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Perspective

The role of blue carbon in reversing mangrove degradation trends in Mexico

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ABSTRACT

Blue carbon projects in Mexico, or the conservation and restoration of tidal wetlands such as mangroves, can reduce carbon emissions while providing additional ecosystem services for local communities. However, at the national scale, the "additionality" (or added project benefits) of mangrove projects is difficult to demonstrate due to recent slowing deforestation rates. While deforestation in Mexico decelerates, mangrove degradation is pervasive and spreading. Reversing or ending mangrove degradation could rapidly protect the carbon stored and reduce future greenhouse gas emissions. Here, we explore Mexico's conceptual, methodological, and social challenges for tackling mangrove degradation and achieving successful rehabilitation outcomes. We identified that the first challenge is establishing an accepted national definition of mangrove degradation compatible with earlier methods and measurable with spatial imaging techniques. Other challenges are aligning on-ground monitoring with remotely sensed degradation assessments, including reference sites, harmonizing national programs with global datasets, and standardizing information to meet blue carbon project accreditation requirements. Finally, knowledge sharing, collaboration, and reporting failed and successful projects are crucial for fast-forwarding reliable and verifiable blue carbon projects that effectively contribute to reversing mangrove degradation trends in Mexico.

1. Introduction

As the impacts of climate change become increasingly evident, we must take action to limit the rise in temperatures below the 2 °C threshold. Additionally, there is a pressing need to implement adaptation measures to address the consequences of climate change (IPCC, 2023). Blue carbon projects, or the conservation and restoration of tidal wetlands, have emerged as an attractive way to reduce carbon emissions (Lovelock and Duarte, 2019). Within carbon market-based mechanisms, the conservation and restoration of tidal wetlands can be awarded carbon credits that can be traded to offset emissions elsewhere or counted toward national emission reduction targets (Lovelock et al., 2022). Although the total contribution of blue carbon to global emissions reduction is limited, some countries will benefit more than others (Taillardat et al., 2018). Blue carbon is attractive in Mexico because it has the potential to mitigate carbon emissions and provide financing for restoration activities that can provide environmental and socioeconomic benefits to coastal communities.

Four potential activities can occur within a mangrove blue carbon project: (a) restoration or assisted recovery of mangroves that have been destroyed or damaged, (b) rehabilitation or reinstating ecological function to degraded mangroves when complete restoration is not the goal, (c) reforestation or replanting mangroves where they previously occurred, and (c) afforestation or establishing of mangroves were they did not recently exist (Lovelock et al., 2022). Mangrove afforestation projects have been increasingly implemented. However, they tend to be

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unsuccessful and can damage other coastal ecosystems, such as when seedlings are planted on low intertidal mudflats or seagrass meadows (Lee et al., 2019). Additionally, afforestation projects may provide relatively few carbon credits compared to restoration or rehabilitation projects, as soil carbon accumulation is generally slow (Song et al., 2023).

In contrast to afforestation, the rehabilitation of degraded mangroves can rapidly protect the remaining carbon stored within soils and biomass, reduce greenhouse emissions, enhance current and future carbon sequestration, and improve the well-being of local communities. Mangrove rehabilitation can help achieve global goals such as the Bonn Challenge target to restore 60 million ha of degraded and deforested land (www.bonnchallenge.org), the Global Mangrove Alliance and the Mangrove Breakthrough targets to restore half of the recent mangrove loss (www.mangrovealliance.org). More recently, mangrove rehabilitation can support the Target 2 of the Kinming-Montreal Global Biodiversity Framework (Convention of Biological Diversity, 2022), which commits nations to restore 30 % of their degraded marine and coastal ecosystems.

Despite the opportunities, there are many challenges to addressing mangrove degradation, which vary among countries within specific socioeconomic and political contexts. For instance, the first challenge is defining "degradation"; the second is quantifying the extent, rate, and drivers of degradation, where methods are less developed than those for quantifying losses. Here, we investigate the extent of mangrove degradation and the factors limiting the rehabilitation of degraded mangroves in Mexico. We aim to answer the following questions: (1) what is considered mangrove degradation in Mexico? (2) what is the rate and extent of mangrove degradation? (3) what are the opportunities to reduce carbon emissions by reversing mangrove degradation? (4) what are the current methodological challenges? (5) what social aspects must be considered when establishing blue carbon projects in Mexico? Finally, we provide examples of a successful reversal of mangrove degradation through blue carbon in Mexico and suggest five steps to address this national environmental challenge.

2. Mangrove degradation definition and extent in Mexico

In Mexico, at least three definitions of mangrove degradation are included in regulatory frameworks (Table 1). The definition of the General Law on Climate Change is based on a reduction of carbon content as a result of human activities; the General Law on Sustainable Forestry is based on a reduction of productivity and ecosystem service provision. In comparison, Mexico's Mangrove Monitoring System (MMMS, National Commission for the Knowledge and Use of Biodiversity) defines degradation as dead or damaged vegetation that may be undergoing regeneration. Many other global degradation definitions primarily focus on the loss of ecosystem service provision without directly considering changes in ecosystem condition. For example, the Global Biodiversity Framework Target 2 guidance notes define degraded ecosystems based on a "*persistent (long-term) reduction in the capacity to provide ecosystem services*". All definitions, from those proposed by scientists (Yando et al., 2021) to those used by carbon accreditation programs, international institutions, and frameworks, are different.

The definition by the MMMS is used to report on mangrove degradation every five years. Within this classification, the area of degraded mangroves in Mexico has increased by an order of magnitude during the last decades; in 1970–1980, 0.1 % (1192 ha) of the mangroves in the country were considered degraded; by 2015, the degraded area had increased to 18,332 ha or 2.1 % of the total (Velázquez-Salazar et al., 2021, Table 2). In contrast, rates of mangrove deforestation in Mexico are decelerating from annual losses of 1.8 % in 2008 to 0.47 % in 2015, consistent with global trends (Friess et al., 2020), although in some years (e.g. 2018) gains of 0.88 % were observed (Global Mangrove Watch v. 3.0, Bunting et al., 2022). Thus, while deforestation appears to have recently been reduced, degradation is ongoing.

Table 1
Definitions of mangrove/forest degradation.

Source	Definition of forest degradation	Reference
General Law on Climate Change (Ley General del Cambio Climático)	*The reduction of the carbon content in the vegetation, ecosystem, or soil as a result of human activities compared to the same vegetation, ecosystem or soil if this activity had not existed*	Mexican Government (2016a)
General Law on Sustainable Forestry (Ley General de Desarrollo Forestal Sustentable)	*The process by which soils and forestry ecosystems reduce their productivity and their capacity to deliver ecosystem services*	Mexican Government (2016b)
Mexico's Mangrove Monitoring System coordinated by the National Commission for the Knowledge and Use of Biodiversity	*Dead arboreal and scrub/shrubby mangrove vegetation or areas undergoing regeneration, including mangroves impacted by tropical storms and hurricanes, and infrastructure (hydraulic structures; highways, roads)*	Rodríguez-Zúñiga et al. (2022) and Valderrama et al. (2014)
	The loss of diversity, structure, function, and resilience beyond the limits of natural variation within a given system due to anthropogenic drivers or the influence of anthropogenic activities on natural drivers	Yando et al. (2021)
Verified Carbon Standard	*The persistent reduction of canopy cover and/or carbon stocks in a forest due to human activities such as animal grazing, fuelwood extraction, timber removal, or other such activities, but that does not result in the conversion of forest to non-forest land.*	VERRA (2022)
Food and Agricultural Organization, United Nations	*The long-term reduction of the overall potential supply of benefits from the forest, which includes carbon, wood, biodiversity and other goods and services.*	FAO (2003)
Intergovernmental Panel on Climate Change	*A direct, human-induced, long-term loss (persisting for X years or more) of at least Y% of forest carbon stocks since time T and not qualifying as deforestation.*	IPCC (2023)
Global Biodiversity Framework – Target 2 Guidance Notes	*Degradation refers to a persistent (long-term) reduction in the capacity to provide ecosystem services. Degraded land includes natural ecosystems which have included a loss of ecosystem functions and services and transformed ecosystems (such as agricultural areas).*	Convention on Biological Diversity (2022)

The increased rates of degradation of mangroves in Mexico, and potentially on a global scale (e.g. Dahdouh-Guebas et al., 2005), may be attributed to cumulative damage caused by activities in catchments over the past 50 years that first caused mangrove losses. For instance, in the 1980s, significant water extraction and agriculture in the Northwest Pacific, agriculture conversion for crops and cattle in the South and Gulf of Mexico, and tourist and urban developments in the Yucatan Peninsula

Table 2
Mangrove degradation assessments and statistics in Mexico from different remote sensing approaches. MMMS is the Mexico's Mangrove Monitoring System.

Program or product	Degraded area (ha)	Year	Indicator	References
MMMS	1192 8906 14,762 18,332 9680	1970–1980 2005 2010 2015 2020	Sentinel-2 images assisted by visual interpretation and values derived from the time series changes in the vegetation index.	Velázquez-Salazar et al., 2021
Global map of restorable mangroves	40,487	2014	Landsat images and vegetation and soil indices (NDVI, SAVI, EVI, NDMI; 1984–2018). A pixel was considered degraded when 9 out of 12 metrics decreased compared to a threshold of change defined per ecoregion.	Worthington and Spalding, 2019
Tropical moist forest dataset	162,095 39,032	<2013–2021 2020–2022	Landsat images and multispectral classification per date that detects disruptions in tree foliage.	Vancutsem et al., 2021

were extensive (Valderrama-Landeros et al., 2020). These activities caused rapid mangrove losses between the 1970s and 1990s, with rates reaching 2 % annually by 2005 in some parts of the country (Valderrama et al., 2014). These human-induced changes in hydrology and water quality in the vicinity of mangroves may have led to subtle yet significant alterations, often referred to as "invisible" or "cryptic" changes (Lewis et al., 2016). Very subtle signs of degradation, initially inconspicuous, can rapidly escalate into widespread mortality of seemingly healthy mangroves during acute events, such as tropical storms (Lewis et al., 2016). Extreme climatic events will exacerbate these mangrove losses (Goldberg et al., 2020) and compromise their resilience to recovery.

3. Methodological challenges to assess mangrove degradation in Mexico

Mangrove degradation is usually estimated from satellite images based on the variation of the vegetation "greenness" (usually measured from indices such as the Normalized Difference Vegetation Index, NDVI), which can infer variation in leaf area, forest density, tree biomass and structure (Tran et al., 2022). A decrease in vegetation greenness can be related to environmental degradation processes, such as defoliation, dieback, and stunted growth (Lee et al., 2021).

Simple measures like variation in NDVI to determine degradation are helpful but have limitations. For example, in Mexico, high values of NDVI may be observed for *Rhizophora mangle*, which can reach 40 m in height in the tropical Pacific. In contrast, low values of NDVI can be obtained for the same species in the Caribbean, where it forms sparse and short (<0.5 m) forests, which are not necessarily degraded (Adame et al., 2013, 2015). Another example is in the Gulf of California, where mangroves have increased in greenness (Vázquez-Lule et al., 2019) despite the increase in mangrove degradation in the area. The change in greenness could be attributable to changes in mangrove species (e.g. expansion of the "greener" *Rhizophora mangle*) in response to increasing temperature and sea level rise (Lopez-Medellin et al., 2011). The increase in greenness could also result from excessive nutrient inputs from aquaculture farming, which can cause eutrophication and increased aboveground growth (Barraza-Guardado et al., 2014; Lovelock et al., 2009). Thus, changes in forest structure, species composition or nutrient inputs may result in changes in greenness that may not be directly attributed to degradation or recovery (Dahdouh-Guebas et al., 2005)

The MMMS provides valuable information for assessing changes in cover and reports on mangrove degradation (as defined in Table 1). The information from the monitoring program allows evaluation against criteria for the approval of environmental compensation projects financed by the National Forestry Commission of Mexico (CONAFOR), which are integral to mangrove ecological rehabilitation programs (Rodríguez-Zúñiga et al., 2022). However, the MMMS was not originally designed to monitor degradation, and measuring degradation requires additional imaging techniques and resources. Additionally, the definition by the MMMS has a caveat as the "degraded" (called "disrupted" in their classification) category includes mangroves in both the process of deterioration and recovery (Table 1), which cannot be discerned without a detailed chronological assessment of change. The MMMS relies on remote sensing and GIS techniques from Landsat, SPOT and Sentinel images. These are inexpensive but have a relatively coarse resolution (10 to 60 m per pixel).

Further, the MMMS report on mangrove cover is released every five years, a time interval that may miss opportunities for timely warnings of mangrove degradation and dieback. For instance, in 2021, a large area of mangroves was suddenly degraded in the Gulf of Mexico. The area did not show any signs of degradation during the assessments in 2020, indicating that degradation was rapid (Fig. 1). However, areas that appear healthy were identified as degraded. The timestep from which degradation is estimated can significantly change the observed rates (e.g. every five years vs annually) because mangrove degradation tends to be slow at first and then sudden and very fast (Abhik et al., 2021).

Changes in classification criteria complicate national degradation assessments. For instance, in 2005, sparsely and short vegetated coastal ecosystems characterized by saltmarshes and scrub mangroves (<2 m tall) were classified with SPOT-5 images in the 'other wetlands' category. By 2020, the classification was improved using Sentinel-2 imagery, which has a better spectral resolution and scrub mangroves were included within the 'mangrove' category (Troche-Souza et al., 2023). This change in classification resulted in an overall increase in the area classified as mangroves within Mexico. The expansion of the mangrove criteria is undoubtedly beneficial; however, it complicates the long-term assessment of mangrove deforestation and degradation in Mexico (Acosta-Velázquez et al., 2023).

Global datasets are becoming increasingly important for assessing changes in mangrove cover and reporting when regional or national data are unavailable. For instance, the global map of mangrove restorable areas (Worthington and Spalding, 2019) reports on mangrove degradation at the national scale. Additionally, the global mangrove fragmentation (Bryan-Brown et al., 2020) dataset can be used to indicate degradation. These global datasets could complement national efforts in Mexico for mangrove assessment. However, the differences in scale and the definition of what is considered degraded can result in significant disparities (Table 2).

Local assessments of mangrove condition indicate areas of degraded mangroves that are not reflected in global data sets. For example, Marismas Nacionales, Nayarit, is one of the most degraded mangrove Natural Protected Areas in the country. Reports of degraded mangroves in Marismas Nacionales vary from 5413 ha in 2015 reported by the MMMS (Velázquez-Salazar et al., 2021) to local estimates of 8688 ha (Villareal-Rosas et al., 2024; Fig. 2). Global datasets such as The Tropical Moist Forest (Vancutsem et al., 2021) estimated a much higher degraded area of 11,443 ha of which 20 % was recently disturbed, and 14 % was regrowing (Fig. S1). Here, we reanalyze data for Marismas Nacionales (see Methods in Supplementary) and obtained a value of degraded mangroves much smaller than any reported so far, with 2634 ha degraded for the year 2014. The differences among global and local data

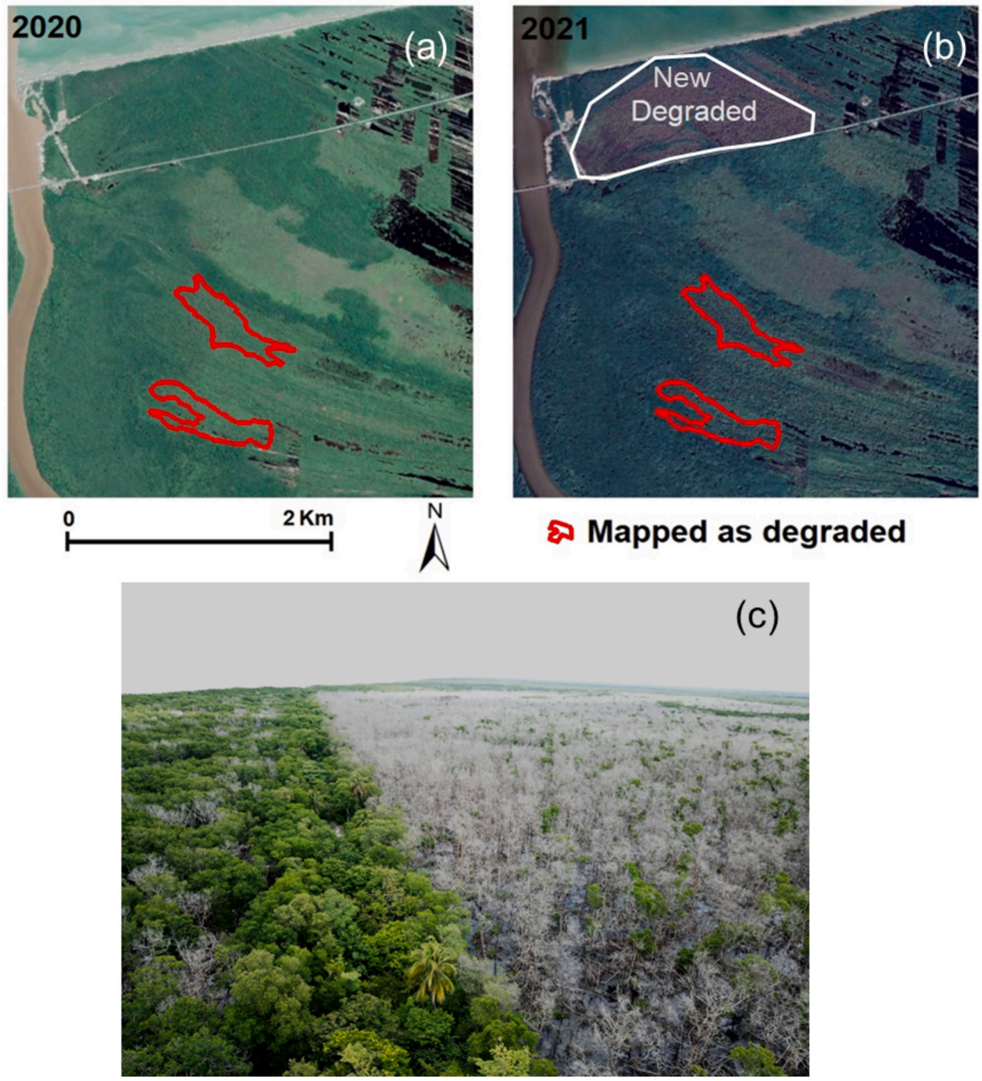

Fig. 1. Mangroves in Campeche, Mexico, (a) with areas identified in 2020 as degraded (red polygons) by the Mangrove Monitoring Program (MMMS) and (b) the same area in 2021, when a large area of mangroves (north of the image) that rapidly degraded was not captured by MMMS; (c) the extent of damage of the new degraded area in 2021, picture by J. Ochoa-Gomez. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sets are considerable but not unique to Mexico (Friess and Webb, 2014). Efforts to standardize the different information sources of mangrove degradation could aid in understanding the disparities and facilitating the comparison of national and global degradation assessments.

In addition to changes in vegetation condition, assessment of local biophysical drivers of degradation can also provide insights into the causes of degradation (Dahdouh-Guebas et al., 2005; Yando et al., 2021). The monitoring program by the MMMS assesses anthropogenic activities (urban or agricultural) and changes in areas of open water as potential drivers of degradation. This information helps determine appropriate management actions and when to intervene. For instance, whether mangrove degradation is caused by road construction or an intense storm can trigger different management responses, such as the construction of road culverts or actions to increase mangrove resilience.

Remote sensing data could be complemented with on-ground measurements of indicators of degradation and local indicators of socio-economic well-being. The current long-term monitoring programs within National Protected Areas of mangroves in Mexico represent excellent reference sites (Botello-Lopez et al., 2022). These on-site measurements of mangrove degradation provide complementary information that may not be visible from remotely sensed imagery. For instance, indicators of degradation can include changes in the level and frequency of inundation within mangroves, increases in soil porewater salinity, reduction in soil oxygen, increase in levels of nutrients, decrease in abundance of seedlings, and changes in pneumatophore density and form (Teutli-Hernández and Herrera-Silveira, 2020; Yando et al., 2021). In Mexico, long-term monitoring in National Protected Areas includes many of these indicators as well as measurements of animal biodiversity, which complement spatial indicators of degradation (Botello-Lopez et al., 2022). Additionally, citizen science could become a powerful tool providing valuable information on mangroves, even those outside protected areas. In Mexico, citizen science has been shown to be important for providing information on remote locations by marginalised rural communities and supporting management based on principles of environmental justice (Fernández-Álvarez and Gutiérrez Ladrón de Guevara, 2022).

Finally, emerging technologies in machine learning and artificial intelligence (ML-AI) coupled with remote sensing data offer promising avenues for enhancing the scalability and accuracy of mangrove habitat mapping. Recent studies have demonstrated the potential and the effectiveness of AI-based modeling in mangrove monitoring, such as using deep learning techniques that generate very high resolution (1 m)

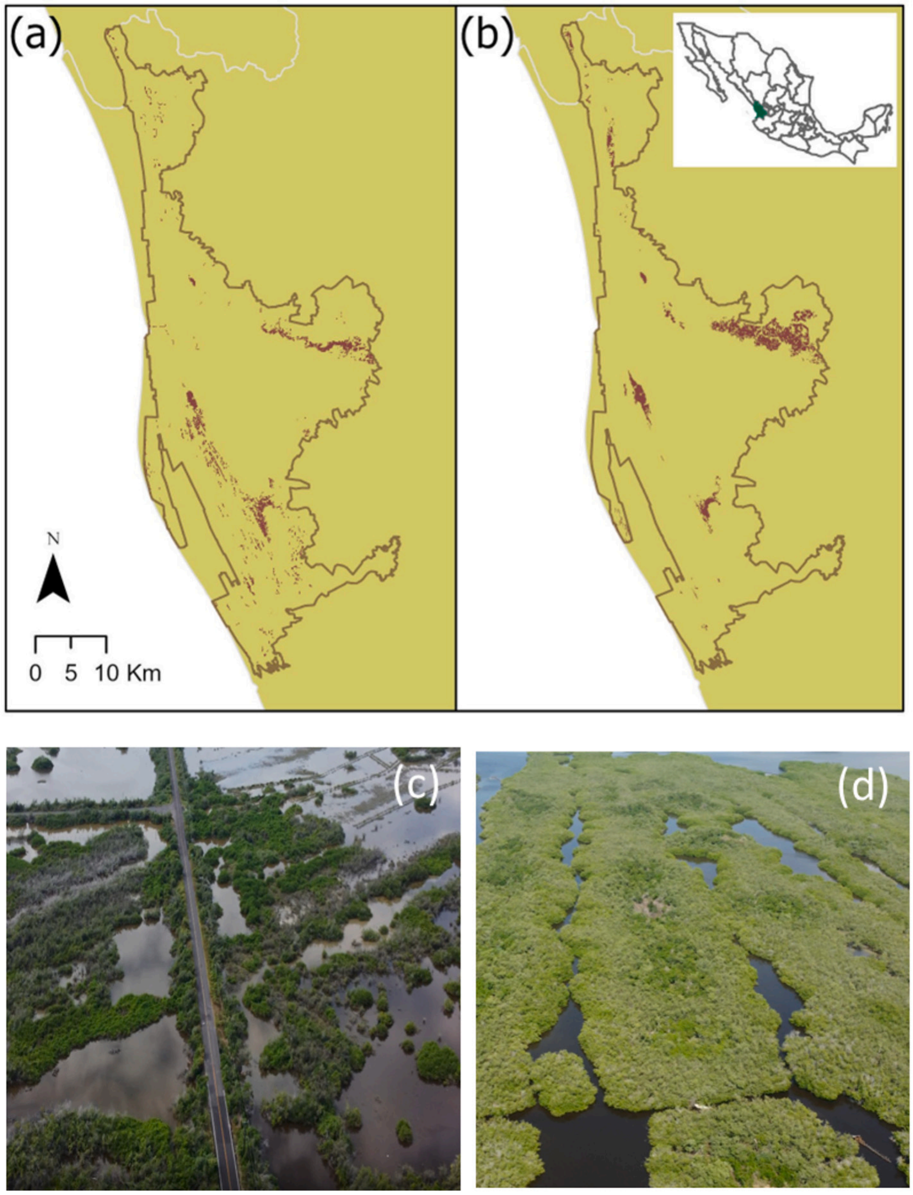

Fig. 2. Comparison of location of mangroves classified as degraded (brown areas) in the Biosphere Reserve Marismas Nacionales Nayarit, Mexico, calculated for (a) 2014 in this manuscript, and (b) in 2016 by the Mangrove Monitoring Program; (c) an example of degraded mangroves within the Biosphere Reserve probably due to changes in hydrology resulting from road construction, and (d) an example of mangrove with no signs of degradation within the same Reserve. Pictures by S. Velázquez-Salazar. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

canopy height maps, mangrove forest classification and estimates of biomass from satellite imagery (Pham et al., 2020; Sylvain et al., 2024; Tolan et al., 2024;). Organizations like the World Wildlife Foundation are exploring the use of these technologies to better understand and protect mangrove habitats (ManglarIA, WWF, 2024). While the initial implementation of these technologies can be costly for restoration projects, future advancements are expected to simplify their use and reduce costs, making them accessible for broader applications. Integrating ML and AI in mangrove conservation projects holds promise for providing high-resolution, real-time data, which is important for effective management and restoration efforts.

4. Blue carbon opportunities to address mangrove degradation

Cumulative greenhouse gas emissions in Mexico from mangrove degradation in 2015 were similar in magnitude to those from mangrove deforestation (0.29 ± 0.13 Tg CO_{2eq} yr^{-1} and 0.21 ± 0.10 Tg CO_{2eq} yr^{-1}, respectively, Adame et al., 2018). Mangrove rehabilitation in Mexico could safeguard 8.6 TgC and avoid the emissions of 0.34 Mt. within 50 years (estimated from 9680 ha of degraded mangroves from the MMMS 2020, mean national carbon stock of 890 MgC ha^{-1} and degradation rates of 0.1 % annually, Adame et al., 2018). Thus, despite Mexico's lower deforestation rates than in the past, blue carbon can contribute to reducing national greenhouse gas emissions by incentivizing reduced mangrove degradation and enhancing rehabilitation.

Opportunities for blue carbon crediting projects are developing. Many early blue carbon projects in Mexico have not been profitable, with carbon market prices around $US 5 per ton of CO_2 for the project's first five years (Zeng et al., 2021). More recently, investment by private companies has been exponentially increasing, and the willingness to pay higher prices for carbon credits in the past years has grown (Friess et al., 2022), possibly because the demand for credits exceeds their availability for purchase. One of the main limitations to increasing the number of carbon credits in the market is meeting the criteria for carbon accreditation methods and standards.

Carbon offset standards are guidelines and criteria for evaluating and certifying projects and actions for reducing or capturing greenhouse gas emissions. These standards ensure that initiatives like rehabilitation provide scientifically rigorous, transparent, and verifiable reductions in greenhouse gas emissions, with the Verified Carbon Standard (VCS, VERRA) being the most used globally. Within VCS, two methodologies can be applied to accredit greenhouse gas reductions from coastal wetland conservation and rehabilitation: VM007 REDD methodology Framework (REDD+ MF) for activities reducing emissions from degradation and deforestation and VM0033 Methodology for Tidal Wetland and Seagrass Restoration (VM0033). The methodology VM0033 is appropriate for use in Mexico and is regarded as a very high standard. However, accreditation through this method tends to be slow and costly.

An alternative option for acquiring carbon credits for the conservation and rehabilitation of forests in Mexico is The Climate Action Reserve (CAR), which has been widely adopted. CAR has developed a methodology specifically for Mexico (Mexico Forest Protocol), which generates carbon credits or Climate Reserve Tonnes (CRT) primarily sold to the USA. So far, over 160 projects through the Climate Action Reserve program have been accredited in Mexico, two of which are blue carbon projects. One of these blue carbon projects is listed, and one is registered (Box 1). The key difference between the CAR and VERRA methods is that the VERRA method has additional verification steps, making it more comprehensive but also a slower approach, with projects taking up to five years to be certified. VERRA is also more expensive, and rural communities may lack the logistics and financial support to pursue certification and verification. Finally, each standard also permits different activities (Table 3).

Other standards that could apply to Mexico include CERCARBONO, which has a methodology on mangroves (AR-AM0014 for afforestation and reforestation of degraded mangrove habitats, v3.0). Finally, emerging methodologies include the Gold Standard Blue Carbon and Freshwater Wetlands methodology (https://www.goldstandard.org/consultations/blue-carbon-activity-requirements-consultation). Plan Vivo is also currently developing a Coastal Blue Carbon methodology (v1.0) that builds on VERRA protocols and could be applicable to Mexico in the future. These multiple methodologies provide flexibility for various types of projects to participate in carbon markets.

5. Mangrove degradation and socioeconomic conditions

Mangroves in Mexico occur from arid to humid tropical regions in diverse geomorphological and socioecological conditions (Espinoza-Tenorio et al., 2019; Rodríguez-Zúñiga et al., 2022). In Mexico, 74 % of the mangrove area (669,615 ha) is within 832 *ejidos*, which are communal lands that are used and managed by local communities; the rest of the mangrove area is managed by the federal government (Acosta-Velázquez and Ochoa-Gómez, 2021). The communal organization through *ejidos* has been recognized by the IUCN (International Union for Conservation of Nature) as "Other Effective Area-based Conservation Measures" (OECMs), providing the management structure from which *ejidos* can participate in conservation and rehabilitation activities.

More than half of all mangrove areas in Mexico (434,144 ha, which includes 358 *ejidos*) are within protected areas (Acosta-Velázquez and Ochoa-Gómez, 2021). However, funding for maintaining and managing protected areas has drastically decreased from $US 3.9 per hectare in 2016 to only $US 0.9 in 2018 (Garcia-Tobon et al., 2020), diminishing funds for managing and rehabilitating mangroves in protected areas.

Box 1
Ejido San Crisanto Mangroves, Yucatan (CAR 1428).

San Crisanto is situated north of Yucatan. The community is of Mayan origin and forms an '*ejido*' with around 600 residents. The project area comprises mangroves and freshwater sinkholes, which provide habitat to 167 species of birds and migratory bird species such as the American flamingo (*Phoenicopterus ruber*). San Crisanto is highly vulnerable to tropical storms that have led in the past to flooding and property loss (Castillo-Burguete et al., 2019; Ojeda et al., 2020). The residents of San Crisanto have a close association with the mangrove ecosystem, engaging in activities such as fishing, coconut cultivation, salt production, and, more recently, sustainable tourism. In 1995, efforts to improve the condition of 840 ha of mangroves commenced, culminating in the formal establishment in 2001 of "Fundación San Crisanto" (San Cristanto Foundation AC). In 2002, Hurricane Isidoro ravaged the area, degrading most of the mangroves. By 2009, a Strategic Plan (2009–2029) was developed to promote sustainable development and use of the mangroves. By 2022, the "San Crisanto Mangroves" project was registered with the Forest Protocol for Mexico of the CAR v1.5. This project was the first of its kind in Mexico. It includes three reporting periods, issuing 10,368 CRTs (Climate Reserve Tonnes) with an estimated 47,908 tons of CO_2 removed. Actions to reduce and reverse mangrove degradation include supporting natural regeneration, waste collection, hydrological rehabilitation, and monitoring.

Picture by VM Nava-Ruiz

Table 3
Activities permitted under the Verra standard methodology VM0033 and the Climate Action Reserve standard methodology, Mexico Forest Protocol (v3.0). Note that the Mexico Forest Protocol will incorporate mangrove soil carbon in the next revisions (v3.1).

Standard	Methodology	Last update	Activities considered within the methodology	Reference
VERRA	VM0033 Methodology for Tidal Wetland and Seagrass Restoration, v2.1	Active from Sept 2023	- Creating, restoring and/or managing hydrological conditions. - Altering sediment supply. - Changing salinity levels. - Improving water quality. - (Re-)introducing native plant communities. - Improving management practices.	https://verra.org/wp-content/uploads/2023/09/VM0033-Methodology-for-Tidal-Wetland-and-Seagrass-Restoration-v2.1.pdf
Climate Action Reserve	The Mexico Forest Protocol v3.0	Active from Oct. 2022	- Mangrove restoration.	https://www.climateactionreserve.org/wp-content/uploads/2023/12/Mexico-Forest-Protocol-V3.0_ENG_Errata-and-Clarifications.pdf

Mexico has committed to the Global Biodiversity Framework, requiring effective conservation and management in protected areas covering 30 % of Mexico and restoration of 30 % of degraded areas by 2030. As funds continue to decrease for protected area management and mangrove degradation increases, carbon credits or other market mechanisms (e.g. for biodiversity), where *ejidos* can directly apply, have become an increasingly attractive approach to fund effective mangrove management and restoration.

Blue carbon and other market mechanisms offer financial incentives to address mangrove degradation and allow coastal communities to participate in voluntary environmental markets. Blue carbon could expand income opportunities and potentially reduce their dependence on federal government funding, which tends to be unreliable. Transitioning from government finance to engagement in international environmental markets presents the prospect of sustaining conservation or rehabilitation projects in the long term, even in the face of changing governments and policies. Financial incentives, such as payment for ecosystem services (PES), have been extensively implemented in Mexico, successfully reducing forest fragmentation (Ramirez-Reyes et al., 2018). Other community forestry programs in Mexico have mitigated carbon emissions and increased biodiversity (Klooster and Masera, 2000). However, these emerging opportunities pose risks and uncertainties for communities, and voluntary markets ought not to replace direct government environmental regulations (Klooster, 2006).

Effective public policies in mangrove conservation and rehabilitation can incorporate co-management strategies, foster the adoption of best practices, promote economic transparency, and establish financing schemes for successful projects (Acosta-Velázquez and Ochoa-Gómez, 2021). These initiatives can actively involve coastal communities and adhere to principles of fair trade in the sale or transfer of carbon credits, respect for human rights and compliance with socio-environmental safeguards within voluntary markets. Both VERRA and CAR accreditation require reporting and monitoring of social safeguards for blue carbon projects. For instance, CAR requires frequent and meaningful engagement with the local people for project approval and consultation throughout the project's life. A comprehensive monitoring approach of blue carbon projects should include spatial, on-ground, and socioeconomic indicators.

6. Moving forward

Achieving successful mangrove rehabilitation projects in Mexico that reduce and mitigate further degradation is a significant challenge. However, there are ways to build on national programs, expertise and expanding technologies to achieve positive outcomes. Here, we propose the following steps:

Step 1: Establish a clear and practical definition of national mangrove degradation.

This initial crucial step involves reaching a consensus among stakeholders in Mexico on what constitutes mangrove degradation. Definitions have critical implications, influencing the areas mapped as degraded, the selection of rehabilitation sites, and the overall success of rehabilitation initiatives. Here, we suggest that the following definition based on the principles stated by Yando et al. (2021) that aligns with the Global Biodiversity Framework and comprises variables that are measurable with spatial imagery and verifiable with on-ground monitoring:

> "Mangrove degradation is the persistent loss of canopy cover over time beyond the limits of natural variation that does not result in the conversion to non-forest land and results in the long-term reduction of ecosystem services."

This definition requires a clear understanding of the average canopy cover and what is natural to define a pre-degradation baseline, comparing similar mangroves in structure, species composition, and geomorphic and environmental conditions. The definition will likely need to be aligned with that used by Mexico in the Global Biodiversity Framework Target 2. Ensuring good alignment between definitions of mangrove degradation will be necessary to harmonize restoration work between the blue carbon and conservation sectors.

Step 2: Strengthening the national mangrove monitoring program to include degradation.

In line with international maps, mangrove degradation in Mexico could be estimated by changes in vegetation metrics over time compared to a reference period (Worthington and Spalding, 2019; see Supplementary Methods for proposed methodology). This approach removes regenerating areas, addressing issues in the country's current mangrove definition (Table 1), which includes both degraded and regenerating mangroves. Ideally, monitoring would be conducted annually, as long-term trends in degradation can often predict catastrophic dieback (Abhik et al., 2021).

The adaptive nature of the MMMS (Rodríguez-Zúñiga et al., 2022) could be enhanced to incorporate a degradation category within their assessment. The incorporation can be achieved through collaborative efforts to integrate robust indicators and monitoring protocols specifically designed to capture and assess degradation processes within mangroves. This recommendation aligns with the international best practices, emphasizing the importance of incorporating comprehensive indicators and monitoring protocols for effective management.

Additional reference sites for monitoring should be selected, including a range of natural variations (species, ages, geomorphologies), and be considered references at the landscape scale (Morales-Barquero et al., 2014). In some locations, completely "undisturbed" reference sites may not be found, and the least disturbed or "best available" option should be selected. The reference sites could be used in rehabilitation programs as indicators of "before" and "after" rehabilitation (as before, after, control, impact design (BACI) experimental design) or as benchmarks to measure greenhouse gas emissions and future carbon sequestration potential. Reference sites must be frequently monitored to detect changes in response to variations in climate, including intense weather events (e.g. before and after hurricanes) or major anthropogenic changes (e.g. before and after a dam construction). Remote sensing data could be complemented with on-ground measurements of indicators of degradation and socioeconomic well-being. The current long-term monitoring programs within National Protected Areas of mangroves in Mexico represent excellent reference sites (Botello-Lopez et al., 2022).

Step 3: Adequate selection of degraded mangroves and appropriate rehabilitation practices

Degraded mangroves selected for rehabilitation should be prioritized based on biophysical (e.g. geomorphology, hydrology), social (e.g. benefits to the communities), governance (e.g. land tenure), logistical (e.g. accessibility), and resources available (e.g. funding; Piccolo et al., 2024). The following rules of thumb can be followed to obtain the most feasible areas for mangrove rehabilitation (Lovelock et al., 2022; Hagger et al., 2023):

1- Prioritise sites with limited degradation or fragmented sites where tidal flows are unaltered and hydrological processes at the landscape scale have not been severely modified. This approach will provide the habitat conditions and the sediment, nutrients, and seeds/propagules necessary for the recovery of the mangroves. However, sites with severe degradation may be priorities for local communities, leading to different strategies.
2- Avoid large-scale planting programs that focus on inappropriate locations. For example, selecting areas that were not previously mangroves or other habitats, such as saltmarshes, beaches, seagrass meadows or mudflats.
3- Focus on reducing underlying pressures of mangrove degradation before moving to recover vegetation loss.
4- Choose "Climate-smart restoration," which will have greater resilience to heat waves, rising sea levels, or increased intensity of tropical storms.

Step 4: Working together

Finally, but importantly, it is essential to work cooperatively among governmental agencies, NGOs, local communities, and scientists to achieve a common goal to reverse the degradation of mangroves in Mexico. There are multiple open-access platforms in Mexico where information can be freely shared and used to enhance communication and knowledge sharing (e.g. Mexican Carbon Program, CarbonNA, Berkley Carbon Credit Program). It is essential to determine and report the characteristics and drivers of successful and unsuccessful projects, which is essential for future learning and improvements (Stanturf et al., 2014; Ghazoul and Shweizer, 2021). Creating and tracking mangrove rehabilitation can be based on accepted measures of success and global tracking of mangrove rehabilitation projects will soon be available (Gatt et al., In press). Defining, measuring, and monitoring degradation will contribute to successful rehabilitation and reverse mangrove degradation trends in Mexico.

CRediT authorship contribution statement

M.F. Adame: Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization. **C. Troche-Souza:** Writing – review & editing, Methodology, Conceptualization. **N.S. Santini:** Writing – review & editing, Investigation, Conceptualization. **J. Acosta-Velázquez:** Writing – review & editing, Visualization, Investigation, Conceptualization. **A. Vázquez-Lule:** Writing – review & editing, Investigation. **J. Villarreal-Rosas:** Writing – review & editing, Visualization, Methodology, Data curation. **T. Worthington:** Writing – review & editing, Validation, Methodology, Data curation. **D. Andradi-Brown:** Writing – review & editing, Methodology. **C.E. Lovelock:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2024.110775.

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