Opportunities for Leveraging New Data Technologies to Inform Disaster Risk Management and Integrated Coastal Zone Management in Latin America and the Caribbean:

The Cases of The Bahamas, Belize, and Mexico

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Opportunities for Leveraging New Data Technologies to Inform Disaster Risk Management and Integrated Coastal Zone Management in Latin America and the Caribbean:

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Abstract

We assess how new data technologies are helping innovative assessment methodologies, implementation, and monitoring of nature-based approaches in integrated coastal zone management and disaster risk management in the Latin America and the Caribbean region. We present new information showing how breakthroughs in data and modeling technologies are supporting better quantification of outcomes of nature-based approaches, in biophysical and social metrics, along coastal regions in The Bahamas, Belize and Mexico. Together, this set of diverse decision contexts demonstrates the power of new technologies in advancing nature-based solutions to climate resilience and accountability for integrated development planning.

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Introduction

Sea-level rise and coastal storms increasingly are imperiling people, property and infrastructure in countries throughout Latin America and the Caribbean (Reguero et al. 2020, IPCC 2013, CMEP 2017; Chaplin-Kramer et al. 2019). Damages in terms of direct financial costs, disruption to businesses and livelihoods, loss of life, and reduced spiritual and cultural wellbeing can be overwhelming to communities who are suffering from more frequent and intense coastal hazards on top of the considerable socio-economic disruption from the COVID-19 pandemic (Beck and Lange 2016, Dasgupta et al. 2011, Gaines et al. 2019, Hsiang et al. 2017, Simpson et al. 2010). Governments, businesses, and civil society are calling for greater resilience to these growing hazards, both in terms of reducing risk and costly damages from flooding and erosion, and also more efficient recovery pathways after disasters strike (ECLAC 2011, IPCC 2013; GFDRR 2016, Risky Business Project 2014, UNISDR 2017).

Traditional approaches to reduce risk from coastal hazards include artificial infrastructure such as sea walls, breakwaters and groynes, which are costly and can cause harm to ecosystems, undermining the intended protective benefits of the built structures. In contrast, nature-based approaches recognize the protective value of coastal habitats (such as coral reefs, seagrasses, mangroves and coppice forests, wetlands, and dunes) in dampening wave energy and reducing flooding and erosion from rising sea-levels (Silva et al. 2021). Also termed ecosystem-based approaches, green infrastructure, and nature-based solutions, these often are more cost effective at reducing risk and conferring climate resilience (Ruckelshaus et al. 2020). Nature-based approaches have the added advantage of providing a suite of co-benefits in addition to protective services, further bolstering economies and wellbeing. Coastal ecosystems are important habitat for many species, including commercially and recreationally valuable species in the Caribbean such as lobster, conch and grouper (e.g., Arkema et al. 2019). Such habitats also are important in mitigating CO2 emissions by storing and sequestering carbon, and also are valuable systems for tourism and culture (Arkema et al. 2021, Davis et al. 2015, Kuwae 2016).

The very ecosystems that can provide efficient protection and other co-benefits to coastal and global communities are themselves at risk from climate and human impacts. Rising sea levels and storm surges can destroy coastal habitats if they are not able to adapt (e.g., through landward migration or sufficiently rapid growth rates of coral reefs.) Coastal development can block upslope habitat migration, cutting off opportunities for such ecosystems to adapt (Silva et al. 2021, Piazza Forgiarini et al. 2019). In addition, development and associated activities such as land clearing, dredging, marine transportation, and oil and gas extraction, also directly destroy or degrade valuable ecosystems and the benefits they provide (Halpern et al. 2012). Degradation of coastal ecosystems in turn increases hazard exposure and costs for people, in loss of life, livelihoods and general wellbeing (Arkema et al. 2013, Chaplin-Kramer et al. 2019). Coastal nations thus need to find the balance between protecting their valued natural ecosystem assets as they also invest in sorely needed development for the betterment of their societies. Healthy, functioning coastal ecosystems can be at the heart of recovery pathways from the global pandemic, while at the same time boosting more climate-resilient communities.

With the goal of bolstering sustainable development in coastal regions, governments and communities are taking action to guide climate-resilient growth and recovery through systematic planning and investment. Cross-sectoral and spatial government processes, such as integrated coastal zone management (ICZM) and disaster risk management (DRM), increasingly are including nature-based approaches as part of their assessment and implementation (Arkema et al. 2015, Reguero et al. 2019, Ruckelshaus et al. 2020). Strategic preparedness for climate impacts and rapid disaster response and recovery requires innovative and cost-effective approaches for mapping and tracking changes in biophysical and socio-economic indicators of overall system state and resilience over time. New data technologies and open-source coastal assessment and analysis tools, management techniques and platforms are revolutionizing the information governments, business, and civil society have to make more strategic and transparent decisions that include nature-based approaches to climate-resilient development (Ruckelshaus et al. 2020).

In this Technical Note, we highlight how new data technologies are available and are helping innovative assessment methodologies, implementation, and monitoring of nature-based approaches in ICZM and DRM in the Caribbean region. Section I describes the experience of The Bahamas. Section II presents the case of Belize. Section III reviews the experience of Mexico.

I. The Bahamas

Decision context

Rising seas, a growing intensity and frequency of storms, and coastal development are posing increasing risk to communities and infrastructure in The Bahamas (Silver et al. 2019). In recent years several major hurricanes have hit the archipelago nation, with the most recent Category 5 hurricane -- Dorian -- causing $3.4 billion in damages, taking 67 lives, and leaving nearly 300 people still missing over a month later (Bello et al. 2020). Coastal development compounds the impact of storms and sea-level rise, putting more people in harm's way and degrading the coral reefs, coastal mangroves, and seagrass beds that have the potential to help reduce risk from coastal hazards (Wyatt et al. in review). Investments in coastal infrastructure is vitally important for economic development in the country, as the tourism industry contributes to more than half of the GDP of The Bahamas (Bahamas Ministry of Tourism 2015, Pathak et al. 2021). However, ad hoc growth threatens the integrity of ecosystems that reduce risk from coastal hazards (Silver et al. 2019), as well as, provide tourism (Arkema et al. 2021), habitat for ecologically and economically important species (Stoner et al. 2003, Arkema et al. 2019, O'Shea et al. 2021), climate regulation (Pendleton et al. 2012, Mandoske et al. 2017), and other benefits.

To address these challenges, The Government of The Bahamas and their NGO, academic, and community-based partners have been engaging in several sustainable development, protected-area, and other integrated planning efforts. In 2015 the administration at the time initiated a national development planning process called Vision 2040. Vision 2040 was based on four pillars -- The Economy, Social Policy, and the Built and Natural Environment -- and aimed to align The Bahamas' development objectives with the 2015 UN Sustainable Development Goals. As a subcomponent of the national development plan, individual islands engaged in island-scale planning efforts to develop so-called "Master Plans." One example is the Andros Sustainable

Development Master Plan (OPM 2017, Arkema 2019). Andros boasts a wealth of natural resources that support fisheries and tourism related livelihoods. Yet, many parts of Andros still lack essential infrastructure, such as piped water supplies, modern educational and healthcare facilities, and roads and marinas to support transportation. The goal of the plan was to identify investments in sustainable economic development that would address these infrastructure needs without sacrificing the natural coastal capital that underlie the economy and sustain the wellbeing of its citizens.

As the National Development Planning process was underway in 2015, The Bahamas joined another integrated management effort -- the Caribbean Challenge 20 by 20 Initiative, committing to protection of 20% of its oceans by the year 2020. The initiative recognizes the need to both increase the overall percentage of marine protected areas (MPA) and to improve management of existing protected areas. A powerful component of both the MPA planning process and the Andros Sustainable Development planning process was the inclusion of a natural capital assessment. Quantifying and mapping benefits of coastal and marine ecosystems with new data technologies and analytical approaches helped stakeholders, policy makers, and coastal planners communicate about the contributions of ecosystems to the wellbeing of Bahamians and explore how development and conservation decisions made today would influence livelihoods and wellbeing of Bahamians in the future.

Nature-based solutions to disaster risk reduction and other ecosystem services

The Bahamas is a county of more than 700 islands, atolls, and cayes. Coastal forests, mangroves, coral reefs, and seagrass beds help to attenuate waves and secure sediments, reducing the risk of flooding and erosion for coastal communities now and under future climate change (Silver et al. 2019). In addition to providing protection for Bahamian shorelines, these ecosystems, along with beaches, blue holes and other natural features, draw more than six million tourists annually (Bahamas Ministry of Tourism 2015, Hargreaves-Allen and Pendleton 2010). Approximately 400,000 of these tourists specifically visit ecosystems within the country's 43 existing MPAs on average each year (Arkema et al. 2021). The coastal and marine ecosystems of The Bahamas also provide habitat for numerous fish and fisheries, including the Caribbean spiny lobster which supports the largest export fishery and uses mangroves, seagrass, and other intertidal vegetation as nursery areas (Arkema et al. 2019). Mangroves and seagrass store and sequester carbon, helping to stabilize the global climate and mitigate climate change.

Analytical approaches and data technologies for natural capital assessment

The MPA planning process and the Andros Sustainable Development process both leveraged new data technologies for coastal analysis and analytical methods for mapping and valuing ecosystem services (Ruckelshaus et al. 2020, Arkema et al. 2017a, Arkema et al. 2017b). For the MPA initiative, the Natural Capital Project, in collaboration with The Nature Conservancy (TNC), the Bahamas Reef Environment and Educational Fund (BREEF), and The Bahamas National Trust quantified the economic value of benefits provided by ecosystems within the existing network of

43 MPAs in The Bahamas (Arkema et al. 2017b). For the Andros Development Plan, the Office of the Prime Minister, the University of The Bahamas, the Natural Capital Project, SEV Consulting, and TNC, in collaboration with community members, leveraged quantitative modeling of ecosystem services to understand how alternative development pathways for the island of Andros would influence future coastal resilience, fisheries, and tourism benefits that ecosystems provide to Androsians (Arkema and Ruckelshaus 2017, OPM 2017, Arkema et al. 2017a, Arkema 2019, Ruckelshaus et al. 2020).

The Andros Sustainable Development Plan resulted from an innovative science-policy process that combined natural capital assessment with stakeholder engagement and scenario design. Through more than six rounds of community consultations across the island, including open-ended discussion, participatory mapping techniques, and one-on-one interviews, Androsians developed three scenarios for the future of their island (Wyatt et al. in review). The Business as Usual scenario represented a future similar to the current situation with little investment in new infrastructure, educational opportunities, or development. The Conservation scenario limited development and maximized setting-aside of lands and waters, such as ratification of a National Park for the Andros barrier reef. The Sustainable Prosperity scenario prioritized strategic development, such as investment in daily ferries and processing factories for local goods, and natural resources such as mangrove restoration for protection from storms and nursery habitat for lobster. The Intensive Development scenario emphasized creation of infrastructure (luxury housing, cruise ships) for near-term economic development. Combining participatory approaches with data and analytics, produce mixed qualitative and quantitative scenarios that were more powerful because they included storylines reflecting stakeholder values and desires for the future of their island with projections about the outcomes of decisions in social, economic, and ecological metrics (OPM 2017, Ruckelshaus et al. 2020).

Using 2015 as a baseline and projecting 25 years in the future, results from the ecosystem service models suggested that development scenarios that safeguarded ecosystems under the Sustainable Prosperity and Conservation scenarios would increase the export value of lobster catch provided Andros by almost 50% from US$14 million (in BAU) to US$20 million (Arkema et al. 2019). Intensive Development would decrease the country-wide catch, reducing export value to approximately US$10 million annually due to degradation of habitats. The Sustainable Prosperity scenario would increase tourism expenditures across all districts of Andros. In contrast, the Intensive Development scenario would concentrate tourism in two of the four districts. More than 60% of the populated north and east coasts of Andros are currently buffered by coral reefs, seagrass, mangroves, and wetlands and coppice. Under the Sustainable Prosperity scenario, 85 km of coastline would be buffered by coastal habitats that shield over 750 people and US$5.8 million in income. Intensive development would more than triple the number of people at risk (Figure 1).

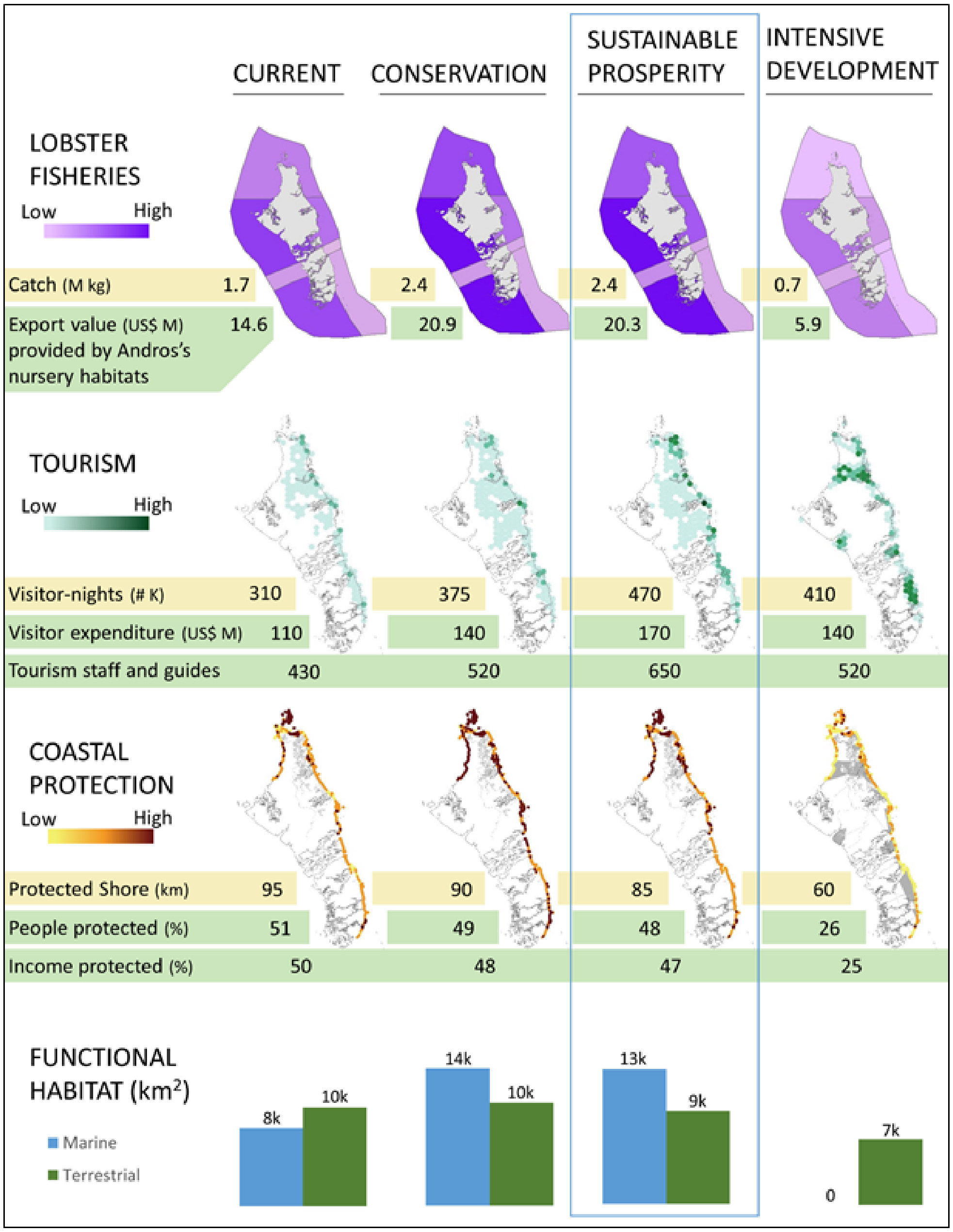


Figure 1. Synthesis of ecosystem service results and selection of the preferred scenario (from Ruckelshaus et al. 2020).

The analysis of benefits provided by ecosystems within The Bahamas MPAs revealed estimates of the overall magnitude of benefits provided by the entire network and also highlighted spatial variation in benefits among MPAs (Figure 2, Arkema et al. 2017b). For instance, mangroves and other coastal forests, coral, and seagrass reduced exposure to 39,000 people and $806 million in annual income. More than $23.5 million in export value annually and 6 million lbs. catch annually are attributable to mangroves and seagrass for providing nursery habitat for the spiny lobster fishery. The coastal and marine ecosystems within the MPA network draw more than 383,000 visitor-days and generate $67.6 million in expenditures annually. Blue carbon habitats such as mangroves and seagrass store and sequester 400 million tons CO_2, worth $5 billion in avoided carbon emissions. Yet, the benefits produced by ecosystems vary by MPA, both due to variation in MPA area and ecological and social characteristics. For example, the Southwest Marine Managed Area receives the most visitors annually, likely due to its proximity to the capital. In contrast on of the oldest parks in the network, and the only no-take area, Exuma Cays Land and Sea Park is the second most-visited area, despite it being much less accessible, likely because it is well-known and its ecosystems biologically diverse and relatively intact compared to more accessible locations (Arkema et al. 2021).

Figure 2. Economic value of four ecosystem services provided by The Bahamas MPA network (from Arkema et al. 2017c)..

Several remote sensing applications and other new technologies generated data that were included in the modeling of ecosystem services for the Andros Plan (Ruckelshaus et al. 2020) and the MPA process (Arkema et al. 2017b). For example, the number of people benefiting from coastal risk reduction provided by ecosystems was determined based on a spatial distribution of demographic data collected during the 2010 Bahamian Census using satellite-derived Nighttime Lights Time

Series (Silver et al. 2019). Remote sensing from Landsat and Rapideye imagery, in addition to local habitat data, were used to model changes in coastal and marine habitats (i.e., coral, seagrass, blue holes, mangrove, pine and coppice forest, wetlands, beaches) on Andros Island and within the MPA network across The Bahamas. Digitized aerial imagery was used for detecting the extent and location of dredging at local scales and density maps of vessel traffic were generated using Marine Automatic Identification System (AIS) responders on boats. Drone-derived aerial imagery was used as high resolution data to estimate the extent and quality of coastal habitats and to capture nearshore bathymetry and beach profiles for improved wave and hazard modeling. Visitation and expenditures related to nature-based tourism activities were estimated from geo-tagged social media data (e.g., flickr and twitter) in the InVEST tourism model, which is free and open source and has been validated globally and applied in multiple locations throughout Latin America and the Caribbean (Wood et al. 2013, Arkema et al. 2015, Arkema et al. 2021). Digitized historical aerial imagery was processed and classified to assess pine, coppice, mixed pine and coppice, mangrove, wetland, blue holes, inland water, and sand and mud at a 1:10000 scale and also used to detect infrastructure and other development (e.g., roads, hotels and other buildings, ports, seawalls, airports).

Lessons learned -- How analysis of ecosystem services and natural capital informed decisions

Natural capital assessments of ecosystems within MPAs and of alternative development scenarios for Andros provided science-based information for both the MPA planning process and the Andros Sustainable Development Master Plan. For the MPA process the quantification of benefits highlighted the importance of MPAs for people and not just species conservation. Traditionally, protected area conservation and management has focused on ecological goals and habitat parameters (Carr 2000). While ecological considerations are essential for conserving sufficient area and diversity of habitats, they may miss the importance of conserving and managing ecosystems for human communities. Using an ecosystem services approach to inform the siting and management of MPAs helped to communicate the importance of MPAs to a diversity of stakeholders. Once the ecosystem and socio-economic benefits of MPAs are widely appreciated, siting of new MPAs, enforcement, and financing can also become easier and more effective (Rogers and Aburto-Oropeza et al. 2020). In fact, partially as a result of this work, The Government of The Bahamas is in the process of siting additional MPAs (Anderson et al. 2018) and the Inter-American Development Bank and the Bahamian government have just agreed to a loan of more than $200 million towards Boosting Resilient and Inclusive Growth in The Bahamas which includes substantial funding for strengthening environmental policies and management of protected areas (Stevenson et al. 2020).

Accounting for ecosystem services in the design of the Andros Sustainable Development Master Plan helped prioritize the financing of ecosystem restoration and conservation of coastal and marine ecosystems in The Bahamas. The Sustainable Prosperity scenario was the result of several iterations of stakeholder engagement and quantitative assessment of benefits. Ultimately this process led to a preferred island-wide future development scenario that in 2017 became the foundation for a community-supported vision within which to embed specific development projects, policies, and investments. Accounting for ecosystem services in the design of the master plan also helped finance investments in NBS for DRR. The sustainable development plan ultimately paved the way for a loan from the IDB to the Government of The Bahamas to invest in "green infrastructure" for coastal resilience and the delivery of co-benefits (OPM 2017, Lemay et al. 2017). The Climate-Resilient Coastal Management and Infrastructure Program specifically includes $3 million USD for restoration of ecosystems such as mangroves. In addition to coastal protection benefits, the co-benefits provided by ecosystems (e.g., fisheries, tourism) are essential to the economy and livelihoods of Bahamians.

II. Belize

Decision context

Globally, a growing intensity and diversity of ocean and coastal uses is threatening ecosystems and the benefits they provide to coastal communities. Recent calls for ocean planning envision integrated management of social and ecological systems to sustain delivery of ecosystem services. To meet these challenges, the Government of Belize passed a visionary Integrated Coastal Zone Management Plan endorsed by the cabinet in 2016 (CZMAI 2016). The Plan is national in scope yet draws on the environmental, social, and economic diversity among nine coastal planning regions spanning the coastal zone and the entire offshore waters of Belize. The plan is one of the first, globally, to be designed using an innovative science-policy process that combined natural capital assessment, scenario development, and stakeholder engagement (Arkema et al. 2015). Five years later, the Government of Belize is now undergoing an adaptive management process. The Coastal Zone Management Authority and Institute (the entity responsible for leading the development of the plan and its implementation) is now updating the ICZM Plan. Despite its overall success, the Plan lacks recommendations for specific climate adaptation strategies and requires further development of finance mechanisms for bolstering nature-based solutions to climate mitigation and adaptation.

To address these challenges, CZMAI, in collaboration with World Wildlife Fund (WWF), and the Natural Capital Project, has identified a portfolio of nature-based climate adaptation strategies, including both watershed interventions, such as protecting and restoring landscapes and riparian zones, and coastal strategies, such as coral and mangrove protection and restoration. In parallel, these organizations and many other agencies across the Belizean government, in addition to environmental NGOs and other public and private sector actors, have been working to update Belize's Nationally Determined Contributions (NDCs) under the Paris Climate Accord. The previous version of Belize's NDCs did not include targets for blue carbon ecosystems (e.g., mangroves and seagrass) which help mitigate global climate change and support communities as they adapt to new coastal conditions. A major advance in the updated NDC for Belize--scheduled for endorsement by the Government of Belize in mid 2021-- will be the inclusion of targets for blue carbon ecosystems informed by a natural capital assessment of the suite of benefits that mangroves and seagrasses provide.

Nature-based solutions to disaster risk reduction and other ecosystem services

Hundreds of kilometers of mangrove forests, extensive seagrass beds, the largest unbroken reef in the Western Hemisphere, and more than 300 cayes characterize the coastal zone of Belize. These reefs, coastal forests, and subtidal vegetation provide important risk reduction benefits for coastal communities by attenuating waves and trapping sediments which in turn diminish coastal flooding and erosion (Arkema et al. 2015). In addition to helping to shield shorelines from hazards, Belize's coastal and marine environments support a diversity of animals and plants and provide numerous benefits to the Belizean people. Thirty-five percent of the Belize population live and work along the coast. Renowned snorkeling and diving draw more than 800,000 tourists to the region annually and several commercial, recreational, and subsistence fisheries are a source of income and sustenance for local people.

Analytical approaches and data technologies for natural capital assessment

Developing and implementing climate adaptation strategies requires information about where nature-based strategies, if implemented, will deliver multiple and equitable co-benefits. To prioritize locations for implementation of climate adaptation strategies for mangroves, we optimized ecosystem service benefits for a suite of potential mangrove conservation (5000, 10000, 20000 ha) and mangrove restoration targets (500, 1000, 5000 ha) reflect. These targets reflected levels of ambition under consideration for the updated NDC. For each target area, we quantified three ecosystem service co-benefits provided by mangroves: tourism and recreation, spiny lobster catch, and coastal risk reduction using the open-source software, InVEST, freely available at https://naturalcapitalproject.stanford.edu. To determine where investments in particular mangrove conservation and restoration projects would provide the greatest co-benefits, we conducted an optimization analysis of the three ecosystem services.

To conduct the optimization analysis, we applied ROOT (Restoration Opportunities Optimization Tool). ROOT is an open-source software available through the Natural Capital Projects suite of tools. ROOT uses information about potential impact of restoration or management activities together with spatial prioritization to identify key areas where interventions will lead to the greatest provisioning of ecosystem services. The multi-objective analysis allows users to consider how to best manage trade-offs between different project goals.

Overlaying model-based priority locations with priority locations based on existing mangrove legislation and maps of MPAs, revealed important areas for investments in mangrove protection and restoration for coastal risk reduction, fisheries, and tourism that have also been selected as legislative priorities, and are outside existing protected areas. Here we show the results for several potential targets for mangrove restoration (Figure 3). More than three quarters of the highest priority target locations for mangrove protection are outside of the existing MPAs, for example in Corazal, Belize City, and Placencia.

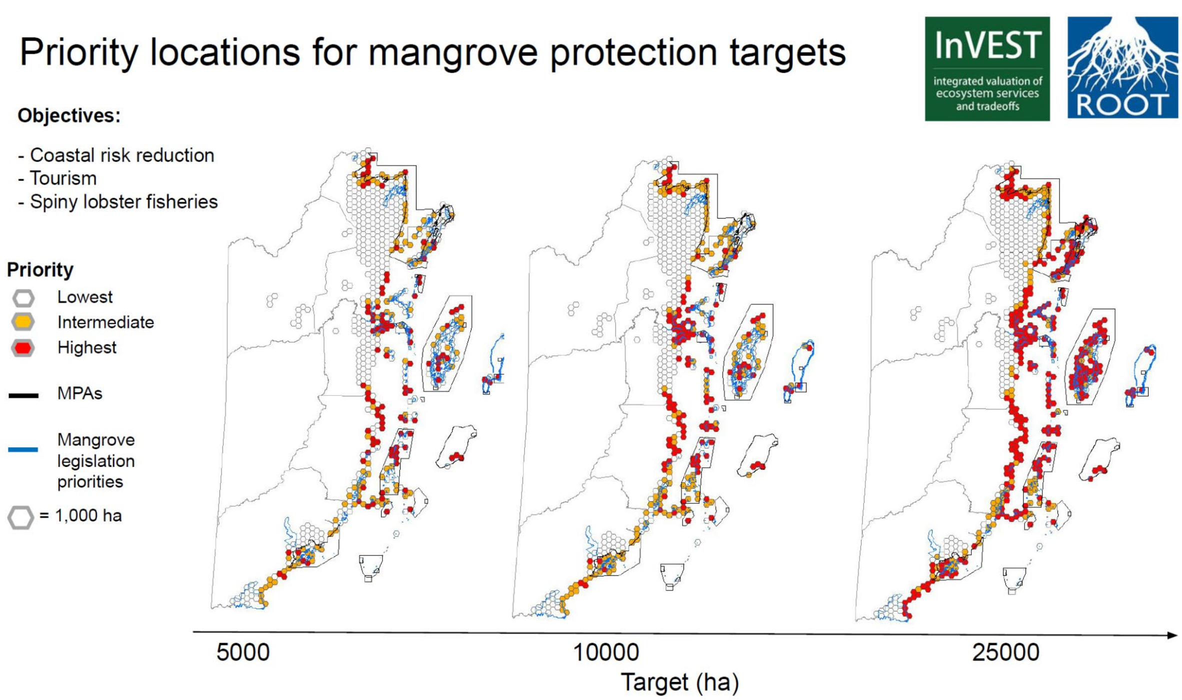


Figure 3. Priority areas for several possible mangrove restoration targets (5,000; 10,000; 25,000 ha) in Belize.

Lessons learned -- How analysis of ecosystem services and natural capital informed decisions

Results from this analysis were then used in consultations with stakeholders, to develop two sets of proposed time-bound targets. These included (1) protection of at least 6,000 hectares coastal wetlands by 2025, with an additional 6000 hectares by 2030 for a total of 12,000 ha protected and (2) at least 2,000 hectares of mangroves including within local communities by 2025, with an additional 2,000 hectares by 2030, for a total of 4,000 ha. restored. The NDC update also includes two additional targets related to developing conservation and development plans for all of Belize's priority mangrove areas by 2025 and community-based management and adaptation plans with robust performance indicators by 2030. Our optimization and natural capital approach can serve as an example for the more than 150 other countries that could enhance greenhouse gas sequestration and climate adaptation by incorporating nature-based solutions into their NDCs. For Belize, in particular, this analysis provided the science support for exploring a suite of potential targets, for informing more effective implementation of climate adaptation strategies, and for making the case for financing NBS in the updated NDCs and the updated ICZM Plan.

III. Mexico

Decision context

Coral reefs sustain the tourism industry of Quintana Roo by providing valuable coastal protection against storms, reducing beach erosion, producing white sand that appeals to tourists, and attracting over one million snorkelers and scuba divers a year. Extreme storms put these services at risk since reefs can lose between 15% to 55% of their coral cover after a strong hurricane. The structure and health of the reef are directly related to flood protection and shoreline stability services onshore. A study valued the flood risk reduction benefits of the Mesoamerican reef and found they extend to 4,600 people, and tally to $42 million USD in avoided flood damage to buildings, and $20.8 million USD avoided damages to hotel infrastructure. For a single event, the coral reefs in Quintana Roo prevented 43% of additional flood damage during Hurricane Dean in (2007) (Reguero et al. 2019). When reefs degrade because of storms or other reasons, they will not be able to protect coastal infrastructure and communities, nor provide additional fisheries or tourism values.

Nature-based solutions to disaster risk reduction and other ecosystem services

To address the crucial importance of protecting the Mesoamerican Reef, TNC and partners established in 2019 the world's first parametric insurance policy for a coral reef ecosystem (Secaira Fajardo et al. 2019). The system includes an immediate post-storm response to deploy people and resources effectively to repair damage. The insurance is part of the Trust for Coastal Zone Management, Social Development, and Security, established in 2018 by state and municipal governments, the tourism industry, and TNC. The trust fund was designed to accept funds from multiple sources to manage beaches and reefs and to purchase hurricane insurance to protect them (Figure 4). The parametric insurance policy is triggered when wind speeds exceed 100 knots within a predefined area around the insured reefs. When triggered, the insurance provides rapid payout for repair activities just after storm impact. This is important to prevent storm debris from further damaging the reef and to reduce the mortality of corals that have been damaged or dislodged during the storm.

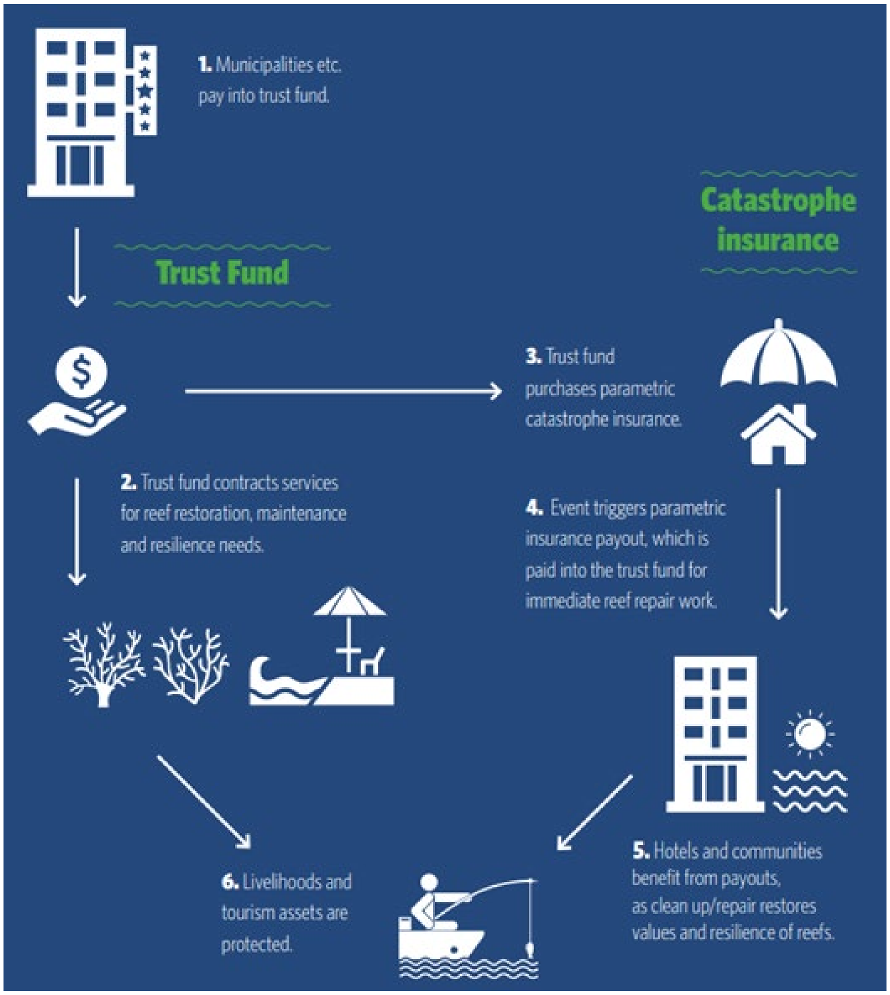


Figure 4. Schematic of Trust for Coastal Zone Management, Social Development, and Security in Quintana Roo, Mexico. Source: Berg et al. (2020).

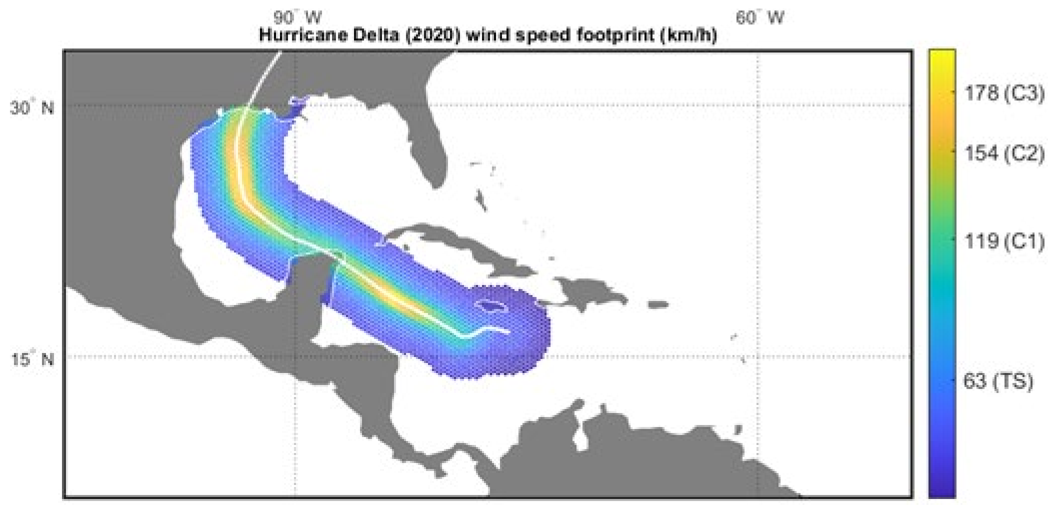
Analytical approaches and data technologies for natural capital assessment

While coastal ecosystems need to be conserved for all the benefits they provide to nature and people, funding for conservation is limited and comes primarily from public and philanthropic sources. Insurance for natural infrastructure is one example of such innovative funding models. The insurance policy is based on a relationship between wind and coral cover loss. If data is available on storm tracks historically, the probability of hurricanes exceeding certain thresholds can be estimated. Based on the probability of impact, a certain premium can be negotiated and specified for protection against hurricanes (Box 1).

Lessons learned -- How analysis of ecosystem services and natural capital informed decisions

The Quintana Roo insurance policy was triggered in October 2020 when Hurricane Delta hit the coast of Quintana Roo, Mexico (Box 1). The insurance covers an area of 160 km along the coast of Quintana Roo and was triggered by wind speeds of 100 knots (185 km/h, reaching Category 3, see Figure). The resulting payout of almost $800,000 is being used to offset the costs of repairing the insured reefs and beaches along the Mesoamerican Reef in the Yucatan Peninsula. The Quintana Roo Government purchased this visionary insurance policy in 2019 and renewed it in 2020, but this is the first time the policy has been triggered, and the first time ever that a coral reef will benefit from this type of insurance payout to repair damage sustained from a hurricane. Mexico's National Commission of Natural Protected Areas (CONANP) launched an impressive post-storm response plan involving nearly 80 reef brigade members; trained volunteers from local communities and the tourism sector, who have been repairing the damage to the reef since the hurricane struck (source: TNC - Source: https://www.nature.org/en-us/newsroom/coral-reef-insurance-policy-triggered/) .

Box 1. Hurricane Delta triggers the first ever coral reef payout.



Box 1 Figure 1. Hurricane Delta wind footprint, which triggered the first insurance policy for an ecosystem

Following the arrival of Hurricane Delta, volunteer reef brigades assessed the damage done to the reef and launched their planned rapid response. For 11 days post-Delta, these brigades stabilized 1,200 large coral colonies in Puerto Morelos National Park which had been displaced and overturned by the storm. The brigades also rescued and transplanted almost 9,000 broken coral fragments, some of which will grow into new colonies. Similar efforts took place in Cancun, Nizuc, and Isla Mujeres Reef National Park. The brigades were formed with the support of TNC and the CRIAP-INAPESCA, a fisheries research center in Mexico.

Flood risk reduction valuations, especially using new data technologies, have informed and encouraged similar approaches in Mexico and the Americas. In the US, coral reefs provide high flood risk reduction benefits (Reguero et al. 2021) valued at $1.8 billion per year nationally. The coral reefs in Hawaii and Florida provide annual benefits of over $10 million/km (Reguero 2021), which suggests high feasibility for similar post-storm response mechanisms for insuring coral reefs in Hawaii and Florida (Berg et al. 2020).

Conclusion

New data technologies and increasingly sophisticated modeling techniques are opening up opportunities to include nature-based approaches in integrated coastal zone and disaster risk management and investment decisions. Risk assessments are urgently needed for understanding where vulnerabilities to climate hazards and increased exposures due to degradation of protective ecosystems are occurring, now and in the future. Until recently, information on ecosystem extent and condition, and impacts of coastal hazards, has been too expensive to collect, inaccessible, or unusable for practical applications. Here, we present new information showing how breakthroughs in data and modeling technologies are supporting better quantification of outcomes of nature-based approaches, in biophysical and social metrics, along coastal regions.

Incorporating the value of nature-based approaches to coastal climate resilience requires understanding how the value of natural assets for coastal risk reduction and key coastal sectors (e.g., tourism and fisheries) vary spatially, now and under future climate scenarios. We illustrated how new technologies and ecosystem service modeling are quantifying co-benefits of nature-based approaches to coastal climate resilience, and how they can add value and efficiency, relative to traditional (grey) approaches. In addition to coastal protection from coral reefs, seagrasses, and mangrove ecosytems, co-benefits accrue through lobster fishery habitat, tourism, and carbon storage and sequestration. We presented examples of applications of new data technologies to incorporating nature-based approaches in (a) Integrated Coastal Zone Management Planning in Belize and The Bahamas, (b) performance metrics for quantifying green infrastructure and marine protected area benefits in loans in The Bahamas, Mexico and throughout the Mesoamerican Reef, and (c) in nationally determined contribution (NDC) planning in Belize. Together, this set of diverse decision contexts demonstrates the power of new technologies in advancing nature-based solutions to climate resilience and accountability for integrated development planning. The urgency for action is dire, but, the scientific and decision-making opportunities are ready to deliver.

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