or highlight places where rehabilitation could require little more than a reduction or cessation of damaging actions.[28]

Height and Biomass. Mangroves exhibit substantial geographic variation in height and biomass as a result of factors such as climate, tidal amplitude, and geomorphic setting. Understanding this variability is crucial for developing accurate models of carbon sequestration and storage within mangrove aboveground biomass (AGB) as part of efforts to mitigate climate change. Initial analyses used correlative approaches linking mangrove AGB to latitude and climate and showed that AGB increased at lower latitudes and with temperature.[41,49,50] More recently, Simard et al.[29] used a global digital elevation model and global Lidar altimetry products to produce a global map of maximum canopy height, basal-area-weighted height, and AGB for the year 2000. Although their study demonstrates global trends in canopy structure with temperature, as well as precipitation and cyclone frequency, the map highlights the significant structural variability at local and regional scales. Areas of Central Africa and South America were hotspots of large (up to 62 m canopy height) and highly productive mangrove forests.[29] Work is underway to update this analysis and to quantify biomass losses from extent change.

Secondary Datasets

Drivers of Change. Understanding the distribution of degradation and loss can provide an impetus for management interventions and for rehabilitation efforts. However, these opportunities are currently hampered by the availability of information on the drivers of mangrove change, which to date have been regionally specific or at relatively coarse resolutions.[10,11] New analyses have used machine learning, decision trees, and cloud computing to map drivers of mangrove loss into categories representing anthropogenic losses (such as commodities, human settlement, and non-productive conversion) and natural losses (such as erosion and dieback from extreme weather events, e.g., cyclones and droughts) globally at a scale of 30 m.[54,55,63] Understanding the socio-economic, political, or environmental background to land-use change can help identify areas better suited for rehabilitation and allow for tailored techniques needed for mangrove rehabilitation.[10] Work is also underway to measure the impacts of anthropogenic and natural loss on the mangrove carbon cycle.

Freshwater Impacts on Mangrove Condition. Whereas *in situ* natural and anthropogenic drivers can result in the conversion of mangrove forests to other land types,[54,55] coastal ecosystems are inextricably linked to processes within the wider landscape. Barrier construction and water abstraction for agricultural, industrial, and residential uses can alter the natural flow regime and sediment delivery, affecting the health and distribution of mangrove forests.[64] Maynard et al.[42] mapped changes in mangroves near river end points within the GMW dataset in relation to metrics of human alteration to free-flowing rivers.[65] The study found that 20% of the global variability in mangrove extent change near rivers could be correlated to river attributes and that the extent of sediment trapping within a river is the biggest driver.[42] Although the study highlights the potential impact of anthropogenic effects on upstream catchment processes, future analysis is needed to identify the direct causal drivers of mangrove change.

Mangrove Typology. The spatial variability in mangrove forests, in terms of their geomorphological setting and structure,

Box 1. Glossary of Key Data Types

The mangrove analyses described below rely on two foundational data types: Earth observation and field measurement.

Foundational Data. Earth observation from remote sensing provides information on the physical characteristics of a location on the basis of the reflected and emitted radiation of objects at that location. *In situ* field measurements provide the "ground reference," allowing the calibration of imagery data to reflect real features.

From the foundational datasets, a range of mangrove-specific data products can be developed; we have classified these into three broad groups:

Baseline Products. Derived directly from foundational datasets, these provide a baseline against which mangrove forests can be assessed. These datasets further our understanding of the critical features of mangrove forests in terms of their extent, condition, structure, and change. The baseline products provide a framework for secondary dataset creation.

Secondary Datasets. These are derived from the interpretation of baseline products and other information leading to the assessment of the drivers of mangrove loss, the effectiveness of protected areas on mangrove extent and condition, and the potential to rehabilitate former mangrove areas.

Analyses of Ecosystem Services and Biodiversity. Also based on the baseline products in combination with additional datasets, these analyses quantify the value of mangroves to people and wildlife populations. Valuations of ecosystem services can also provide information that feeds into secondary datasets, such as identifying areas of rehabilitation potential (Figure 2).

has long been recognized[66,67] but until recently has been poorly quantified. Variability in geomorphic settings can influence the delivery of ecosystem services[30,68] and influence appropriate rehabilitation techniques.[32] Worthington et al.[28] developed a global typology of mangroves on the basis of their geomorphic and sedimentary setting and showed the spatial distribution of key geomorphic types: deltas, estuaries, open coast, and lagoonal systems. Although this is only a partial categorization focused on broader landscape-scale geomorphic units, it provides a framework for developing more spatially nuanced valuations of ecosystem services, such as climate regulation and fishery enhancement,[28] and for understanding deforestation dynamics across different settings. Improvements to this model—or more local-scale modifications to incorporate finer-scale variation in mangrove dynamics, geomorphology, and structure—could further help to refine the quantification of how ecosystem services are delivered.[69]

Mangrove Fragmentation. Ecosystem loss and degradation typically lead ecosystems to become increasingly fragmented.[70] Fragmented mangrove forests can be ecologically and hydrologically isolated and can suffer from reduced fish diversity, pollinator visitation rates, and fruit production and recruitment.[71,72] Quantifying rates of fragmentation thus might reveal information on the impacts of human pressures that metrics based solely on extent cannot. To assess global trends in mangrove fragmentation, Bryan-Brown et al.[43] derived spatial fragmentation metrics from Hamilton and Casey's[40] global mangrove time series. Quantified metrics include measures of three aspects of fragmentation: increasing patch isolation (e.g., mean Euclidean nearest neighbor), increasing patch shape complexity (e.g., perimeter-area fractal dimension), and decreasing patch area (e.g., mean patch extent).

Protected-Area Effectiveness for Mangrove Conservation. Protected areas can safeguard biodiversity[73] and reduce land-cover conversion;[74] however, in tropical areas, protected areas have not fully mitigated the impacts of human pressure.[75] A considerable proportion of the global mangrove distribution is within nationally recognized protected areas; over 30 countries have designated >50% of their mangrove extent within protected areas.[28] At local scales, mangrove loss has been shown to be reduced after protected-area designation.[76] Ongoing analyses are aimed at investigating whether similar reductions of mangrove loss and degradation are reduced at larger spatial scales by the presence of protected areas. Currently, such assessments are based largely on mangrove losses. However, with the combination of other global layers, it should be relatively simple to also consider the role of protected areas in preventing degradation and protecting ecosystem services.

Restoration Potential. Over the last decade, there have been significant efforts to increase mangrove extent through restoration and rehabilitation. The dominant mechanism with which restoration has been approached is through mangrove planting,[62] which has often had low long-term success.[77,78] A number of the aforementioned datasets, as well as valuations related to ecosystem services (see below), have been or are in the process of being linked to provide a landscape-scale assessment of the restoration potential of mangroves globally (Figure 2; http://maps.oceanwealth.org/mangrove-restoration/). The first release of this study identifies 8,120 km^2 of mangrove forests that have the potential to be restored and quantifies the potential returns in terms of carbon and fisheries from restoring those areas.[28] The restoration-potential dataset identifies the biophysical constraints of restoration at the landscape scale. Translating this to on-the-ground action requires an understanding of the local enabling ecological, political, social, legal, and economic factors.

Ecosystem Service and Biodiversity Analyses

Mangrove forests support a range of valuable ecosystem services, including climate-change mitigation, biodiversity maintenance, coastal protection, fishery enhancement, and tourism.[16,17] However, the full value of services provided by mangroves is often not captured in the development of policies and funding mechanisms for conservation.[79,80] Recently, global institutions such as the World Bank have started developing frameworks and approaches to include the monetary value of natural capital within national wealth-accounting systems. These efforts focus on quantifying the economic benefits of the ecosystem services that mangroves and other ecosystems provide to encourage fair valuation when conservation and land-use choices are made.

Soil and AGB Carbon. Given the large amounts of carbon sequestered and stored in vegetated coastal ecosystems,[19,34] one area that has gained considerable traction is the role of mangroves in mitigating climate change.[81] Mangrove forests have been shown to be capable of storing up to an average 1,023 Mg C ha^{-1},[19] and they are able to sequester up to four times more carbon than terrestrial tropical forests.[82] Given the range of modeling approaches, underlying data sources, and variation in the mangrove extent data used, estimates for the global carbon stocks vary from 1.32–4.03 Pg C in mangrove biomass[39,49] to (4.28 ± 0.62)–5.03 Pg of total carbon in 2000[29,45,51] to (5.00 ± 0.94)–6.40 Pg C for the top 1 m of soil alone.[44,46] Such datasets are consistent across countries and so are suitable for inclusion in a country's intended nationally determined contributions (NDCs) to the Paris Agreement (see below), which requires national-scale reporting of carbon stocks and fluxes.

Mangrove Tourism. Unlike carbon assessments, global models of other mangrove ecosystem service values are still nascent; however, several initiatives are now underway (Figure 2). By examining user reviews on the travel website TripAdvisor, Spalding and Parrett[52] identified 3,945 mangrove attractions across 93 countries and found that boating and wildlife watching were the most frequently stated activities. Site-level statistics from just a few of the areas identified describe hundreds of thousands of visitors a year,[83,84] most likely translating into a multibillion-dollar global industry.[52]

Coastal Protection. The potential for mangroves to provide effective coastal defense is well known,[25,85] and future climate-change impacts, combined with increasing coastal populations, are likely to increase vulnerability and the need for such defense.[9] The value of mangrove forests in terms of reducing flood risk to people, property, and infrastructure has been measured at local, national, and multinational scales.[15,86,87] A global valuation model that estimates the annual benefits of mangroves in reducing wave- and storm-induced flooding[88] to people and property has been developed after a successful implementation of similar models for coral reefs.[89]

Fishery Enhancement. Mangrove forests also play a critical role in fishery enhancement.[90] A simple initial attempt to model fishery value was published in 2015,[91] but efforts are now underway[28] to build ecologically driven models based on field-based assessments of mangrove dependency for specific invertebrate and finfish species, as well as other ecologically relevant input data, including mangrove geomorphic type. These new models further incorporate an estimate of fishing pressure based on socioeconomic variables and the proximity of fishing habitats. Although global in extent, variation in the availability of representative field data (including a notable deficit for West Africa) could lead to regional variability in the depth of coverage.

Conservation Hotspots. The existence of improved data on extent, fragmentation, degradation, ecosystem services, and conservation effort is greatly helping our understanding of both progress and needs for mangrove conservation. In addition to the data described here, there is growing information on aspects of associated biodiversity, including mangrove species range maps,[5] and the patterns of distribution of associated species and ecosystems. Such information can be used in multiple ways, including identifying priority mangrove areas for conservation attention or ensuring that mangroves are included in wider conservation and natural-resource planning efforts, such as the identification of key biodiversity areas and ecologically or biologically significant marine areas. For example, Sievers et al.[22] intersected distributions of threatened, mangrove-associated megafauna (e.g., turtles, sharks, rays, dugongs, and manatees) with high rates of global mangrove loss (0.2° × 0.2° cells within the top tenth percentile for cells that experienced loss from Hamilton and Casey's dataset[40]). Hotspots of concern were identified throughout Southeast Asia, the US (Florida), Mexico, and northern Brazil.[22] Although such datasets and maps can help, at a very broad level, to direct conservation resources, it is important to acknowledge that they do not incorporate certain important conservation-relevant variables such as opportunity and feasibility.

Translating Global Datasets into Policy Action

The volume of research into mangrove ecosystems is increasing rapidly and is starting to stimulate management and policy impact.[7] The datasets highlighted here have the potential to support a range of policy mechanisms. This includes informing global policy frameworks about trends in mangrove health and distribution, identifying drivers of loss and recovery, and mapping mangrove values in addition to setting and monitoring targets for conservation and rehabilitation (Table 3). At a national scale, the datasets could support policy frameworks needed to fulfill global commitments such as the Convention on Biological Diversity Aichi targets, UN Sustainable Development Goals (SDGs), NDCs, national adaptation plans, nationally appropriate mitigation actions, and designation of large-scale protected areas. For instance, the GMW dataset is the official dataset on mangrove extent for the SDG 6.6.1 (change in the extent of water-related ecosystems over time) indicator reporting (https://www.sdg661.app/).

In relation to climate change, there has been stronger guidance from the International Panel on Climate Change (IPCC) to report on all greenhouse gas (GHG) sinks and sources. The IPCC guidance[92] includes a tiered approach incorporating national capacity and the need for flexibility in accounting. Inclusion in tier 1 GHG inventories requires an understanding of changes in mangrove cover due to management activities within countries, and countries can use default values assigned to carbon stocks.[92] Global datasets on distribution change therefore provide an opportunity for countries that do not have the remote-sensing abilities in house to use time-series datasets[8] to include mangroves in their GHG inventory. Additionally, country-level data on mangrove biomass[29] and soil carbon[45,46] allow countries to develop a tier 2 inventory, which requires country-specific data on land use and carbon stock. Tier 2 inventories can help inform national-level decisions needed for reducing emissions from land-use change and stimulating restoration to enhance carbon stocks. In addition, the recent IPCC Special Report on Oceans and the Cryosphere pays specific attention to the value and effectiveness of mangroves and other coastal ecosystems as adaptation strategies for vulnerable low-lying coastal communities.[93]

In parallel, efforts to both protect and restore mangroves on the ground are growing around the world. NGOs, government agencies, community groups, and the private sector have built a considerable body of experience on aspects of mangrove management, conservation, and rehabilitation ranging from field

Table 3. The Policy Frameworks and Information Needs that Can Be Supported by Global Mangrove Datasets

Policy Framework	Information Needs	Mangrove Datasets
UN SDGs, including SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), SDG 14 (Life under Water), and SDG 15 (Life on Land)	resilience value, mitigation value, food security (including fish production), and human well-being; trends in mangrove health and distribution	mangrove tourism, coastal protection, fishery enhancement, total carbon, mangrove extent, mangrove degradation, protected-area effectiveness for mangrove conservation
UN Framework Convention on Climate Change	mitigation value (carbon stores, sequestration rate, avoided loss, and rehabilitation potential); adaptation value (reduction in flooding, coastal erosion, and wave attenuation); greenhouse gas inventories: trends in mangrove health and distribution for tier 1 reporting	total carbon, coastal protection, drivers of mangrove extent change, mangrove extent, mangrove degradation
Convention on Biological Diversity	trends in health and distribution, including in protected areas; selection of new protected areas on the basis of ecosystem services; identification of biodiversity hotspots	mangrove extent, mangrove degradation, protected-area effectiveness for mangrove conservation, conservation hotspots
Sendai Framework on Disaster Risk Reduction	coastal protection, food security	coastal protection, fishery enhancement
Ramsar Convention	status of protected areas (i.e., degraded or not); Ramsar sites in areas of high ecosystem services and biodiversity	mangrove extent, mangrove degradation, protected-area effectiveness for mangrove conservation
Bonn Challenge	areas for rehabilitation and rehabilitation success	restoration potential
IUCN General Assembly and World Conservation Congress	areas for rehabilitation and rehabilitation best practices; identification of areas in need of protection and sustainable management	restoration potential, protected-area effectiveness for mangrove conservation, conservation hotspots

methods to financing. Unfortunately, much of this work remains disaggregated and small scale. Individual project successes and failures are not translated for rehabilitation or conservation.

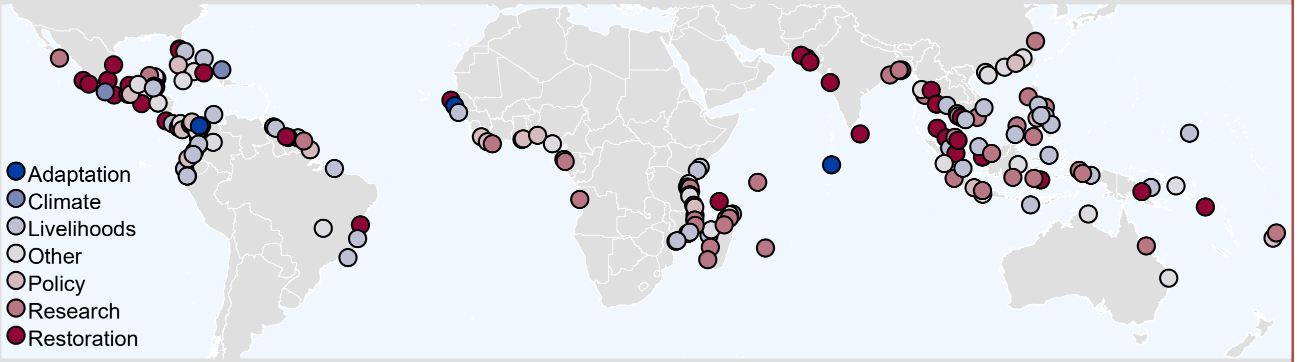
Despite their potential utility for informing policy development and practice, the use of global mangrove datasets has not achieved its full potential. Historically, such datasets have been criticized for their inability to provide information relevant to local, on-the-ground conservation action. This could have been related to the relatively low resolution of global datasets, lack of time series, different definitions of mangrove ecosystems (e.g., thematic resolution), and locally developed datasets of higher accuracy, but it could also have been hindered by issues of local access to data and to its interpretation. Although there have been some successes (e.g., the Global Forest Watch deforestation alert system), the problem remains.[94] Importantly, however, the new and forthcoming datasets reviewed here are part of a global surge wherein data are becoming available in near real time and at resolutions capable of guiding national- and local-scale policymaking and even supporting field-scale management decisions.

Improved strategies are needed to facilitate the dissemination and interpretation of large-scale data and to support the integration and coordination of local and global mangrove datasets. Expertise is needed to ensure that data outputs and conservation recommendations are relevant to decision makers operating across all scales of management. In parallel, locally derived information needs to be better shared to be "fed up" into global analyses. Guidelines for data standards could greatly support future data-gathering and monitoring efforts across scales. A number of global, regional, and national mangrove and coastal ecosystem networks have been established and are already enabling such work. These include the International Union for Conservation of Nature (IUCN) Mangrove Specialist Group, an expert-led body that aims to support mangrove research and conservation and assess the conservation status of all mangrove species (https://www.zsl.org/iucn-ssc-mangrove-specialist-group); the Global Mangrove Alliance (GMA; Box 2); the International Society for Mangrove Ecosystems (http://www.mangrove.or.jp/english/index.html); the ASEAN Mangrove Network (formed after the 14th ASEAN Senior Officials in Forestry meeting in 2011); the International Blue Carbon Initiative (https://www.thebluecarboninitiative.org/); the Western Indian Ocean Mangrove Network (http://wiomn.org); the Mesoamerican Mangrove and Seagrass Network; and the International Partnership for Blue Carbon (https://bluecarbonpartnership.org/).

Any agreed-upon framework for monitoring mangrove data could be widely implemented if it were developed in consultation with existing mangrove networks, local stakeholders, and end users to ensure that specific management needs are met. For example, the Group on Earth Observations Biodiversity

Box 2. The Global Mangrove Alliance

The GMA (http://www.mangrovealliance.org) is a partnership of 19 institutions and is led by a steering group comprising Conservation International, the IUCN, the Nature Conservancy, Wetlands International, and the World Wildlife Fund. The GMA has developed a global mangrove strategy to achieve global priorities in climate adaptation, mitigation, sustaining biodiversity, and improving human well-being. The GMA consists of working groups organized around improving policy, building science capacity, and enhancing communications. The strength of the GMA comes from its global member network, comprising NGOs, universities, and research institutions. It further benefits from its collaboration with the IUCN Species Survival Commission Mangrove Specialist Group and from endorsement by nine governments. The members and partnerships allow the GMA to promote the mangrove agenda across multiple governance scales ranging from policy targeting international conventions and national and provincial governments to local NGOs and communities who are undertaking on-the-ground initiatives associated with protection, restoration, and adaptation.



This figure shows the location and focus of mangrove projects within the GMA network. Note that projects can belong to multiple classes; however, only one is shown for clarity.

Observation Network's approach for global coordination has been to establish multiple biodiversity observation networks that operate at regional, national, and global scales but follow a standardized framework for monitoring biodiversity by using essential biodiversity variables that ensure information cross-scalability.[95,96] Likewise, multiscale scenario modeling of the integrated mangrove datasets, if developed with input from stakeholders who work across disciplines and spatial scales, would provide locally relevant recommendations for conservation action based on future predictions of ecosystem change.[95,97,98] This multiscale approach to scenario modeling has been embraced by the Intergovernmental Platform on Biodiversity and Ecosystem Services to help guide managers locally and globally.[97,98]

A Platform for Visualizing and Disseminating Global Datasets

If the growing wealth of data being developed around mangrove forests is to have an influence beyond the academic literature,[99] it will be critical to develop a platform to provide decision makers with clear and easy-to-access information.[100,101] The research community behind many of the datasets reviewed here has begun a collaboration to achieve this goal. A new mangrove data platform is being developed within the GMA to provide clear, interpreted access to data, empowering NGOs and communities undertaking practical conservation and rehabilitation actions. The platform seeks to emulate the success of other data-sharing and advocacy platforms such as the Global Forest Watch (https://www.globalforestwatch.org), Global Intertidal Change (https://intertidal.app), and Global Fishing Watch (https://globalfishingwatch.org). These platforms are new and vital conduits between the data producers (who are seeking to realize the benefit and impact of their analyses) and the data users (who are seeking to base their decision-making processes on the best openly accessible available data).[100,101]

The new GMA GMW platform will illustrate near real-time trends in mangrove forest loss, map drivers of loss, and communicate emerging threats and conservation solutions. Part of this development will include the enhancement and harmonization of different datasets, for example, by aligning products across the best foundational data layers or enabling their interoperability. The platform will also incorporate datasets with regional and national extents that have the potential to provide more accurate local information suitable for on-the-ground management. The interface will allow users to seamlessly transition between these datasets and display information relevant to their situation. Tools will be provided to allow users to query the datasets and produce national statistics suitable for reporting against global commitments, e.g., SDGs and NDCs.

The information provided by the GMW platform will target a range of stakeholders to advocate for mangrove conservation, ultimately resulting in better integration of mangroves in climate, biodiversity, and sustainable development strategies, enhanced decision making and law enforcement, and improved practice on the ground. It would be possible, for example, to build mangrove benefits into coastal planning, to incorporate mangrove carbon into climate mitigation, to generate coastal protection models to inform industry and insurance, and to leverage funds for local communities to rehabilitate or maintain mangrove resources.

Future Directions

Although the availability of new global-scale datasets, connected alliances, and a push toward greater data sharing hold great promise for mangrove conservation, opportunities to strengthen these areas still remain. On the basis of the previous sections, we provide recommendations of potential areas to prioritize.

Fine-Grained Socio-economic Spatial Data

The majority of the global datasets highlighted in the first section map and/or are derived from biophysical variables. However, mangrove conservation and rehabilitation are multifaceted problems incorporating economic, social, and political drivers alongside the environmental and biological settings. Factors such as land and ocean tenure are critical to rehabilitation and protection success,[102] but it is difficult to disentangle these even at the most local scales. Datasets on local, regional, and national laws and policies that are relevant to mangrove management are needed. It is challenging to produce spatially explicit socio-economic data from SRS,[103] and large-scale maps often rely on proxy variables (e.g., the distribution of nighttime lights and gross domestic product[104]) or the disaggregation of national statistics such as population density.[105] Initiatives such as Trase (https://trase.earth/), which maps commodity supply chains and approaches such as data mining social-media datasets[106] or mobile-phone use to infer socio-economic status at the individual level,[107] could result in more spatially relevant and fine-grained socio-economic data that can help identify the drivers of mangrove degradation and impediments to conservation efforts.

Protocols for Monitoring and Data Collection

The underlying driver behind the creation of global mangrove datasets, as well as the development of a data-sharing platform to translate science into action, is to stimulate more effective and successful mangrove rehabilitation and conservation. Significant effort and investment in mangrove rehabilitation have already been undertaken, and ambitious rehabilitation targets have been set (e.g., the Bonn Challenge, http://www.bonnchallenge.org/content/challenge). Understanding progress toward these areal targets should in theory be relatively straightforward given the availability of Earth observation data.[108] However, recording of the location, design, costs, monitoring, and outcomes of rehabilitation attempts is generally *ad hoc* and incomplete.[28,108] The lack of well-defined targets and post-intervention monitoring has the potential to inhibit understanding of success and failure. In addition, measures of rehabilitation success must also move beyond simple metrics of the number of individual mangroves planted or the area created to incorporate socio-economic and ecosystem-function indicators.[62,102]

Integration of Field and Citizen-Science Data

In some geographies, local-scale mangrove data can provide more accurate and/or higher-resolution data than global datasets and could therefore be more useful in addressing on-the-ground conservation questions. The integration of citizen-science data to ground truth analyses has the potential to improve their accuracy and further stimulate community participation in mangrove conservation. A platform that allows for the integration of field data could enhance accuracy, relevance, buy-in, and utilization at local scales. For instance, the incorporation of field data is required for providing more accurate and locally relevant assessments of mangrove resilience to sea-level rise. To date, the collection of these data has been somewhat limited geographically, although efforts to address this are underway,[7] and greater data availability would allow for regional and global assessments of mangrove risk.[109] Incorporation of field data will require standardized protocols and criteria for submission and would also require some capacity for addressing quality-control issues (e.g., Coastal Carbon Research Coordination Network, https://serc.si.edu/coastalcarbon).

Real-Time Data on Mangrove Extent, Health, and Threats

As noted previously, efforts to map global mangrove extent on a near annual basis have allowed for an estimate of mangrove change over time.[8,11] Improved satellite technology can lead us toward a near real-time mangrove monitoring system that detects changes in mangrove cover and distribution on a finer temporal basis. Upcoming L-band instruments, such as the NASA-ISRO SAR, will provide free access to global data every 6 days with fine spatial resolution. These frequent observations will provide a powerful tool that would help to mobilize on-the-ground resources to address threats to mangroves as they emerge while also improving the ability to predict changes in mangrove forest extent and condition under different threat, management, and policy scenarios.[110] Near real-time data would also allow iterative forecasting of mangrove change, whereby predictions are continuously compared with new data, enabling adaptive management of mangrove forests.[111] A major barrier to incorporating predictive ecology into the management of mangrove forests is latency—the time required for transferring big data from collection, processing, and analysis to dissemination of usable decision-making products.[111] However, these processes can be automated,[112] and the GMA is well positioned to play an integral role in facilitating these types of actions.

Prioritization of Conservation and Rehabilitation

Although some conservation prioritization is already underway,[22] a more comprehensive approach could take into account key social and economic influences that will affect operationalizing rehabilitation actions on the ground following the framework developed by McGowan et al.[113] Such enabling conditions could cover biophysical, climatic, social, political, operational, and economically important factors that could rule a country (or subunit) in or out of the analysis *a priori*. Tools and outputs could allow users to define key attributes of the cost-effectiveness analysis, which would then deliver a ranked list of the remaining candidates according to their expected return on investment. In addition to the standard aspects of cost-effectiveness analysis, such as benefits, costs, and feasibility, the framework places a large emphasis on the consideration of threats to ecosystems by remembering that most conservation or management actions mitigate only some threats.[113]

Monitoring Rehabilitation Effectiveness

Mangrove rehabilitation is already widely attempted but has resulted in very mixed outcomes. Initial reviews of such work need to be built up into more comprehensive meta-analyses that can then be used for cross-validating some of the global models and projections. In parallel, better guidance and data are needed on "effective restoration" to ensure small-scale rehabilitation activities, following accepted best practices, are designed to achieve desired goals and have permanence.[62]

Enhancing Value Assessments of Ecosystem Services

Although the mapping and valuation of ecosystem services are advancing, more work is needed to develop consistent, objective, and practical metrics for the use of such valuations in planning and finance settings. This will include monetization of existing data, considerations of bundling ecosystem services, trade-offs, and opportunity costs.

Conclusions

Big data and remote-sensing approaches have developed rapidly, permitting unprecedented assessment of the state of the world's mangroves. This proliferation of open-access datasets presents both a challenge and an opportunity for improved collaboration among mangrove networks and stakeholders at the global and local levels. As described here, there is already a notable degree of cooperation and data sharing among mangrove researchers, yielding rapid progress in the development of baseline, secondary, and enhanced products. These new analyses have supported, and will continue to support, policy change that benefits both mangroves and the communities that depend on them. However, progress is still needed in providing data products that can support improved management at local scales, as well as improving access to data and ensuring that such access is equitable. In reviewing the broad range of existing and forthcoming mangrove datasets and exploring the challenges of translating these analyses into policy action and on-the-ground conservation, this Perspective also points to critical future outputs (including the development of a new platform for mangrove data) that can facilitate collaboration by ensuring that the best available data can be shared efficiently, thus reducing the risk of duplicated efforts and helping to identify opportunities to pool resources toward shared priorities.

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AUTHOR CONTRIBUTION

Conceptualization, T.W., M.S., E.L., P.v.E., L.H., K.L.W., P.B., N.T., and N.M.; Writing – Original Draft, T.W. and M.S. with significant input from all authors; Writing – Review & Editing, T.W. with significant input from all authors.

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