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Community-led Design of Nature-based Solutions for Mangroves in Placencia, Belize

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Abstract

Context.

Mangrove protection and restoration are increasingly prioritized as nature-based solutions for climate mitigation, coastal resilience, and livelihood support. However, implementation is often constrained by a lack of fine-scale, locally relevant evidence linking ecosystem conditions to benefits for people. Integrating community knowledge with spatial modeling can improve the design and investment readiness of nature-based solutions in coastal landscapes.

Objectives.

We developed and applied a collaborative framework to co-design mangrove nature-based solutions in Placencia, Belize, addressing two objectives: (1) identify community-prioritized areas for mangrove restoration and protection, and (2) quantify the ecosystem service benefits associated with these priorities.

Methods.

We combined participatory mapping across five stakeholder workshops with high-resolution habitat mapping and ecosystem service modeling. Community-informed baseline maps of mangrove extent and condition were used to define three scenarios: local priority restoration, local priority protection, and the proposed Placencia Lagoon Management Plan. We quantified changes in four ecosystem services—blue carbon, spiny lobster fisheries, tourism and recreation, and sociocultural values—using InVEST models and spatial analyses.

Results.

Communities in Placencia identified 83 ha of local degraded mangroves to prioritize for restoration and 174 ha of local healthy mangroves to prioritize for protection. Restoring priority areas could sequester ~ 18,500 MgC over 10 years (≈ US$644,000), increase lobster catch by ~ 640 lbs yr^{-1} (≈ US$5,000), and generate ~ US$32,000 yr^{-1} in additional tourism expenditure. Protecting priority areas could safeguard ~ 69,500 MgC over 10 years (≈ US$2 million) and maintain ~ 1,400 lbs yr^{-1} (≈ US$11,000) of lobster production and ~ US$5,400 yr^{-1} in tourism expenditure. Conserving 752 ha of mangrove in the Placencia Lagoon Management Plan could safeguard ~ 1.2 million MgC over 10 years (≈ US$32 million) and maintain ~ 10,000 lbs yr^{-1} (≈ US$80,000) of lobster catch and ~ US$23,000 yr^{-1} in tourism expenditure. Beauty and recreation were ranked the most important sociocultural values of mangroves in each scenario.

Conclusions.

Our results demonstrate that community-driven, fine-scale analysis can identify opportunities for mangrove restoration and protection that deliver measurable ecological and socioeconomic benefits while aligning with local and national priorities. This integrated approach enhances the relevance of ecosystem service assessments for spatial planning and supports the development of investment ready, locally supported mangrove conservation and restoration strategies.

Introduction

Nature-based solutions — interventions that restore, protect, and sustainably manage ecosystems while addressing societal challenges — are central to climate mitigation and adaptation strategies for coastal communities (Cohen-Schacham et al. 2016). According to the International Union for Conservation of Nature (2016), nature-based solutions target societal challenges ranging from climate change to food and water security while simultaneously benefiting people and nature. Protecting and restoring mangrove forests is particularly important for improving climate resilience, as these ecosystems provide benefits that support coastal livelihoods and reduce vulnerability to climate impacts (Arkema et al. 2015, 2023; Chen et al. 2024; Mutanda and Nhamo 2026). Locally, mangroves buffer coastal infrastructure from storm surges, provide nursery habitat that sustains commercially valuable fisheries, filter land-based pollutants before they reach coral reefs, and offer recreational spaces supporting tourism economies (Arkema et al. 2015; Carlson et al. 2019; Spalding and Parrett 2019; Sundaramanickam et al. 2021; Chen et al. 2024; zu

Ermgassen et al. 2025). Globally, they help regulate climate by absorbing carbon and reducing net emissions in the atmosphere, sequestering four to five times as much carbon as terrestrial forests (Alongi 2014, 2016, 2018, 2022).

However, mangroves are threatened by multiple stressors, including deforestation driven by coastal development, conversion for aquaculture and agriculture, and climate change impacts such as sea-level rise and extreme weather events (Gilman et al. 2008; Ashton 2022; Akram et al. 2023; Choudhary et al. 2024). Furthermore, coastal nations often struggle to secure adequate conservation funding to implement nature-based solutions for mangroves; hence, to unlock climate and conservation finance for nature-based solutions projects, they must demonstrate quantifiable social, economic, and environmental outcomes that meet investor expectations for verifiable returns. Realizing the full potential of mangrove nature-based solutions requires recognition of their value, understanding of spatial variation in benefits, and incorporating local knowledge through stakeholder engagement for effective planning processes (Miteva et al. 2015; Sidik et al. 2018). The success of nature-based solutions is highly dependent on community buy-in, thus emphasizing the need for an inclusive process in the design, implementation, and monitoring of projects that reflect local goals and priorities (Coleman and Mwangi 2013; Boyland et al. 2022; Olander et al. 2022; WWF 2025a). Co-design of equitable nature-based solutions improves livelihoods, ecosystem outcomes, and climate adaptation benefits.

Belize, a Small Island Developing State in the Mesoamerican Reef region, has emerged as a global leader in leveraging policy and finance innovations to restore and conserve mangrove ecosystems as part of its sustainable blue economy development strategy. The country has made ambitious international climate commitments under its Nationally Determined Contributions, initially setting goals in 2021 to restore 4,000 hectares and conserve 12,000 hectares of mangrove by 2030 (Belize 2021). These commitments were updated in June 2025 in Belize's NDC 3.0, raising total mangrove restoration and protection targets to 4,500 hectares and 14,000 hectares respectively by 2035 (Belize 2025). These targets align with goals established under Belize's landmark Blue Bond, launched in 2021 through a pioneering debt restructuring that freed $4 million USD annually for marine conservation, including a commitment to protect 30% of its ocean area by 2026 (TNC 2022, 2023). Central to meeting these objectives is the Belize Sustainable Ocean Plan, a comprehensive marine spatial management plan developed under the Blue Bonds framework that identifies priority zones for mangrove protection, coral reef conservation, and sustainable fisheries management (TNC 2022; McKenzie et al. 2025). In parallel, the Resilient Bold Belize Project Finance for Permanence initiative, led by the World Wildlife Fund (WWF), aims to secure long-term financing for protected areas, strengthen community-based co-management, and advance integrated ridge-to-reef management (WWF 2025b). Belize is also developing a national carbon policy and working with development banks and the private sector to explore pathways for entering voluntary carbon markets, positioning mangrove blue carbon as a key revenue stream.

Belize has over 15 years of experience using natural capital approaches, ways to pinpoint areas of the landscape and seascape that provide benefits to people, through collaborations with the Natural Capital Alliance. Through this partnership, The Natural Capital Alliance has developed an ecosystem services modeling approach to spatially link coastal and marine ecosystem health and extent to the provisioning of ecosystem services benefits using the open-source Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) toolbox (e.g., fisheries, coastal protection, and tourism) (Arkema et al. 2015). These natural capital approaches were embedded into the 2016 Integrated Coastal Zone Management Plan and reiterated in the interim 2021 Integrated Coastal Zone Management Plan (Arkema et al. 2015). Then, Arkema et al. (2023) adapted the methods for the NDC in 2021 to help identify areas for mangrove nature-based solutions that provide the most benefits to people. In addition, Delevaux et al. (2024) expanded the approach through the Smart Coast project to the Mesoamerican Reef region to inform land-sea integrated management. To refine these national-scale blue carbon evaluations and ecosystem service assessments for Belize using remote sensing and spatial modeling, there is a need to conduct field-based investigations that integrate local knowledge and community priorities (Arkema et al. 2023; Morisette et al. 2023; Delevaux et al. 2024). Our work demonstrates a collaborative framework to inform mangrove nature-based solutions strategies that reflect both ecological potential and local values.

Our team, comprised of scientists from Stanford University's Natural Capital Alliance, community fellows from Placencia village through the Strong Coasts project (hereafter the NSF Strong Coast Team), and practitioners at WWF Belize, collaborated to center local Belizean values and priorities in mangrove nature-based solution designs. Lifting community voices can inform successful nature-based solution strategies being led by government agencies, development banks, and conservation organizations. Our work involved extensive engagement with a diverse range of stakeholders and villagers conducting work and/or living around Placencia Lagoon, including resident fishing and tourism operators, NGOs, government members, and researchers (hereafter referred to as the local community; see Table 1 for specific stakeholder sectors), to provide input focused on three questions: (1) Where does the local community seek to prioritize mangrove restoration and protection nature-based solutions? (2) What benefits to people are enhanced by restoring mangroves in those areas? (3) What benefits to people are safeguarded by protecting those mangrove areas?

We selected Placencia as our field site for several strategic reasons aligned with national conservation goals and local management planning. Located in southern Belize, Placencia is a fishing village that has transitioned into a major tourism economy and sits adjacent to Placencia Lagoon, a large coastal wetland system supporting extensive mangrove and seagrass habitats, that play a nursery role for commercially valuable fish and invertebrates species, and tourism-based livelihoods (Key & Pillai 2007; Wildtracks 2015). The lagoon provides critical ecosystem services including nursery habitat for commercially valuable species (e.g. spiny lobster larvae), protection of coastal infrastructure from storm surge, opportunities for mangrove-based ecotourism, and sustenance for local communities (Wildtracks 2015). Since 2012, the WWF and local NGOs have sought to protect the lagoon's health and proposed the Placencia Lagoon Management Plan 2015–2020. The plan explicitly identifies the need to reduce impacts on mangroves by promoting replanting, establishing mandated buffer zones, and creating zoning schemes that balance conservation with sustainable development (Wildtracks 2015). This existing management framework and demonstrated community interest in restoration and protection efforts made Placencia ideal for co-designing nature-based solutions to build climate resilience.

To address these questions, we adopted a collaborative science approach combining participatory workshops and ecosystem service modeling. We led five participatory mapping workshops over the course of two years in Placencia with local community participants to identify local priority sites for implementing mangrove nature-based solutions. In order to quantify the expected benefits from mangrove nature-based solutions at community preferred sites, we designed three scenarios evaluating the potential changes in benefits to people: (1) mangrove restoration within community-identified priority sites – where degraded or cleared mangrove ecosystems were restored to ecological function, (2) mangrove protection within community-identified priority sites – where existing mangrove areas were protected from clearing, and (3) mangrove protection within the Placencia Lagoon Protection Plan – where existing mangroves within the proposed management area were protected from clearing. To quantify benefits associated with the three mangrove nature-based solutions scenarios, we mapped sociocultural values of currently present mangroves, and used the InVEST software to model changes in tourism and recreation opportunities, spiny lobster fisheries production, and blue carbon storage and sequestration–in both monetary value and sociocultural values. Our collaborative approach to identifying nature-based solutions sites and conducting comprehensive valuation demonstrates the bankability of community-identified priority areas while ensuring conservation strategies reflect local priorities, knowledge, and the lived experiences of people whose livelihoods and cultural identities are deeply connected to mangrove ecosystems.

Methods

Collaborative research

To collaboratively design locally driven mangrove nature-based solutions, we hosted five workshops with the local community between 2024 and 2025 to map mangrove health and extent, identify priority mangrove nature-based solutions sites, and map sociocultural values of mangroves. We used outputs from these workshops to model and quantify ecosystem service benefits associated with implementing mangrove restoration and protection. The first workshops had 20 participants and attendance grew in subsequent meetings, with 100 participants in the final workshop (Table 1). Participants represented a diversity of local residents from villages around Placencia Lagoon, representatives from key sectors (e.g., fishing and aquaculture, tourism, restaurants, hotels, education), government, NGOs, and academic institutions (See Supplementary Table 2 for participant breakdown; Delevaux et al. 2024, 2025a, b).

Figure 1 shows the collaborative integration of community workshops, modeled nature-based solutions scenarios, and potential policies our work can inform. In the initial two workshops, we conducted participatory mapping to validate and update existing national scale maps of mangrove habitat health and extent, mark locations of local anthropogenic stressors, and map tourism and recreation sites and attractions (Table 1, W1 & W2; Fig. 1a). We used a combination of the participatory mapping data, remote-sensing data, and mangrove ground-truth data to create a high resolution, local baseline mangrove map (Fig. 1a). Subsequent workshops used this baseline map to identify priority mangrove nature-based solutions sites (Table 1, W3; Fig. 1b) and map sociocultural values associated with coral and mangrove ecosystems and fisheries value chain (Table 1, W4; Fig. 1c and 1d). We used both spatial (e.g. mangrove extent, priority sites) and non-spatial data (e.g. lobster price) collected during the participatory mapping workshops as inputs to three InVEST models (carbon, lobster fishery, tourism & recreation) to quantify and value mangrove ecosystem service benefits (Fig. 1c and 1d). The team presented the nature-based solutions sites and benefits to the larger Placencia peninsula community in October, 2025 (Table 1, W5; Fig. 1e).

Table 1
Five workshops were conducted throughout the co-produced research to gather community input on mangrove health conditions, anthropogenic stressors, social and ecological values, and preferred restoration and protection sites, and share findings with the community for feedback.

Workshop	Date	Activities / Goals	# of Participants	Affiliation
W1	2/2/2024	Participatory Mapping of Mangrove and Coral Ecosystem Health	20	- Placencia Tour Guide Associations - NGOs (Fragments of Hope, Crocodile Research Coalition) - Placencia Village Council - NSF Strong Coast Team
W2	2/3/2024	Participatory Mapping to Inform the Modeling of Tourism & Recreation and Coastal Hazard Risk	20	- Placencia Tour Guide Associations - NGOs (Fragments of Hope, Crocodile Research Coalition) - Placencia Village Council - NSF Strong Coast Team
W3	10/24/2024	Share Progress on Nature-based Solutions Scenarios and Benefits Modeling Participatory Mapping of Mangrove and Coral Nature-Based Solutions Priority Sites	38	- Fishers / Fishing Guides - Placencia Tour Guide Association - Village Councils (Monkey River, Placencia, National Garifuna) - NGOs (Fragments of Hope, Southern Environmental Association, Wildlife Conservation Society) - Government Department (Forests) - NSF Strong Coast Team
W4	10/25/2024	Participatory Mapping of Social and Cultural Values of Mangrove Forests and Coral Reefs Mapping Fisheries Value Chain	59	- Fishers / Fishing Guides - Restaurant Industry - Placencia Tour Guide Association - Village Councils (Monkey River, Placencia, National Garifuna) - No Occupation - NGOs (Fragments of Hope, Southern Environmental Association, Wildlife Conservation Society, World Wildlife Fund, Humana Belize, Wildtracks) - Government Department (Forests) - Development Bank - NSF Strong Coast Team
W5	10/25/2025	Share Results and Key Messages	107	- Fishers / Fishing Guides - Aquaculture Industry - Tourism & Service Industry - Restaurant Industry - Education Organizations - Tour Guide Associations (Independence, Placencia)

Workshop	Date	Activities / Goals	# of Participants	Affiliation
				- Village Councils (Monkey River, Placencia, National Garifuna, Seine Bight, Independence) - NGOs (Fragments of Hope, Southern Environmental Association, Wildlife Conservation Society, World Wildlife Fund, Humana Belize, Crocodile Research Center, Healthy Reefs Initiative) - Government Departments (Fisheries, Forests, Land and Surveys) - NSF Strong Coast Team

Study area

Belize is a tropical Caribbean country on the Yucatan Peninsula known for its rich biodiversity on land and sea (Fig. 2a). Belize has expansive mangrove forests (~ 76,300 hectares) throughout the country that support people by reducing coastal vulnerability to storms and flooding, regulating climate, and providing habitat for valuable commercially important species and recreation (WWF Mesoamerica 2025). However, Belize's mangroves are threatened by high deforestation rates (5.4% or 44 ha/year from 1980 to 2017) and rapid coastal development, putting these ecosystems and the benefits they provide at risk (Cherrington et al. 2020). Coastal communities, the Belizean government, and NGOs are working to strategically protect and restore mangrove ecosystems to maintain their benefits to people through a combination of policy, finance, and climate commitments.

Here, we investigate the ecosystem service benefits of restoring and protecting mangroves located around the Placencia Lagoon. Denser, uninterrupted swathes of mangrove forest are situated on the west side of the lagoon and patches of mangrove forest are found on cayes and along the lagoon side of the Placencia peninsula, a flat sandbar facing the Caribbean Sea (Fig. 2b & c). There are three species of mangroves found in Placencia and throughout Belize: red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*), and white mangrove (*Laguncularia racemosa*) (Morrissette et al. 2023).

Coastal communities along the Placencia peninsula are historically fishing villages that have transitioned to tourism, given their proximity to major coral snorkeling and diving sites found among nearby cayes. The scenic beauty of this area has accelerated development, exacerbating the consequences of coastal erosion and reduced coastal protection (Trotz et al. 2023). Placencia is vulnerable to climate change impacts (e.g., increasing storms and flooding), risks which can be mitigated through nature-based solutions, including restoring and protecting mangroves (IADB 2015). To address these pressures and ensure effective management of the area, WWF, Southern Environmental Association, and Friends of Placencia Lagoon collaborated to conduct six consultations with communities along the lagoon and a rapid assessment. Their work culminated in a proposed plan to integrate the Placencia Lagoon in the National Protected Areas Systems of Belize as a wildlife sanctuary under the authority of the Forest Department (Wildtracks et al. 2015). The Placencia Lagoon Management Plan (2015) demonstrates the lagoon's potential to be a global model of balanced community values, development, and conservation (Wildtracks et al. 2015).

Mapping mangroves' current extent and health

We created a mangrove extent and health baseline map of the broader Placencia Lagoon area using a combination of datasets, collaborations, and community feedback. We began with compiling mangrove extent data. Cherrington et al. (2020) created a national map of mangrove extent in Belize based on imagery from Landsat satellite data to track progress in sustainable management of coastal forest ecosystems (30m resolution). In 2019, Fragments of Hope collected drone imagery of the inner cayes surrounding Placencia Lagoon, which was processed by The Nature Conservancy (TNC) through hand-digitization to create a mangrove extent map as part of its regional Caribbean mapping effort in 2021. This effort by TNC was conducted in partnership with the United Nations Food and Agriculture Organization, using remote sensing techniques to map and monitor mangroves at fine scales (< 5m) and create open-access mangrove data (Schill et al. 2021, 2024). For our baseline map, we combined the national and local-scale mangrove extent data, then manually refined the map at a fine-scale (< 5m) to match the mangrove extent shown in 2023 Google

Earth satellite imagery. We further refined the extent of the baseline map with mangroves presence and absence data and coordinates collected from sites around the Placencia Lagoon (Baron-Aguilar et al. 2024 *unpublished data*).

We then added the mangrove health conditions to our baseline map by using the InVEST Habitat Risk Assessment (HRA) map produced by the Natural Capital Alliance in partnership with the Coastal Zone Management Authority Institute for coastal and marine planning (Arkema et al. 2015; Delevaux et al. 2022 *unpublished*; Natural Capital Alliance 2026; see Supplementary Methods for more details). The HRA model is a tool that assesses the risk to ecosystems from human activities given their spatial overlap and known impact. The HRA map of Belize illustrates the levels of risk to mangroves from coastal development, dredging, aquaculture, agricultural runoff, marine transportation, oil exploration, marine recreation, and fisheries activities (Arkema et al. 2014, Arkema et al. 2015, Delvaux et al. 2022 *unpublished*, Supplementary Table 4). We overlayed the HRA map on our baseline mangrove extent map and used the risk classifications as proxies for health conditions, assuming that habitat classified as high risk from human impact equated to “cleared” mangrove (i.e., mangroves that have been mostly cleared or removed for construction and can no longer be restored), medium risk habitat corresponded to “degraded” mangrove (i.e., mangroves impacted by anthropogenic and natural drivers that can feasibly be restored to healthy levels if left undisturbed), and low risk habitat was equivalent to a “healthy” state of mangroves (i.e., mangroves as those that are stable or undisturbed, showing no obvious anthropogenic or natural disturbances) (See Supplementary Table 4 for further detail).

We conducted a participatory mapping workshop in February 2024 to solicit feedback on our mangrove baseline map (Table 1, W1). We asked participants to validate whether our map accurately reflected mangrove extent and health (healthy, degraded, and cleared) around the Placencia Lagoon, and to indicate where dredging among mangroves had occurred to capture local human impacts. We digitized the community’s input and shared our revised baseline map with our partners at WWF to include in their national assessment of mangrove health conditions. WWF integrated our baseline map into their national mangrove health assessment and improved it using various remote-sensing, spatial analysis, field-verified data, and additional community participatory mapping sources (e.g., Forest Department, Coastal Zone Management Authority Institute, Morrissette et al. 2023, etc.) to generate a baseline mangrove extent and health map with seven classifications (Stable, Regeneration, Degraded, Transitioning, Cleared, Filled, Construction, see Supplementary Table 4 for definitions) (Villarreal-Rosas et al. 2026 *unpublished*). We used WWF’s mangrove health condition map as our final baseline map and to build scenarios by condensing the seven mangrove health classifications down to three main health conditions (healthy, degraded, and cleared; see details in Supplementary Table 4).

Mapping mangrove nature-based solutions scenarios

We developed three scenarios to map mangrove nature-based solutions in Placencia: (1) community-priority restoration sites, (2) community-priority protection sites, and (3) Placencia Lagoon protection. These scenarios built on national policies (e.g., Nationally Determined Contributions mangrove restoration and protection targets, Belize Blue Bond conservation targets, Resilient Bold Belize nature-based solution targets) and local management goals (participatory mapping, Placencia Lagoon Management Plan).

We created the community-priority restoration scenario by first mapping the mangrove nature-based solution restoration opportunities. From our baseline mangrove map, we identified degraded mangrove as a target for restoration efforts given their potential to become healthy mangrove under management or if left undisturbed by human and environmental stressors. We then led a participatory mapping workshop with the local community (Table 1, W3) to identify a subset of the opportunity restoration area to target with mangrove nature-based solutions; there was no constraint on the total area they could select. We constructed our community-priority restoration scenario by converting baseline degraded mangrove within these community-identified restoration sites to healthy mangrove to calculate the change in ecosystem service benefits. In this scenario we assume that restored areas provide the same number of benefits as healthy mangrove ecosystems, 10 years after restoration (Arkema et al 2023, Delevaux et al. 2024).

To create the community-priority protection scenario, we first identified healthy mangrove in our baseline map as having nature-based solution protection opportunities. We define “protection” as areas where healthy mangrove can be conserved and remain undisturbed from human and environmental stressors. In our participatory mapping workshop (Table 1, W3), the community identified a subset of protection areas to target with mangrove nature-based solutions, with no constraint on total area they could select. For the community-priority protection scenario, we captured the present value of healthy mangroves by calculating the avoided loss of

mangrove ecosystem service benefits. In the scenario, we cleared all baseline healthy mangrove within the community-identified protection sites and calculated the total loss of benefits.

For the Placencia Lagoon protection scenario, we used the Placencia Lagoon Management Plan's proposed management area which covers the entire lagoon and inshore healthy mangroves on the west side (2015, Fig. 2c). For this scenario, we assumed all healthy mangrove in the proposed management area has mangrove protection nature-based solution opportunities. We captured the present value of healthy mangroves within the Placencia Lagoon protection scenario by calculating the avoided loss of mangrove ecosystem service benefit. In the scenario, we cleared all baseline healthy mangroves within the management area and calculated the total loss of benefits.

There is limited overlap between the two protection scenarios. The community prioritized protecting recently privatized mangroves in the northern lagoon whereas the proposed Placencia Lagoon protection area encompasses the aquatic environment and associated tributaries of the lagoon which are largely found on the southern half of the lagoon. Together, these two protection scenarios complement each other by encompassing the majority of inland mangroves, thus allowing us to capture mangrove benefits throughout the lagoon.

Modeling, mapping, and valuing the benefits nature provides to people

To quantify the benefits that mangrove restoration and protection nature-based solutions provide to people, we considered four ecosystem services: (1) blue carbon storage and sequestration, (2) lobster fisheries output, (3) visitation, and (4) sociocultural values. The InVEST software (Version 3.16.0) was used to quantify and value the potential benefits from the restoration and protection mangrove nature-based solutions scenarios: (1) blue carbon stock of mangroves, (2) change in lobster catch and revenue, and (3) change in visitation and revenue from tourism. We collected data capturing sociocultural places of significance through a participatory mapping workshop in October 2024 (W4 Table 1).

Blue Carbon Model

To quantify the blue carbon stock in local mangroves, in terms of biomass (tons) and market value ($ USD), we used the InVEST carbon model to calculate the carbon storage and sequestration under each scenario. The model requires a land use cover map and a biophysical table with carbon densities for four carbon pools (above-ground biomass, below-ground biomass, soil, and dead organic material) to calculate the total sum of carbon in each land use type (Natural Capital Alliance 2026). The model calculates sequestration and the net present value of carbon with an alternative land cover scenario and carbon market rate values, including the price of carbon ($), annual market discount rate (%), and annual price change (%) (Natural Capital Alliance 2026). The model outputs show the carbon stored in the baseline and alternative scenarios, the sequestration between the scenarios, and the calculated net present value of carbon. We used our baseline mangrove extent and health condition map for the land use cover map and the Morrissette et al. 2023 Belize mangrove carbon density data to calibrate the model (Supplementary Table 5).

To calculate the carbon stock and sequestration under each scenario, the model was run three times, each with the baseline land cover map for current stocks and then the scenario's land cover map for the future carbon stocks and sequestration (Fig. 3a, 4a, 5a). In each model run, we set the price of carbon to $35 per metric ton of carbon dioxide equivalent with a discount rate of 5% and no annual price change (Giangola et al. 2024). We selected the price of carbon based on market conditions in 2020 and a discount rate of 5% in line with Belize's national debt discount rates (Green Finance Institute 2026; Natural Capital Alliance 2026). To calculate the total carbon stock, sequestration, and monetary value of mangrove blue carbon in each scenario, we first calculated the baseline stock of carbon. Then, we used the InVEST model to provide the blue carbon sequestration value and net present monetary value (US$) by calculating the marginal change between the nature-based solutions scenarios and the baseline conditions. Lastly, we conducted zonal statistics to obtain the total amount of blue carbon stock, sequestration, and monetary value from the community-priority restoration sites, community-priority protection sites, and Placencia Lagoon protection area.

Spiny Lobster Model

We used the InVEST Lobster model to assess the impact of mangrove restoration on spiny lobster (*Panulirus argus*) catch in Belize in terms of biomass (lbs) and market value (USD $), following the modeling framework and parameterization established by Arkema et

al. (2015) and leveraging inputs from fishers during workshop 4 (Table 1) (Arkema et al. 2019). The spiny lobster model is an age-structured population matrix model, emphasizing age-based habitat dependencies, where the availability of nearshore nursery habitat (e.g., mangroves and seagrass) and coral reefs influence survivorship and catch, respectively (Arkema et al. 2015, 2019). The model uses lobster catch data, market values, and changes in lobster habitat (mangroves, coral reefs, seagrass) size to estimate the change in the distribution and catch of spiny lobster. We kept the parameters from Arkema et al. (2019) in this analysis.

For each scenario, we recalculated the total lobster catch using the baseline catch rates from Arkema et al. 2019. In the InVEST Lobster model, we computed the change in catch by comparing the total hectares of mangrove in the restored and conservation scenarios to the baseline, estimating both absolute and percentage changes across Coastal Planning Units. These results inform how restoration and conservation of mangroves can affect lobster fishery production. To capture the total change in lobster catch within priority areas, we first calculated the density of lobster larvae among restored and conserved mangrove within 250m of the coastline. We then performed zonal statistics to sum the change in lobster production within restoration and protection sites in each scenario. We multiplied the change in lobster production by the whole lobster average sale price for Placencia (BZD $15.6/lb), which we collected during interviews with fishers in the fourth workshop while mapping the fisheries value chain, to calculate the total monetary value of the change in lobster production (Table 1, W4) (Olaya et al. 2026 *in review*). Complete methodological details, data processing steps, and geospatial tools used are provided in the Supplementary Methods and Supplementary Table 6.

Tourism & Recreation Model

To quantify the contribution of mangroves in Placencia to tourism in terms of the number of visitors and revenue generated by tourism ($ USD), we estimated the spatial distribution of visitation to Placencia using the social media-based approach in the InVEST Recreation model (Arkema et al. 2015; Natural Capital Alliance 2026). The approach uses geotagged posts to Flickr and Twitter (from 2012 to 2017) as a proxy for visitation. Posts to these social media platforms are well-correlated with empirical visitation numbers and are useful for filling in gaps in other visitation datasets (Wood et al. 2013; Sessions et al. 2016; Fisher et al. 2018; Arkema et al. 2021).

Based on the positive relationship between tourism and mangroves in our regression model, we predicted how visitation might change with mangrove restoration and protection (see Supplementary Methods and Supplementary Table 7 for more methodological details and data processing steps). These predicted values represent the marginal effect of mangrove habitat on tourism, holding all other variables constant. We then calculated the difference between the number of tourists predicted under the restoration scenario and the number of tourists predicted under the baseline (using the change in the proportional estimated visitation computed based on the regression), for each grid cell. Additionally, we calculated the difference between the number of tourists predicted under both the two protection scenarios and the baseline. Total tourism expenditure was derived by multiplying the change in the number of visitors for each scenario by the 2024 average daily expenditure (US $227.71) provided by the Belize Tourism Board (2024). We used zonal statistics to sum the change in benefits and their values within each nature-based solutions priority site.

Sociocultural Values

In addition to community-identified priority areas for nature-based solutions, we also captured social and cultural values associated with the coastlines of Placencia. Through participatory mapping workshops (Table 1, W4 & W5), we asked community members to place different colored stickers that represented different types of social and cultural connections: these connections were beauty, sense of community, heritage, education, and recreation/relaxation. The workshop consisted of 31 participants representing a diversity of local occupations (see Supplementary Information for more information). The sticker placements were digitized into points and summed by area to represent a range from lowest to highest frequency of points (or areas of low to high levels of social and cultural importance). To adjust for local spatial scales of social and cultural connections in Placencia, spatial autocorrelation was used to determine the distances of pattern clustering, which was then used to determine the suitable area in which the points were summed (see Supplementary Information and Supplementary Fig. 1 for more information). Sociocultural values were captured by summing the frequency of different types of connections to mangroves throughout the Placencia Lagoon area to identify the places with the greatest levels of cultural importance to the local community. We then clipped and quantified the sociocultural values intersecting with each scenario.

Results

Community-priority sites for mangroves nature-based solutions

Through the third participatory mapping workshop (Table 1), the community identified a total of 83 hectares of degraded mangrove for the community-priority restoration scenario (Fig. 2b) and 174 hectares of healthy mangrove for the community-priority protection scenario (Fig. 2c). These restoration sites are all found on the peninsula where there is more development whereas the protection sites are found in the undeveloped northern inland side of the lagoon and on cayes around the entrance of the lagoon. In the Placencia Lagoon protection scenario (Fig. 2d), there are 752 hectares of healthy mangrove, largely found on the undeveloped west inland lagoon side. The community-identified protection sites do not overlap with the Placencia Lagoon Management Plan area except for one patch of inland mangrove north of Maya Beach (Fig. 2c).

Restoration nature-based solutions benefits to people

Our results reveal that mangrove restoration throughout the Placencia peninsula would enhance all ecosystem service benefits. The 83 hectares of mangrove identified for restoration could potentially sequester 18,500 metric tons of carbon over 10 years (Fig. 3a), valued at $644,000 USD ($1.3 million BZD) in net present terms. Second, restoring these mangroves could yield 640 pounds of lobster annually and generate an additional $5,000 USD ($10,000 BZD) in wholesale revenue to local fishers (Fig. 3b). Third, mangrove restoration efforts in these priority sites could attract approximately 140 additional visitors (Fig. 3c). Collectively, these visitors could contribute an estimated $32,000 USD ($64,000 BZD) in annual tourism expenditure. Finally, we found that natural beauty and recreational opportunities are the most important sociocultural values that mangroves within community-priority restoration sites provide to the local community, particularly within Placencia Caye and Village (Fig. 3d). The community and educational value of mangroves have a medium-level of sociocultural importance; these values are concentrated among mangroves in Maya Beach and Cocoplum.

Protection nature-based solutions benefits to people

Under both protection scenarios, mangrove protection would safeguard all ecosystem service benefits modeled in this study. Within the community-priority protection sites, the 174 hectares of healthy mangrove identified by the community could protect 69,500 metric tons of carbon over 10 years (Fig. 4a), valued at $2 million USD ($4 million BZD) in net present terms. Second, protecting these mangroves could maintain 1,400 pounds of lobster catch annually, worth $11,000 USD ($22,000 BZD) in wholesale revenue to local fishers (Fig. 4b). The greatest production of lobster (940 pounds of lobster per year) that could be preserved comes from the north inland side of the lagoon. Third, protecting mangroves in these priority sites could sustain approximately 24 additional visitors (Fig. 4c), with the greatest density of visitors from Placencia Caye. Collectively, these visitors could contribute an estimated $5,400 USD ($10,800 BZD) in annual tourism expenditure. Lastly, recreation, beauty, and community are the most important sociocultural values provided by mangroves within the community-priority protection sites, particularly from mangroves in Placencia Caye and Village (Fig. 4d). The heritage value of mangroves has medium-level of sociocultural importance and is emphasized among mangroves on the northern inland side of the lagoon.

Under the Placencia Lagoon protection scenario, protecting 752 hectares of inland mangroves would safeguard 1.2 million MgC of blue carbon, valued at $32 million USD ($64 million BZD) over 10 years (Fig. 5a). Next, protecting these mangroves could maintain 10,000 pounds of lobster catch annually, worth $80,000 USD ($160,000 BZD) in wholesale revenue to local fishers (Fig. 5b). Furthermore, conserving these mangroves could help support the visitation of about 100 people in the area, corresponding to approximately $23,000 USD ($46,000 BZD) in annual tourism expenditure (Fig. 5c). Lastly, beauty, recreation, and community are the most important sociocultural values safeguarded by protecting lagoon mangroves, particularly among mangroves in Placencia Caye and Village (Fig. 5d). Mangrove areas in Maya Beach represent medium levels of sociocultural importance and would protect community values. Mangrove areas on the inland lagoon side, across from Cocoplum and north of Maya Beach, show medium levels of importance, with greater emphasis on education, recreation, and aesthetic value.

Discussion

This study demonstrates how collaborative science – conducting fine-scale habitat mapping and ecosystem service valuation with local communities – improves nature-based solutions design for real-world decision making. Publicly available global and national mangrove maps often lack information on ecosystem health, which can be sufficient for national target setting, but they are often too coarse to support site selection, landowner engagement, or project-level monitoring and verification. Here, we improved the spatial

fidelity of mangrove extent and condition data by integrating participatory mapping of mangrove health, manual digitization from high-resolution imagery, local ground-truth points, and a habitat risk assessment. This approach breaks down the scale of policy ambition (e.g., national targets) to the scale at which nature-based solutions projects are negotiated and implemented (e.g., parcels, community, municipality). By having a fine scale map of mangrove ecosystem health, we were able to create our nature-based solution scenarios, in which community participants identified 83 ha of degraded mangrove as restoration priority areas and 174 ha of healthy mangrove as priority protection areas. The proposed Placencia Lagoon Management Plan (PLMP 2015) encompasses a larger protection footprint with 752 ha of healthy mangrove. Across all three scenarios, every ecosystem service benefit was enhanced by mangrove restoration or safeguarded by mangrove protection. Blue carbon potential could help create a stream of revenue in Placencia (via carbon markets) to support mangrove habitat (Arkema et al. 2023). These nature-based solutions could enhance fisheries and tourism benefits, the main sources of livelihoods in the area, while also conserving multiple socioculturally important areas. Community-led mangrove nature-based solution design could therefore contribute to climate resilience, create pathways to conservation finance, while protecting sociocultural values and ways of life by securing local livelihoods, wellbeing, and ecosystem health.

Conservation and nature-based solution projects rarely attract multi-million-dollar investments from international finance institutions because they lack demonstrated “bankability” — measurable outcomes, predictive models, and automated monitoring enabling risk assessment and results-based disbursement (Sheikh et al. 2025). Our study helps translate nature’s benefits to people in metrics that resonate with investors. Carbon sequestration dominates the estimated monetary benefits across all restoration and protection scenarios (ranging from ~$1–32 million USD), suggesting that developing blue carbon finance mechanisms could be the most direct route to acquire funding for large-scale nature-based solutions interventions. These blue carbon values provide localized data to support projects that can help Belize reach its Project for Finance Permanence (PFP) conservation targets, Belize NDC 3.0, and sustainable development goals (Belize 2021; McKenzie et al. 2025; TNC, 2022; Arkema et al. 2023; Delevaux et al. 2025c). Carbon credits can provide revenue to small land holders or community-owned land, and current standards prioritize projects that support both livelihood and environmental benefits (Perera et al. 2024; Plan Vivo 2026). However, many blue carbon projects fail without community buy-in and equitable benefit sharing, thus emphasizing the need for policies and practices to include clear disclosures on direct community benefit sharing (monetary and non-monetary) from the start (Perera et al. 2024). Successful examples, like mangrove restoration and reforestation in Kenya, have helped communities pay for infrastructure and supplies such as school construction projects, books, and water pumps (Wylie et al. 2016).

While carbon credits can yield many benefits, obtaining them can be challenging at best. From a blue carbon finance perspective, mangrove restoration is more straightforward than conservation due to additionality requirements – evidence that healthy mangrove forests will face imminent threat (e.g., logging, fire) if they are not protected (Mason and Plantinga 2013; Purushotham et al. 2026). However, local conservation practitioners indicated that protecting mangroves was a more realistic pathway forward given the long time horizon and feasibility challenges of restoring mangroves. High costs for validation and verification, minimum scale requirements, and revenue benefit sharing linked to land ownership may also bar small-scale projects or communities from being eligible for receiving carbon credits and their revenue (Perera et al. 2024; Plan Vivo 2026; Purushotham et al. 2026). Furthermore, avoiding “bad” actors who intentionally exploit carbon schemes to prioritize commodification over conservation requires governance of blue carbon projects, primarily through establishing national level legislation frameworks, increasing local community participation, and institutional accreditation of stakeholders involved (Rosli et al. 2025, Purushotham et al. 2026). The Belizean government is currently in the process of setting up its national carbon policy which could establish a community sharing benefits framework (PMI 2026). Our methodologies and findings could help create a blueprint for integrating community participation in blue carbon projects in Belize.

Mangrove nature-based solutions can also help support fisheries and tourism, the main economic sectors that support coastal livelihoods in Belize. Tourism alone contributed to an estimated 33% of Belize’s GDP and 46% of employment in 2025 (World Travel & Tourism Council 2025). Belize’s wild capture fisheries contribute to nearly 2% of the GDP as of 2022 and employ approximately 3,000 fishers, aiding in local food security and production for consumption in the tourism industry (Gachot et al. 2024). Spiny lobster is the most productive and main income-generating capture fishery in Belize, exporting most products to the US market (Gachot et al. 2024). However, these key GDP sectors are vulnerable to climate impacts, through storms that can damage infrastructure, change in SST that can impact fisheries productivity and coral habitat health. To help make these sectors more resilient, Belize has developed a National Sustainable Tourism Master Plan (as part of the Belize Blue Bond), in which diversifying livelihoods is a resilience strategy – tourism provides alternative livelihoods in seasons when fishing is closed and low tourism periods coincide with the opening of the

lobster and conch fishing seasons (Europraxis Consulting 2011; Murray 2021). Within Placencia, our analysis revealed that combining restoration and protection can benefit both tourism and fisheries, which is important from a local perspective because community members in Placencia typically live on tourism and fishing based on the season. Thus, restoring and protecting mangroves ecosystems that underpin these sectors critically supports these sectors and related jobs. Capturing the value of these sectors locally with nature-based solution scenarios grounded in local priorities can also help communities access funding for implementation from initiatives like WWF's Project for Finance Permanence (WWF 2025a, b).

Mapping sociocultural values provides an additional layer of information increasingly sought out by investors and granting agencies that is not captured by market metrics (Maia de Rocha et al. 2017; Sangha et al. 2025; WWF 2025a). In Placencia, mangrove landscapes are integral to the community's sense of place by providing spaces for recreational opportunities, educational development, and cultural activities. These sociocultural values, while not monetizable, can foster local stewardship commitments needed for successful long-term mangrove protection and restoration implementation. Blending biocultural metrics with biophysical and economic metrics also provides a pathway to blend indigenous knowledge and western science (Sangha et al. 2025). Pairing biophysical dimensions with socio-cultural indicators, local knowledge, and societal health outcomes can help communities engage in decision-making that informs effective conservation and management outcomes which increase their resilience to climate impacts (Neef et al. 2018; Nand et al. 2024; Sangha et al. 2025). For example, places of knowledge transfer and cultural heritage or identified as living playgrounds and central to community life may warrant priority habitat protection given their importance to supporting mental wellbeing, physical health, and social resilience in the face of coastal disasters (Maia de Rocha et al. 2017; Neef et al. 2018; Nand et al. 2024; Sangha et al. 2025).

Our modeled results reflect limitations and simplifying assumptions that should be considered when reviewing these ecosystem service benefits. First, global and national habitat maps can be limited in their local scale resolutions and require further inputs to refine for participatory mapping. Second, our condition mapping collapses mangrove structure and function into discrete classes, which does not capture variability in carbon density among different mangrove species, habitat quality, or habitat type. Third, we assumed that all degraded mangrove is restored to healthy mangroves after 10 years, simplifying recovery outcomes. Fourth, the lobster model simplifies nursery function by relating catch to mangrove area and proximity to shore; it does not represent fine-scale differences in larval supply and distribution from mangrove patch structure, lagoon currents, and fishing pressures. Fifth, the tourism model uses only X/Twitter and Flickr social media-derived visitation patterns and estimates the marginal effect of mangroves on visitation while holding other predictors constant. This approach may underrepresent local recreation and domestic visitation (more locals share photos on Facebook), or the cultural importance of mangroves that is not expressed in geotagged posts. Further, this model does not tell us why people are visiting specific sites nor what they are doing there (e.g., wildlife ecotourism, fishing), information that would be useful for informing sustainable and equitable ecotourism development. Despite these limitations, the strength of these InVEST models lies in the relative spatial patterns they illuminate rather than the absolute values, which provide a sense of magnitude of impact to compare to field observations and establish a baseline for valuation (Hamel et al. 2015). Additionally, the simplicity of the models allows for local engagement and reiteration to embed local values into scenarios and improve outputs for nature-based solutions projects, hence our multiple workshops to ground the research and findings in local priorities.

Several extensions would increase both the scientific robustness and the practical utility of this study. Not measured here but important to evaluate in future work is the coastal protection mangroves provide against storms and flooding in the area. Mangroves are the habitat most effective at protecting the coast under storm and non-storm conditions, as demonstrated in national level studies in Belize (Arkema et al. 2013, 2015; Gaunnel et al. 2016). Localized information on where Placencia's communities are most vulnerable, and where mangroves best shield developments and protect eroding coastline, is critical for avoiding loss of life, major infrastructure damage, and economic consequences. Adding this ecosystem service benefit in future analysis can inform more strategic policy and coastal development decision-making. Next, for the carbon model, field measurements of biomass and soil carbon in the Placencia Lagoon area would improve carbon estimates and reduce uncertainty for project-level accounting (Morrissette et al. 2023). Ecological monitoring of restoration sites could better constrain timelines for benefits recovery. Furthermore, incorporating cost and feasibility layers (e.g., hydrologic constraints, permitting, and restoration costs) would enable cost-effectiveness comparisons among sites. For example, investigations on private landowners' willingness and incentives to protect mangroves and participate in benefit-sharing mechanisms would assist in determining the feasibility of these nature-based solutions efforts (Dario et. al *in prep*; Marsan 2004; Wildtracks et al. 2015; Gloss et. al, 2019; Rasheed et. al, 2025). With this additional information, future scenarios could explicitly test how benefits change under sea-level rise, storms and flooding, parcel-level

willingness, and land-use change. They could also account for ridge-to-reef interactions that influence lagoon water quality and mangrove conditions.

A major contribution of this work is the methodological pathway to reproduce and scale this work in other communities. Importantly, we placed community expertise at the center of the workflow and from the onset of the study (e.g., site identification, value elicitation, feasibility) and iteratively returned results to the community for feedback and refinement. By combining community-led mapping, fine-scale habitat baselines, and ecosystem service benefit valuations, this study provides an actionable pathway for designing mangrove nature-based solutions that both protect local livelihoods and are functional for policy and finance audiences. Our results show that in Placencia, community-identified restoration and protection priorities sites improve carbon sequestration, fisheries, tourism, and sociocultural benefits, and that a lagoon-scale protection plan can substantially increase total climate and fisheries benefits. This approach breaks down the scale of policy ambition (e.g., national targets) to the scale at which nature-based solutions projects are negotiated and implemented (e.g., parcels, community, municipality). Further, our results can help provide communities with language to speak with investors as well as a budget for project implementation and local benefit sharing, a practice which is not conducted in most carbon and conservation projects. This study contributes to evidence that workflows integrating community participation and fine-scale habitat mapping are replicable and valuable for co-designing nature-based solutions that are implementable, locally supported, and aligned with Belize's evolving national climate and ocean commitments. Nature-based solutions projects with high social buy-in are also more likely to succeed due to the long-term commitment of the community, who are the stewards of these places.

Declarations

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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Author Contribution

Conceptualization: Jade M.S. Delevaux; Methodology: Jade M.S. Delvaux; Data Collection: Natasha M. Batista, Julian Olaya-Restrepo, Carlie Dario, Jessica Silver, Nadia Bood, Monique Vernon, Delcia McDougall, Jade Delevaux; Formal analysis and investigation: Natasha M. Batista, Julian Olaya-Restrepo, Jessica Silver, Jade M.S. Delevaux; Writing - original draft preparation: Natasha M. Batista; Writing - review and editing: Natasha M. Batista, Jade M.S. Delevaux, Julian Olaya-Restrepo, Carlie Dario, Jessica Silver, Anne Guerry, Monique Vernon; Funding acquisition: Jade M.S. Delevaux; Resources: Natasha M. Batista; Supervision: Jade M.S. Delevaux, Anne Guerry; Project Administration: Jade M.S. Delevaux, Anne Guerry

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Data Availability

The datasets generated during and/or analyzed during the current study are available in the Figshare repository, DOI: 10.6084/m9.figshare.32789013.

References

1. Akram H, Hussain S, Mazumdar, P, Chua, KO, Butt TE, Harikrishna JA (2023) Mangrove health: A review of functions, threats, and challenges associated with mangrove management practices. Forests 14(9), 1698. https://doi.org/10.3390/f14091698
2. Alongi DM (2012) Carbon sequestration in mangrove forests. Carb Manag 3(3), 313–322. https://doi-org.stanford.idm.oclc.org/10.4155/cmt.12.20
3. Alongi DM (2016) Climate Regulation by Capturing Carbon in Mangroves. In: Finlayson C et al. The Wetland Book. Springer, Dordrecht, pp 1–7. https://doi-org.stanford.idm.oclc.org/10.1007/978-94-007-6172-8_236-5
4. Alongi DM (2018) Mangrove Forests. In: Blue Carbon. SpringerBriefs in Climate Studies. Springer, Cham. https://doi-org.stanford.idm.oclc.org/10.1007/978-3-319-91698-9_3
5. Alongi DM (2022) Impacts of Climate Change on Blue Carbon Stocks and Fluxes in Mangrove Forests. Forests 13(2), 149. https://doi.org/10.3390/f13020149
6. Arkema KK, Guannel G, Verutes G, Wood SA, Guerry A, Ruckelshaus M, Kareiva P, Lacayo M, Silver JM (2013) Coastal habitats shield people and property from sea-level rise and storms. Nat Clim Chan 3(10), 913–918. https://doi-org.stanford.idm.oclc.org/10.1038/nclimate1944
7. Arkema KK, Verutes G, Bernhardt JR, Clarke C, Rosado S, Canto M, Wood SA, Ruckelshaus M, Rosenthal A, McField M, De Zegher J (2014) Assessing habitat risk from human activities to inform coastal and marine spatial planning: a demonstration in Belize. Env Res Let 9(11), 114016. https://doi.org/10.1088/1748-9326/9/11/114016
8. Arkema KK, Verutes GM, Wood SA, Clarke-Samuels C, Rosado S, Canto M, Rosenthal A, Ruckelshaus M, Gaunnel G, Toft J, Faries J, Silver JM, Griffin R, Guerry AD (2015) Embedding ecosystem services in coastal planning leads to better outcomes for people and nature. PNAS 112(24), 7390–7395. https://doi-org.stanford.idm.oclc.org/10.1073/pnas.1406483112
9. Arkema KK, Fisher DM, Wyatt K, Wood SA, Payne HJ (2021) Advancing Sustainable Development and Protected Area Management with Social Media-Based Tourism Data. Sust 13, 2427. https://doi.org/10.3390/su13052427
10. Arkema KK, Delevaux JMS, Silver JM, Winder SG, Schile-Beers LM, Bood N, Crooks S, Douthwaite K, Durham C, Hawthorne PL, Hickey T, Mattis C, Rosado A, Ruckelshaus M, von Unger M, Young A (2023) Evidence-based target setting informs blue carbon strategies for nationally determined contributions. Nat Ecol Evol 7, 1045–1059. https://doi.org/10.1038/s41559-023-02081-1
11. Ashton EC (2022) Threats to mangroves and conservation strategies. In Mangroves: Biodiversity, livelihoods and conservation. Spring Nat Sing pp 217–230. https://doi.org/10.1007/978-981-19-0519-3
12. Belize (2021) Belize Updated Nationally Determined Contribution. UNFCCC. https://unfccc.int/sites/default/files/NDC/2022-06/Belize%20Updated%20NDC.pdf. Accessed 1 October, 2025
13. Belize (2025) Belize's Third Nationally Determined Contribution NDC 3.0. UNFCCC. https://unfccc.int/sites/default/files/2025-06/BELIZE%20FINAL%20NDC%203.0.pdf. Accessed March 18, 2026
14. Belize Tourism Board (2024) Travel & Tourism Statistics Digest 2024. Belize Tourism Board. https://infogram.com/2024-travel-tourism-statistics-digest-1h0n25o9jjoyl4p. Accessed 28 June 2025
15. Boyland M, Tuhkanen H, Green J, Barquet K (2022) Principles for Just and Equitable Nature-based Solutions. Stockholm Environment Institute. https://www.sei.org/wp-content/uploads/2022/05/principles-for-just-and-equitable-nature-based-solutions.pdf. Accessed 16 May 2026
16. Carlson RR, Foo SA, Asner GP (2019) Land Use Impacts on Coral Reef Health: A Ridge-to-Reef Perspective. Front Mar Sci 6:562. https://doi.org/10.3389/fmars.2019.00562
17. Chen X, Yin Z, Li Z, Wang B, Tao A, Guo Z, Wang F, An Y, O'Driscoll K (2024) Overview on Mangrove Forest Disaster Prevention and Mitigation Functions. J Ocean Univ China 23, 46–56. https://doi-org.stanford.idm.oclc.org/10.1007/s11802-024-5672-3
18. Cherrington EA, Griffin RE, Anderson ER, Sandoval BEH, Flores-Anderson AI, Muench RE, Market KN, Adams EC, Limay AS, Irwin, DE (2020) Use of public Earth observation data for tracking progress in sustainable management of coastal forest ecosystems in Belize, Central America. Rem Sens Env 245, 111798. https://doi.org/10.1016/j.rse.2020.111798

19. Choudhary B, Dhar V, Pawase AS (2024) Blue carbon and the role of mangroves in carbon sequestration: Its mechanisms, estimation, human impacts and conservation strategies for economic incentives. J Sea Res, 199, 102504. https://doi-org.stanford.idm.oclc.org/10.1016/j.seares.2024.102504
20. Cohen-Shacham E, Janzen C, Maginnis S, Walters G (2016) Nature-based solutions to address global societal challenges. IUCN. https://doi.org/10.2305/IUCN.CH.2016.13.en. Accessed 22 May 2026
21. Coleman EA, Mwangi E (2013) Women's participation in forest management: A cross-country analysis. Glob. Environ. Change 23, 193–205. https://doi.org/10.1016/j.gloenvcha.2012.10.005
22. Delevaux J, Batista N, Neal H, Wallen M, Gibson N, Faux V, Cheek L, McKenna R, Baron-Aguilar C, Trotz M (2024) Mapping mangroves and coral habitats health and benefits to people, Nature-Based Solutions Workshop & Ground Truthing Report: Placencia, Belize (report no. 5). Strong Coasts Collection. https://doi.org/10.5038/RZJQ9204
23. Delevaux JMS, Silver JM, Winder SG, Bood N, Chevez L, Velásquez, Vela ACV, Varlet R, Parta MA, Wolny SA, BAiley A, McField M, Muñiz-Castillo AI, Arkema KK (2024) Social–ecological benefits of land–sea planning at multiple scales in Mesoamerica. Nat Sust 7, 545–557. https://doi.org/10.1038/s41893-024-01325-7
24. Delevaux JMS, Zarger RK, Dario C, Hinds K, Batista N, Olaya-Restrepo JM, Webb WA, McDougall D, Vernon M, Gibson N, McKenna R, Trotz MA (2025) Mapping Co-benefits and Cultural values for Nature-based Solutions: Palcencia, Belize (report no. 9). Strong Coasts Collection. https://doi.org/10.5038/FNZD2673
25. Delevaux JMS, Dario C, Batista N, Olaya-Restrepo J, McDougall D, Vernon M, Gibson C, Lee Hing M, Requena M (2025) Nature-based Solutions Values: Placencia, Belize (Report no. 12). Strong Coasts Collection. https://doi.org/10.5038/QEYM6667
26. Delevaux J, Ruckelshaus M, Wade B, Dario C, Batista N, Blanc PL, Bood N, Martinez L, Samayoa O (2025) Monitoring Progress Toward a Prosperous, Sustainable Future: Belize Final Report. IADB. https://doi.org/10.18235/0013713. Accessed 16 October 2025
27. Europraxis Consulting (2011) National Sustainable Tourism Master Plan of Belize 2030. Ministry of Tourism, Youth, Sports & Diaspora Relations. https://drive.google.com/file/d/1rZabc9eohBV7DuZ2RpkDDZEu5PhLL6fS/view?usp=sharing. Accessed 18 March 2026
28. Gachot S, Carcamo R, Rondinone G, De Salvo CP (2024) Analysis of Agricultural and Fisheries Policies in Belize: Quantification of Support and its Relationship to Greenhouse Gas Emissions in 2015–2022. IADB. https://doi.org/10.18235/0013227. Accessed 18 March 2026
29. Guannel G, Arkema K, Ruggiero P, Verutes G (2016) The power of three: coral reefs, seagrasses and mangroves protect coastal regions and increase their resilience. PloS one 11(7), e0158094. https://doi.org/10.1371/journal.pone.0158094
30. Giangola L, Stiles ML, Self R, Stamoulis K, Delevaux JMS, Kozuszek L, Wiggins M, Gallagher K (2024) Investing in Resilience: Blue Carbon Ecosystems, Communities, and Finance for the Indo-Pacific. USAID. https://stilesworks.com/wp-content/uploads/2025/03/USAID_305-Blue-Carbon-Report-Final-508.pdf. Accessed 14 August 2025
31. Gilman EL, Ellison J, Duke N C, Field C (2008) Threats to mangroves from climate change and adaptation options: a review. Aqua bot 89(2), 237–250. https://doi.org/10.1016/j.aquabot.2007.12.009
32. Gloss L, Myron E, Ahmed H (2019) International Outlook for Privately Protected Areas: Belize Country Profile. International Land Conservation Network. https://landconservationnetwork.org/wp-content/uploads/2022/09/Belize20Country20Profile20on20Privately20Protected20Areas_7_24_2019-1.pdf. Accessed 4 May 2026
33. Green Finance Institute (2026) Government of Belize Debt Conversion for Marine Conservation. Green Finance Institute. https://www.greenfinanceinstitute.com/hive/revenues-for-nature/case-studies/government-of-belize-debt-conversion-for-marine-conservation/. Accessed 7 August 2025
34. Hamel P, Chaplin-Kramer R, Sim S, Mueller C (2015) A new approach to modeling the sediment retention service (InVEST 3.0): Case study of the Cape Fear catchment, North Carolina, USA. Sci Tot Env 524, 166–177. http://dx.doi.org/10.1016/j.scitotenv.2015.04.027
35. Key C, Pillai VK (2007) Tourism and Ethnicity in Belize: A Qualitative Study. Int Rev Mod Soc 129–150. https://www.jstor.org/stable/41421258
36. Maia de Rocha S, Almassy D, Pinter L (2017) Social and cultural values and impacts of nature-based solutions and natural areas. Naturvation. https://naturvation.eu/sites/default/files/result/files/social_and_cultural_values_and_impacts_of_nature-

based_solutions_and_natural_areas.pdf. Accessed 22 May 2026

37. Mason CF, Plantinga AJ (2013) The additionality problem with offsets: Optimal contracts for carbon sequestration in forests. J Env Econ Man 66(1), 1–14. https://doi.org/10.1016/j.jeem.2013.02.003
38. Marsan J (2004) Private lands conservation in Belize. University of Colorado Boulder Natural Resources Law Center. https://scholar.law.colorado.edu/cgi/viewcontent.cgi?article=1156&context=books_reports_studies Accessed 4 May 2026
39. Mckenzie RM, Santa Pena CA, Blanc PL, Wade B, Balderamos J, Vasquez S (2025) Blue Forum: Knowledge, Innovation and Action for Belize's Ocean and Thriving Blue Economy. IADB. https://dx.doi.org/10.18235/0013739 Accessed 25 October 2025
40. Miteva DA, Murray B, Pattanayak S (2015) Do protected areas reduce blue carbon emissions? A quasi-experimental evaluation of mangroves in Indonesia. Ecol. Econ. 119, 127–135. https://doi.org/10.1016/j.ecolecon.2015.08.005
41. Morrissette HK, Baez SK, Beers L, Bood N, Martinez ND, Novelo K, Andrews G, Balan L, Beers CS, Betancourt SA, Blanco R, Bowden E, Burns-Perez V, Carcamo M, Chevez L, Crooks S, Feller IC, Galvez G, Garbutt K, Gongora R, Grijalva E, Lefcheck J, Mahuna A, Mattis C, McKoy T, McLaughlin D, Meza J, Pott E, Ramirez G, Ramnarace V, Rash A, Rosado S, Santo H, Santoya L, Sosa W, Ugarte G, Viamil J, Young A, Young J, Canty SW (2023). Belize Blue Carbon: Establishing a national carbon stock estimate for mangrove ecosystems. Sci Tot Env 870, 161829. https://doi.org/10.1016/j.scitotenv.2023.161829
42. Murray R (2021) A governance analysis of three MPAs in Belize: Conservation objectives compromised by tourism development priorities? Mar Pol 127, 104243. https://doi.org/10.1016/j.marpol.2020.104243
43. Mutanda GW, Nhamo G (2026) Livelihoods vulnerability and adaptive strategies for coastal communities. A systematic review. Mar Pol 189, 107094. https://doi.org/10.1016/j.marpol.2026.107094
44. Nand MM, Clissold R, McNamara KE, Yee M (2024) Guiding our responses to climate change by what people value: Insights from Fiji. Geoforum 155, 104080. https://doi.org/10.1016/j.geoforum.2024.104080
45. Natural Capital Alliance (2026) InVEST User Guide 3.20.0. The Natural Capital Alliance. https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/en/index.html
46. Neef A, Benge L, Boruff, B, Pauli N, Weber E, Varea R (2018) Climate adaptation strategies in Fiji: The role of social norms and cultural values. World Dev 107, 125–137. https://doi.org/10.1016/j.worlddev.2018.02.029
47. Olander L, Laymon K, Tallis H (2022) Opportunities for Accelerating Nature-Based Solutions: A Roadmap for Climate Progress, Thriving Nature, Equity, and Prosperity. White House. https://bidenwhitehouse.archives.gov/wp-content/uploads/2022/11/Nature-Based-Solutions-Roadmap.pdf. Accessed 22 May 2026
48. Perera NS, Costa MD, Macreadie PI, Wartman M (2024) Trends in market-based blue carbon projects. Sust Dev 33(3), 3377–3402. https://doi.org/10.1002/sd.3293
49. Plan Vivo (2026) Eligibility, costs & fees. Plan Vivo Foundation. https://www.planvivo.org/projects/certify-a-project/pvclimate/pv-climate-eligibility-costs-fees. Accessed April 2, 2026
50. PMI (2026) Belize. The Partnership for Market Implementation. https://www.pmiclimate.org/country/belize. Accessed 26 May 2026
51. Purushotham MK, Thompson BS (2026) Incorporating blue carbon into climate change mitigation policies: Multi-level governance challenges for carbon credits and NDCs. Ecol Econ 240, 108800. https://doi.org/10.1016/j.ecolecon.2025.108800
52. Rasheed AR, Macreadie PI, Rowland PI, Wartman M (2025) What drives landholders to engage in coastal wetland programs? A synthesis of current knowledge and opportunities for future research. Conserv Sci Prac 7(5), e70030. https://doi.org/10.1111/csp2.70030
53. Rosenthal A, Arkema K, Verutes G, Bood N, Cantor D, Fish M, Griffin R, Panuncio M (2015). Identification and valuation of adaptation options in coastal-marine ecosystems in Placencia, Belize. IADB. https://doi.org/10.18235/0012637. Accessed 22 May 2026
54. Rosli FN, Yana R, Rozaimi M (2025) Conservation versus commodification: synthesizing stakeholders' perceptions of the blue carbon credit ecosystem. Anthro Coasts 8(1), 34. https://doi.org/10.1007/s44218-025-00105-w
55. Sangha KK, Ahammad R, Russell-Smith J, Woolley LA (2025) A nature-based solutions assessment framework integrating indigenous biocultural and ecosystem services perspectives: An Australian example. Eco Ind 172, 113230. https://doi.org/10.1016/j.ecolind.2025.113230
56. Schill SR, McNulty VP, Pollock FJ, Lüthje F, Li J, Knapp DE, Kington JD, McDonald T, Raber GT, Escovar-Fadul X, Asner GP (2021) Regional High-Resolution Benthic Habitat Data from Planet Dove Imagery for Conservation Decision-Making and Marine

Planning. Rem Sens 13(21), 4215. https://doi.org/10.3390/rs13214215

57. Schill S, McNulty C, Perez D, Shono K, Friedman K (2024) Remote sensing techniques for mapping and monitoring mangroves at fine scales. FAO. https://doi.org/10.4060/cd0823en
58. Sessions C, Wood SA, Rabotyagov S, Fisher DM (2016) Measuring recreational visitation at U.S. National Parks with crowd-sourced photographs. J Env Man 183, 703–711. https://doi.org/10.1016/j.jenvman.2016.09.018
59. Sheikh HA, Narain D, Bartlett C, Christiaen C (2025) Unlocking private finance for nature: Addressing barriers and reframing risk-return dynamics. Iscience 28(11). https://doi.org/10.1016/j.isci.2025.113669
60. Sidik F, Supriyanto B, Krisnawati H, Muttaqin MZ (2018) Mangrove conservation for climate change mitigation in Indonesia. WIREs Clim Change 9, e529 (2018) https://doi.org/10.1002/wcc.529
61. Spalding M, Parrett CL (2019) Global patterns in mangrove recreation and tourism. Mar Pol 110, 103540. https://doi.org/10.1016/j.marpol.2019.103540
62. Sundaramanickam A, Nithin A, Balasubramanian T (2021) Role of Mangroves in Pollution Abatement. In: Mangroves: Ecology, Biodiversity and Management. Springer, Singapore, pp 257–258. https://doi.org/10.1007/978-981-16-2494-0_11
63. TNC (2022) Case Study Belize Blue Bonds for Ocean Conservation. TNC. https://www.nature.org/content/dam/tnc/nature/en/documents/TNC-Belize-Debt-Conversion-Case-Study.pdf. Accessed 28 June, 2025
64. TNC (2023) Belize Blue Bonds for Ocean Conservation Impact Report. TNC. https://www.nature.org/content/dam/tnc/nature/en/documents/Belize-Blue-Bonds-2023-Impact-Report.pdf Accessed 28 June, 2025
65. Trotz MA, Webb WA, Brinton A, Zarger RK, Carne L, Bood N, Hinds K, Mckenna R, Fogg S, Neal J, Guerry A, Lasserre CG, Gutierrez D, Silver J, Moore T, Beck M (2023) Nature-Based Solutions Workshop Report: Placencia, Belize (report no. 3). Strong Coasts Collection. https://doi.org/10.5038/LEEY7236
66. Wildtracks (2015) Placencia Lagoon Management Plan 2015–2020. Casado Internet Group, Belize. https://ambergriscaye.com/art3/Placencia-Lagoon-Management-Plan_draft-2.pdf. Accessed 1 October 2025
67. Wood SA, Guerry AD, Silver JM, Lacayo M (2013) Using social media to quantify nature-based tourism and recreation. Sci Rep 3, 2976. https://doi.org/10.1038/srep02976
68. World Travel & Tourism Council (2025) Travel & Tourism Economic Impact 2025 Belize. World Travel & Tourism Council. https://cdn.prod.website-files.com/6329bc97af73223b575983ac/68416a9ec518ece9327b0a42_EIR2025-Belize.pdf. Accessed 22 May 2026
69. WWF Mesoamerica (2025) Advancing Actions for Mangroves in Belize: the Role of Land Tenure Analysis. WWF. Accessed 12 November 2025
70. WWF (2025) Improving Stewardship and Sustainable Livelihoods SCCF-Resilient Bold Belize Stakeholder Engagement Plan. WWF. https://assets.worldwildlife.org/www-prd/documents/SEP_SCCF_Belize.pdf. Accessed April 18, 2026
71. WWF (2025) Resilient Bold Belize Stakeholder Engagement Plan. WWF. https://files.worldwildlife.org/wwfcmsprod/files/Publication/file/8r8phh011x_Annex_F_SEP_Resilient_Bold_Belize_WWF_GEF.pdf. Accessed March 27, 2026
72. Wylie L, Sutton-Grier AE, Moore A (2016) Keys to successful blue carbon projects: Lessons learned from global case studies. Mar Pol 65, 76–84. https://doi.org/10.1016/j.marpol.2015.12.020
73. zu Ermgassen PSE, Worthington TA, Gair JR, Garnett EE, Mukherjee N, Longley-Wood K, Nagelkerken I, Abranted K, Aburto-Oropeza O, Acosta A, Araujo ARR, Baker R, Barnett A, Beitl CM, Benzeev R, Brooks J, Castellanos-Galindo GA, Chong VC, Connolly RM, Cunha-Lignon M, Dahdough-Guebas F, Diele K, Dwyer PG, Friess DA, Grove T, Hoq ME, Huijbers C, Hutchinson N, Johnson AF, Johnson R, Knight J, Krumme U, Kuguru B, Lee SY, Lobo AS, Lugendo BR, Meynecke JO, Munga CN, Olds AD, Parrett CL, Requero BG, Rönnbäck P, Safryghin A, Sheaves M, Taylor MD, Mendonça JT, Waltham NJ, Wolff M, Spalding MD (2025) Mangroves support an estimated annual abundance of over 700 billion juvenile fish and invertebrates. Com Earth Env 6, 299. https://doi.org/10.1038/s43247-025-02229-w

Figures

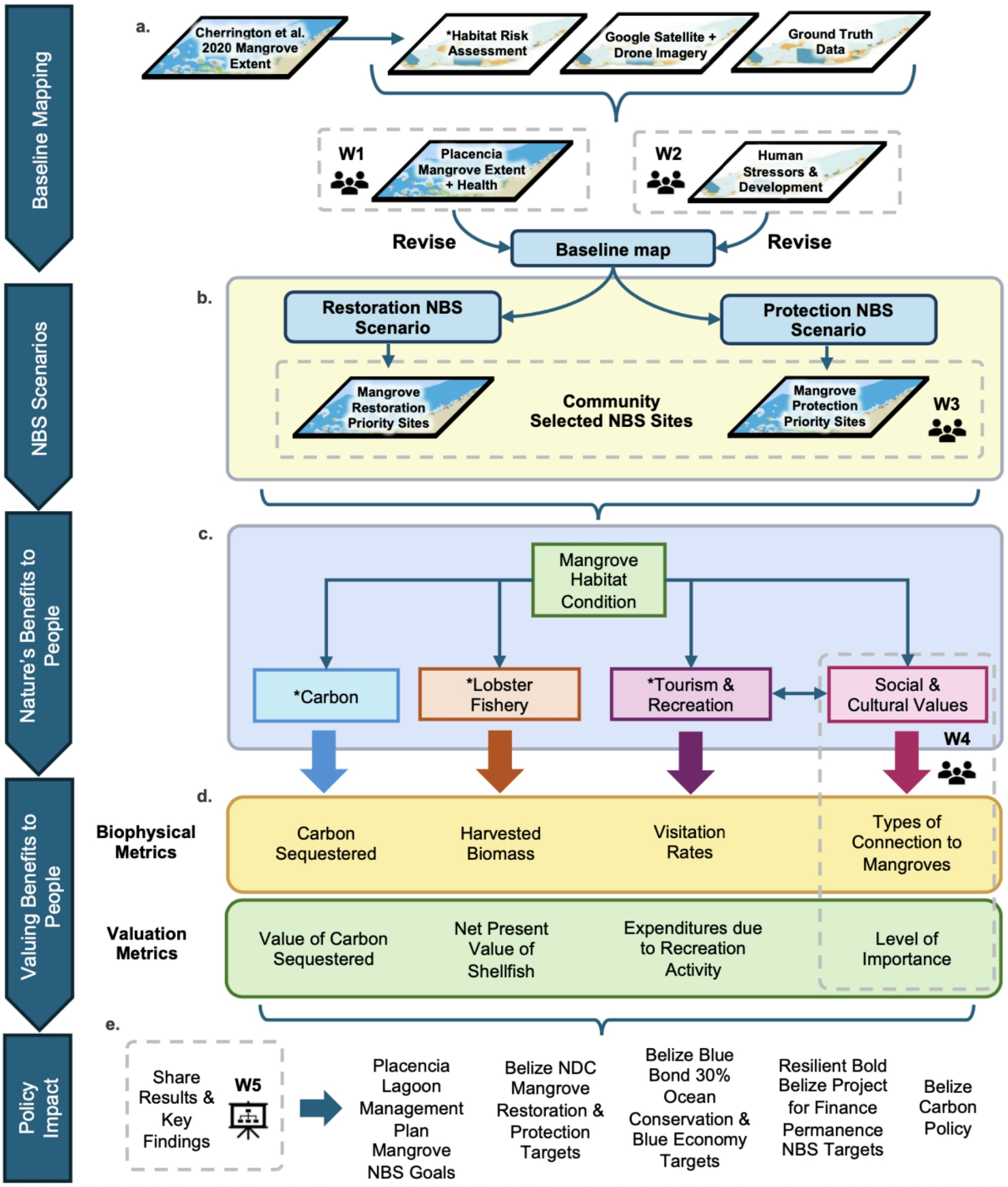


Figure 1

Collaborative research framework to co-design mangrove nature-based solutions (NbS) using a combination of workshops and ecosystem service modeling. (a) We developed the mangrove health baseline scenario by combining existing mangrove extent spatial layers and modeling habitat health based on participants' inputs, human stressors, and development impacts on mangroves (W1 & W2). The baseline map was presented in a third workshop (W3) to (b) identify community-preferred nature-based solutions sites for the mangrove restoration and protection scenarios as well as sociocultural values (W4). We modeled (c) and quantified (d) changes in mangrove benefits under nature-based solutions scenarios using InVEST software (indicated with an asterisk). We shared key findings back with the Placencia community in a final workshop (W5).

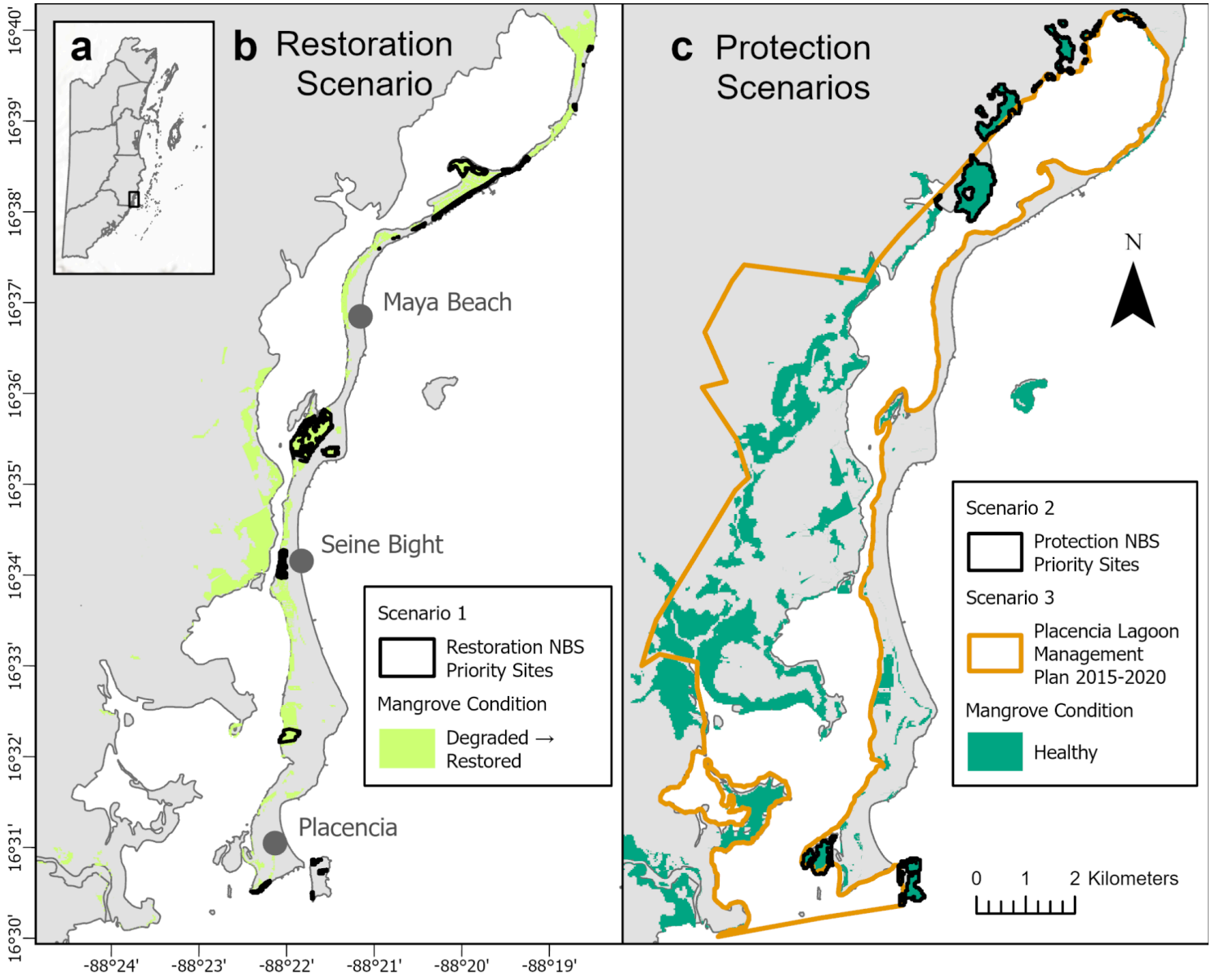


Figure 2

Mangrove conditions and scenarios. (a) Map of Belize with an inset of the study area (black rectangle). (b) Community-identified restoration sites intersecting with degraded mangrove for the community-priority restoration scenario (1). (c) Community-identified protection sites for the community-priority protection scenario (2) and the proposed Placencia Lagoon Management Plan area for the Placencia Lagoon protection scenario (3) intersecting with healthy mangroves.

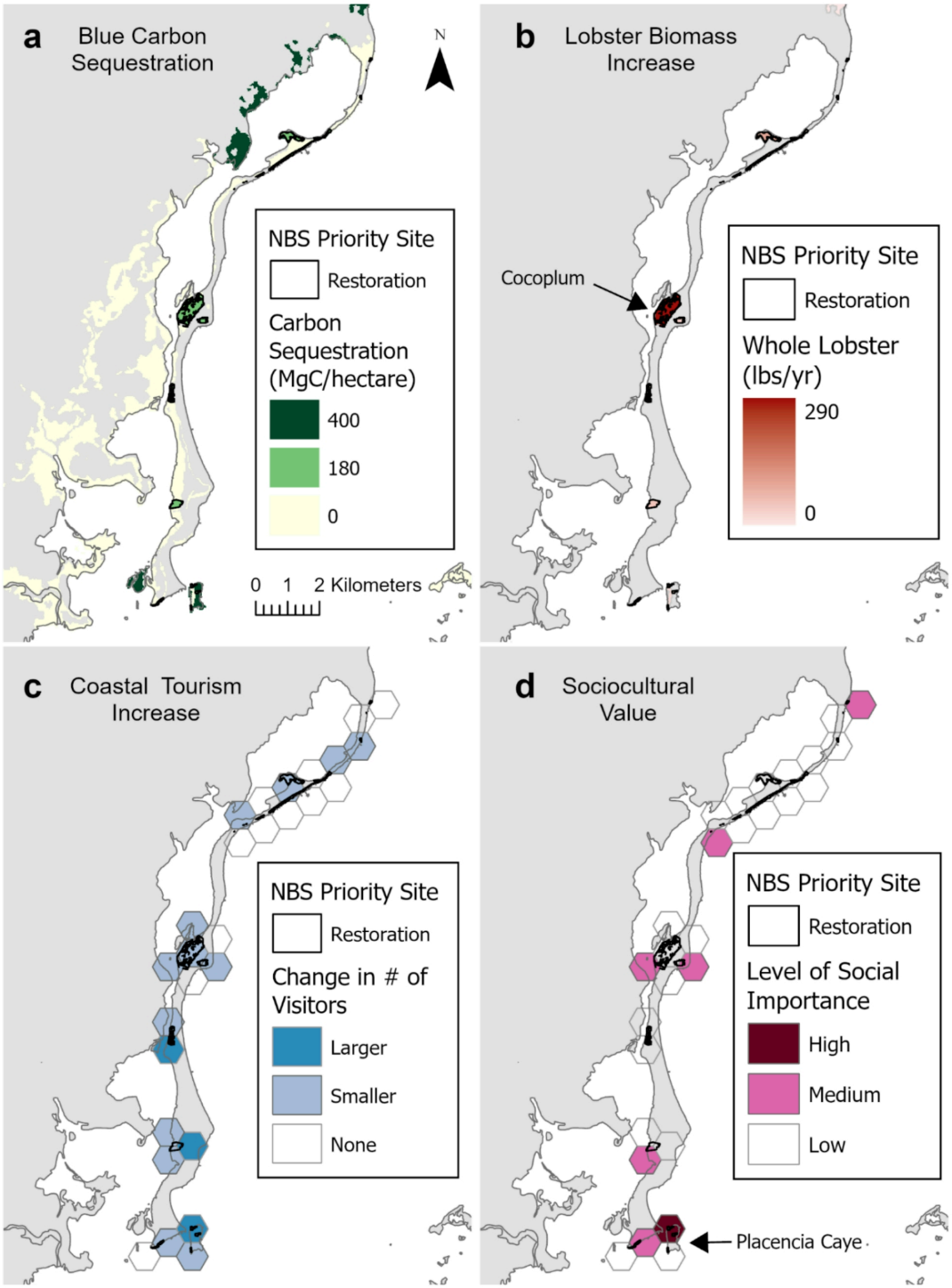


Figure 3

Change in nature-based solutions restoration benefits between the baseline and community-identified mangrove restoration scenario. (a) Blue carbon sequestration (MgC/ha), (b) lobster biomass increase (lbs/yr), (c) tourism visitation increase (number of visitors), and (d) sociocultural value (level of importance).

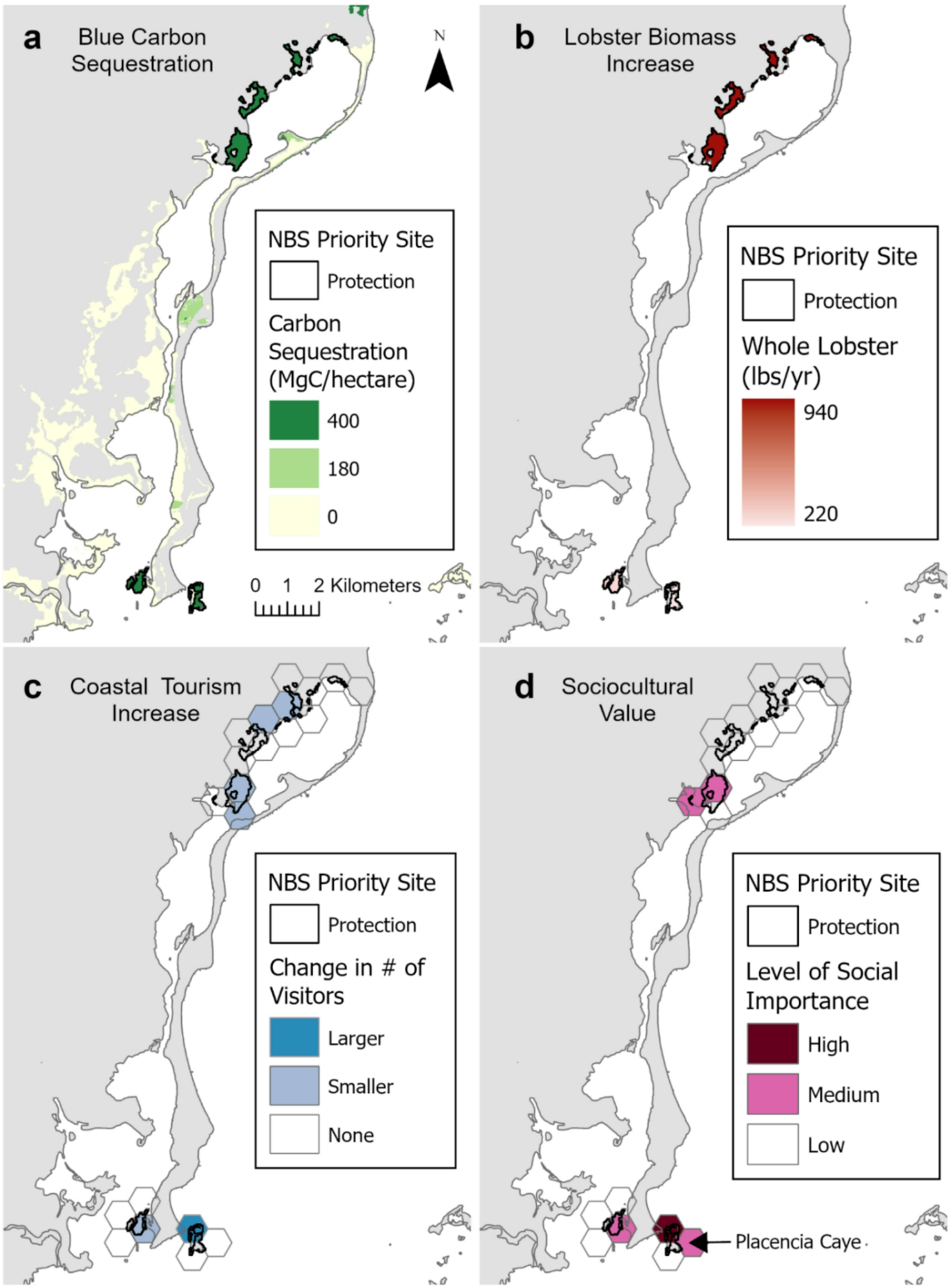


Figure 4

Change in nature-based solutions protection benefits between the baseline and community-identified mangrove protection scenario. (a) Blue carbon sequestration (MgC/ha), (b) lobster biomass decrease (lbs/yr), (c) tourism visitation decrease (number of visitors), and (d) sociocultural value (level of importance).

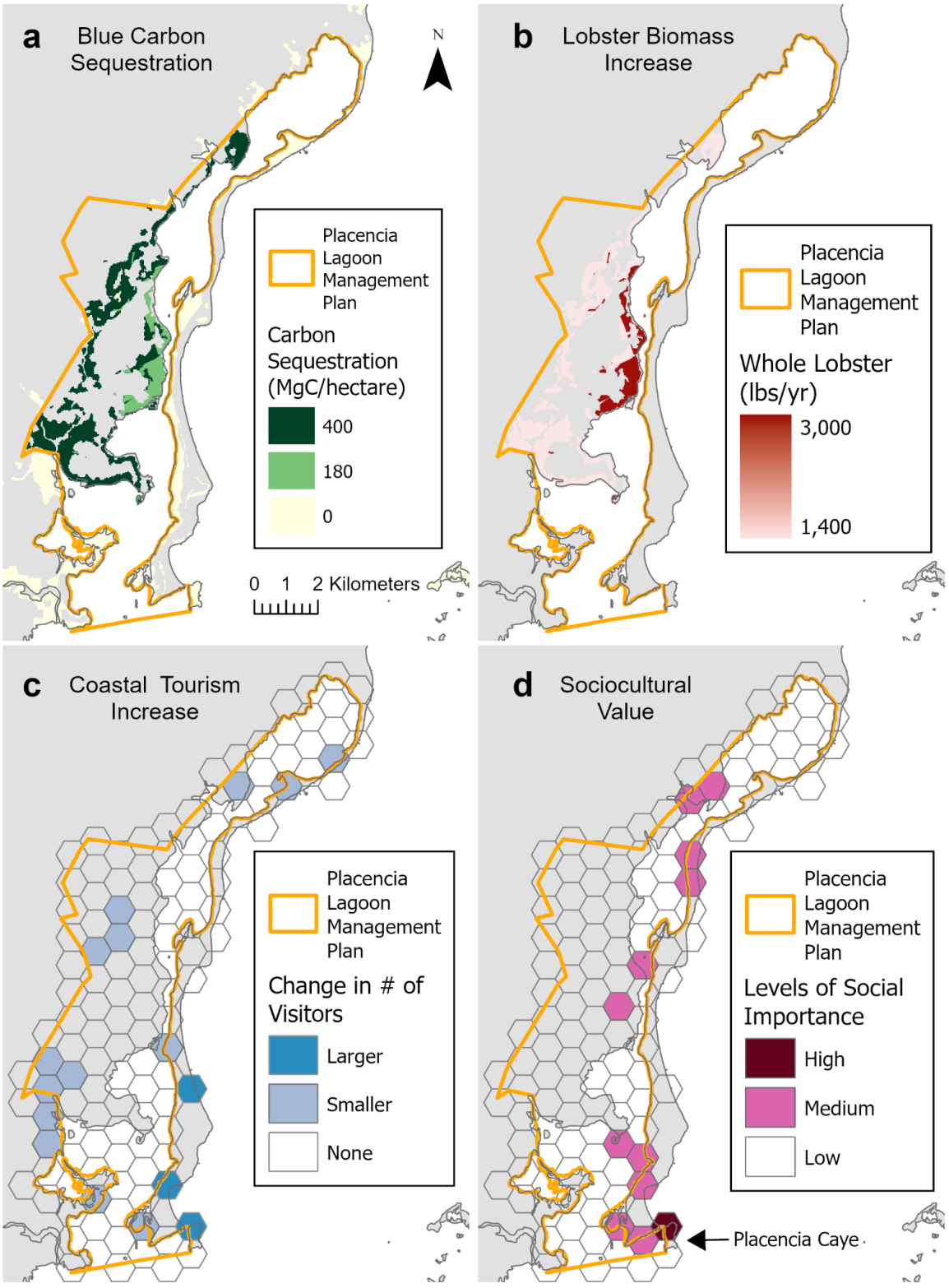


Figure 5

Change in nature-based solutions protection benefits between the baseline and mangrove Placencia Lagoon Management Plan protection scenario. (a) Blue carbon sequestration (MgC/ha), (b) lobster biomass decrease (lbs/yr), (c) tourism visitation decrease (number of visitors), and (d) sociocultural value (level of importance).

Supplementary Files

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