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Reducing Caribbean Risk: Opportunities for Cost-Effective Mangrove Restoration and Insurance

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Photograph on the cover: Tim Calver @ The Nature Conservancy.
Red Mangrove (*Rhizophora mangle*) grows along the edge of Baie Liberté, Haiti.

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Carlton Ward Jr. @ The Nature Conservancy. Aerial photography of Punta Gorda, on Florida's Gulf of Mexico coast at the north end of Charlotte Harbor near the mouth of the Peace River.

Executive Summary

Mangrove forests play a critically important role in coastal protection. They can dissipate wave energy, which can lower flood risk and minimize erosion. Mangrove forests, however, are threatened by a number of natural and man-made factors, including storm events. Often times, mangroves are able to recover post-storm with limited intervention, but active post-storm restoration efforts are required to re-establish mangroves and hasten recovery, particularly when hydrological damage has occurred.

Insurance is a unique market-based mechanism that can cost-effectively protect and restore coastal habitat. In Quintana Roo, Mexico, The Nature Conservancy helped launch the first-ever insurance product to protect coral reefs from storm damage. We consider whether a similar mechanism could be developed for the protection and restoration of mangroves following storm events. For example, under a parametric insurance policy, payment would be triggered by a natural event and mangroves could be rapidly restored post-storm. Unlike coral reefs, however, mangroves do not usually require rapid post-storm interventions in order to survive. In this case, an indemnity insurance policy may be created that delivers payments based on ex-post assessments of mangrove damage. There are a variety of insurance products available that can be tailored to meet the specific needs of mangroves with initial payouts made quickly through parametric covers and assessed payouts made through indemnity cover at a later stage.

The market for mangrove insurance products will likely vary based on the category of assets most protected by mangroves. In locations where private assets are protected, mangrove insurance could target residential or commercial customers. In other regions, mangrove forests may protect critical public infrastructure, making a mangrove insurance policy targeting public entities a feasible alternative.

To measure mangrove benefits, we estimate the economic value of mangrove forests for flood risk reduction.

Across the Caribbean, we have quantified the cost effectiveness of mangroves for flood risk reduction. To measure mangrove benefits, we estimate the economic value of mangrove forests for flood risk reduction in 20 km study units. These results are based on industry-standard approaches using probabilistic and process-based valuations of flood risk and the damages averted by mangroves. We estimate damages averted by mangroves for four storm frequency events - 1 in 10, 25, 50, and 100-year storm events. We combine these modeled mangrove forest benefits for coastal protection with mangrove restoration costs—estimated to be $45,000/hectare in Florida and $23,000/hectare in the rest of the Caribbean—to develop spatially explicit benefit-cost ratios.

We find that there are 20 states, territories and countries in the Caribbean that have sections of coastline (i.e., ~20 km coastal study units) with cost effective opportunities for mangrove restoration. In total, we identified more than 3,000 km of coastline that have cost effective opportunities for mangrove restoration, with Cuba, the Bahamas, and Florida having the most study units with cost effective opportunities for mangrove restoration. In this study, restoration includes the management, recovery or replanting of damaged or degraded mangroves in existing stands (i.e., where mangroves have or do occur naturally).

For seven of the countries that had the largest amount of mangrove coastline which would be cost-effective to restore, we then looked in greater detail at the governance and market characteristics that would most enable the development of a mangrove insurance product. These countries were: the Bahamas, Belize, Cuba, the Dominican Republic, Jamaica, Mexico, and the United States (e.g., Florida). We show that while the Bahamas and the United States have the most robust insurance markets, mangrove forests in the Dominican Republic and Jamaica potentially protect the largest number of people due to their high population densities.

The findings here provide a positive perspective as to the feasibility of developing and deploying a mangrove insurance product in the Caribbean region. These results, however, are only preliminary. Prior to the development and deployment of a mangrove insurance policy, a full feasibility study would need to be conducted. This full feasibility study should include higher-resolution flood-risk models, estimation of the wind reduction benefits of mangroves, and the construction of fragility curves to show the relationship between damage to a mangrove forest and some component of a storm event, such as storm surge or wind speed.

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20 states, territories and countries in the Caribbean that have sections of coastline with cost effective opportunities for mangrove restoration.

Tim Calver @ The Nature Conservancy. Red Mangrove (*Rhizophora mangle*) grows along the edge of Baie Liberte, Haiti.

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Introduction

Mangrove forests currently cover approximately 14 million hectares across 118 countries (Giri, 2010). This expanse of mangrove forests, however, is drastically smaller than what it once was; between 1980 and 2005 about 20% of mangrove forests were lost globally (Spalding et al., 2010, Giri, 2010) and the overall historical loss is probably 50% or more. Fortunately, the rate of mangrove loss has slowed substantially in the last two decades, but mangrove forests continue to be lost each year (Sanderman, 2018). Finding ways to slow or reverse this loss is critical because mangrove forests provide a suite of important ecosystem services (Barbier, 2011). Mangrove forests enhance fish abundance in nearby coral reefs (Mumby, 2004; Serafy, 2015), and they sequester and store a disproportionate amount of carbon relative to their landcover (Hutchison, 2014). They play a particularly important role in flood risk and erosion reduction by slowing storm surge and dissipating wave energy (World Bank, 2016; Menéndez et al. 2020), which is especially important in terms of risk reduction and insurance considerations.

There are critical opportunities to harness the power of wetlands and reefs to reduce the impacts of storms and other natural hazards (Narayan et al., 2016; Narayan et al., 2017; Beck et al., 2017; Beck et al., 2018a,b; Beck et al., 2019a,b, Reguero et al., 2018; Menéndez et al., 2020). The good news is that we can restore mangroves, if we identify the resources with which to do so.

> The good news is that **we can restore mangroves**, if we identify the resources with which to do so.

This report assesses the potential of mangroves as cost-effective risk reduction mechanisms and identifies where insurance could be used to help guarantee the continuation of this benefit for communities and countries alike. First, we provide an overview of habitat insurance and the risk reduction benefits of mangroves. Then, we make a spatially explicit benefit-cost analysis for mangrove restoration across the entire Caribbean to identify where there may be cost effective opportunities for insurance and investment in mangroves. Lastly, we provide a high-level market analysis of opportunities in the Caribbean for mangrove insurance based on these benefit-cost analyses and our experience with the reef insurance model.

Insuring natural assets is a novel and innovative concept. The Nature Conservancy and the Government of Quintana Roo, Mexico launched an insurance product for coral reefs and beaches in 2019. Using the context of coral reefs, we can illustrate how such an insurance product could be used to protect and restore mangrove forests and other natural storm defenses such as coastal marshes.

Tim Calver @ The Nature Conservancy. A Conservation Planner from the Nature Conservancy Grenada office stands with young red mangrove seedlings which are part of the At the Water's Edge Mangrove restoration project on Telescope Beach near Grenville, Grenada.

The concept of the coral reef insurance product is relatively straight forward. Coral reefs reduce 97% of wave energy (Ferrario et al., 2014) and significantly reduce property damage during storms (Beck et al., 2018a). Protecting coral reefs is an effective means of reducing the risks people and properties are subject to because of storms, and we have found that coral reef insurance can be an effective protection mechanism to preserve risk reduction and other benefits provided by the reefs. Insurance can be used to guarantee funding to repair coral reefs after a major storm, much like other artificial infrastructure, to restore and preserve these protection benefits for future events.

The insurance product set up by TNC and partners in Quintana Roo, Mexico, was designed around this logic. The team established a parametric insurance product to help maintain coral reefs and beaches along over 160 km of the coast. The insurance is triggered if wind speeds in a designated area are recorded in excess of 100 knots. The maximum payout over the 12-month period, or the Annual Aggregate Limit, was $3.8 million (USD).[1] The ultimate payout of the insurance product is based on the maximum recorded wind speed during a storm event: (i) a payout equal to 40% of the maximum payout (~$1.5 million) if wind speeds are between 100 and 130 knots; (ii) a payout equal to 80% of the maximum payout (~$3.0 million) if wind speeds are between 130 and 160 knots; and (iii) a payout equal to 100% of the maximum payout (~$3.8 million) if wind speeds are in excess of 160 knots.

Coral reefs reduce **97% of wave energy** and significantly reduce property damage during storms.

The implementation of the coral reef insurance product in Quintana Roo, Mexico follows a trust fund mechanism (see Figure 1) which is designed to collect and disburse funds for coastal management. In this case, the trust fund purchases the insurance product. The trust fund then acts as the single purchaser of the insurance product. The trust is designed to be able to accept funds from public, private and philanthropic sources as well as a federal fee collected from beachfront property owners who wish to use the beach for commercial purposes. Property owners and coastal communities benefit from the coastal protection provided by the coral reefs and from the fact that having coral reefs situated right off their shorelines attracts many tourists. The municipalities collect the federal fee from property owners that benefit from the coral reef's protective capacity and transfer it to the trust fund.[2] This also helps to ensure that there are no free riders.

To expand the reef insurance example and assess opportunities for a mangrove insurance product, we address two key components in this pre-feasibility assessment. We consider where mangroves and mangrove restoration can offer cost-effective benefits for risk reduction and where there are likely to be suitable insurance market conditions.

[1] The description of the Quintana Roo coral reef insurance policy relates to the inaugural policy which began on June 1, 2019.
[2] At the time of writing, funding is provided by the State Government of Quintana Roo.
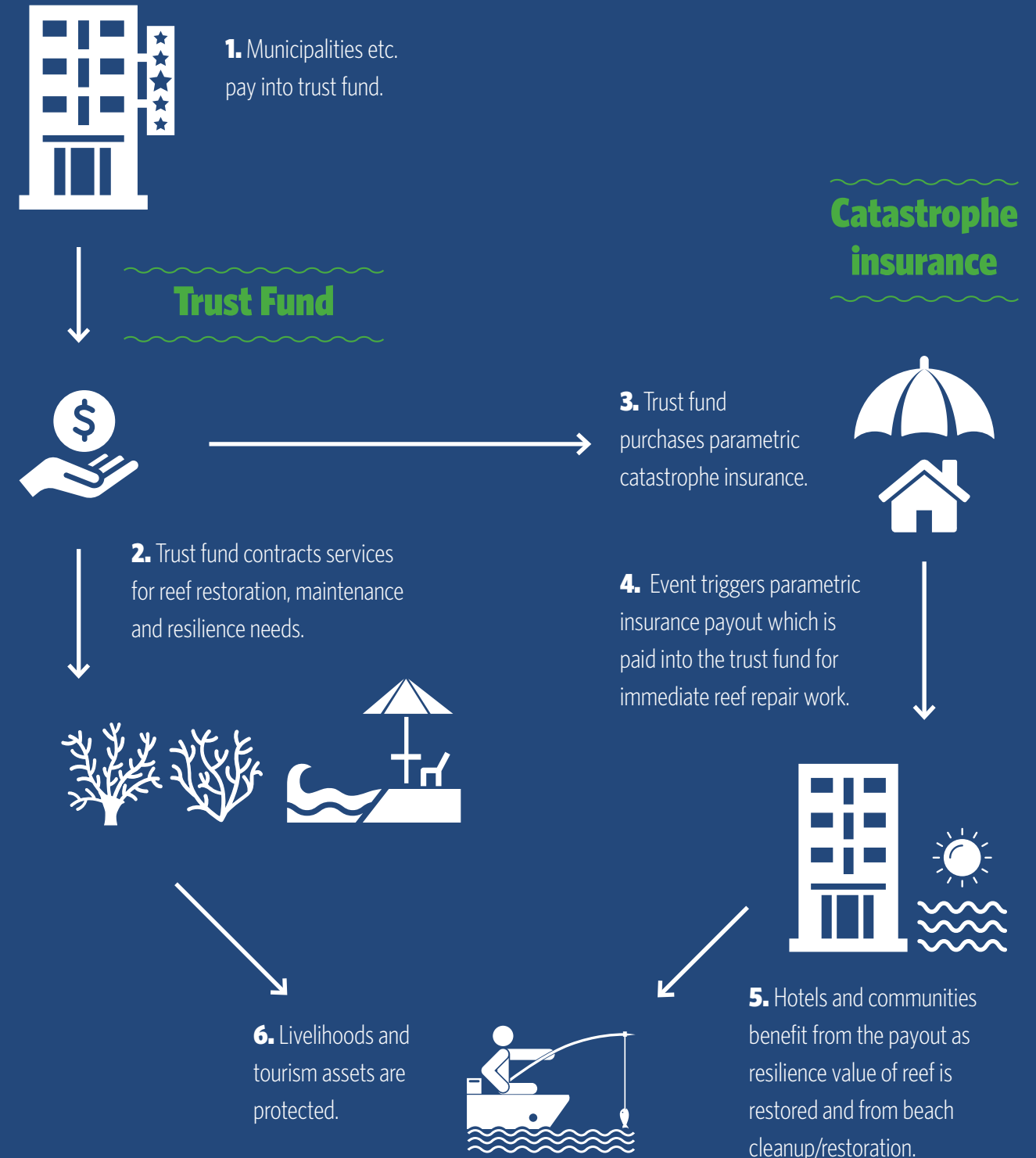
Hotels pay to municialities

1. Municipalities etc. pay into trust fund.

Trust Fund

2. Trust fund contracts services for reef restoration, maintenance and resilience needs.

Catastrophe insurance

3. Trust fund purchases parametric catastrophe insurance.

4. Event triggers parametric insurance payout which is paid into the trust fund for immediate reef repair work.

5. Hotels and communities benefit from the payout as resilience value of reef is restored and from beach cleanup/restoration.

6. Livelihoods and tourism assets are protected.

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Figure 1
Trust Fund and Insurance Mechanism.
Adapted from T. Zoltani, 2017

Mangrove Risk, Restoration and Insurance Opportunities

Risks to Mangroves

Tim Calver @ The Nature Conservancy. A dead mangrove forest resulting from being cut off from water circulation by a road and railroad, Salt River, Jamaica.

Mangroves are threatened by a number of different factors, both natural and man-made.

Mangrove degradation can result from several naturally occurring events. Strong storms, such as hurricanes, can impact mangrove forests by damaging, or killing, mangrove trees. Mangrove damage from hurricanes in the Caribbean has been shown to be primarily a function of wind speed; the relationship is sigmoidal with some evidence of damages around 100 km/hour and much higher rates of loss at wind speeds of 130 km per hour (approximately 70 knots) and above (Imbert, 2018). Besides wind speed, several other aspects affect damage rates including distance of the mangrove forest from the center of the storm, orientation of the mangrove forest with respect to the storm, and mangrove species with red mangroves being more susceptible to storm damage than black mangroves (Imbert, 2018). In addition, strong wave surges associated with storms can have devastating impacts for mangrove forests particularly to forests on exposed windward coasts (Cahoon and Hensel, 2002).

There are many additional factors—outside of just storm events—that affect mangrove growth and recovery trajectories. Sea level change will have a varying, but often negative, effect on mangroves. Mangroves have the potential to accumulate sediments and grow land vertically and thus keep up with moderate sea level rise. In this regard, mangroves are likely more resilient to sea level rise than marshes (which can also raise sediments and create land, but not as quickly). However, sea level rise will also 'push' mangroves landward and losses will occur more often due to coastal squeeze, where mangroves may have the necessary conditions to move inward to avoid sea level rise but there is no suitable space for them to go (due to either man-made or natural barriers) (Alongi, 2015).

Changes in precipitation patterns will impact the extent and health of mangroves, which, in general, tend to migrate inland during periods of high rainfall and to contract seaward during periods of low rainfall (Lovelock et al., 2017; Ward, 2016). A decline in precipitation, for example, could limit a mangrove forest's ability to naturally migrate and respond to sea level rise (Ward, 2016). One of the worst mangrove die offs recorded was in Australia's Gulf of Carpentaria in the summer of 2015-2016. During the event, below-average rainfalls, high temperatures and low sea levels combined to result in the dieback of mangroves along 1,000 kilometers of coastline (Duke et al., 2017). Mangrove diebacks have also been shown to follow El Niño events in Australia when sea levels can be 20-30 centimeters lower (Lovelock et al., 2017).

Finally, mangroves are also predicted to expand their ranges as average temperatures rise. Mangrove extent is generally limited by, among other things, the frequency of extreme cold events, defined as days cooler than -4°C (25°F). On the east coast of Florida, the area of mangrove forests has doubled at the northern end of their range over the last 28 years as the frequency of extreme cold events has decreased (Cavanaugh et al., 2014).

Mangrove forests are threatened by various man-made impacts. For example, the growth of shrimp aquaculture, coastal development, timber harvesting, and pollution runoff have all been linked to mangrove forest degradation or destruction. (World Bank, 2019). Altered landscapes can also affect ecosystem characteristics, such as tidal flows, in a way that is detrimental to mangrove health (Lewis, 2016).

Mangrove Restoration

Mangroves are able to recover post-storm with minimal or no intervention as long as the elevation and hydrology have not been deeply affected (for example by sediment loss). In many respects, mangroves act like weed species and can grow quickly in an intertidal environment with few competitors. Overall, their natural recovery is often faster than for any other marine ecosystem. Initial recovery can be seen in 3-5 years when new generations of mangroves are able to take hold, but full recovery of an ecologically functioning forest can take time (Imbert, 2018). However, mangrove recovery could face several different hurdles. Strong winds and waves can combine for significant erosion that reduces elevation below the tidal threshold for propagule (seed) establishment (Asbridge, 2018). Mangrove forests can be suffocated by excessive sediment deposits if the storm brings the sediment too far landward (Cahoon, 2002).

In many circumstances, particularly those where mangroves are situated around human developments, more active restoration efforts are required to re-establish mangroves and to hasten recovery. An assessment of post-storm status can provide valuable information on whether or not the impacted area would be suitable for planting or whether it requires interventions such as hydrological modifications. A review of 160 documented mangrove restoration efforts across 24 countries illustrated a largely positive picture of mangrove restoration success (Worthington and Spalding, 2018). For projects that are well-documented, survival rates range from 60-90% after 10 years (Worthington and Spalding, 2018).

A review of 160 documented mangrove restoration efforts across 24 countries illustrated a largely positive picture of mangrove restoration success.

Some restoration efforts have been less successful. A review of large-scale mangrove restoration efforts in Sri Lanka following the 2004 tsunami showed 54% of plantings, and roughly one-third of sites, had no surviving plants after 5 years, one-third of the sites had survival rates under 10%, and the remaining one-third of sites had survival rates of between 10% and 78% (Kodikara et al., 2017). Common factors that have been identified in limiting the success of mangrove restoration efforts include placing plants in locations not suitable for mangroves due to topography and flooding (Kodikara et al., 2017), planting in areas where mangroves did not previously exist (Lewis, 2005), and a mismatch of species selection that does not consider the biodiversity needs of the site (Lewis, 2005). While these examples highlight the need to consider ecological factors in mangrove restoration, such restoration can be successful in cases that incorporate proper planning. For example, of the 160-plus mangrove restoration projects reviewed by Worthington and Spalding (2018) over 80 of them were deemed successful.

Mangrove restoration for risk reduction is likely to include innovative approaches to ensure and speed up the delivery of flood and erosion risk reduction benefits. These approaches could include planting more mature trees in the front line to break waves and slow erosion, thus offering immediate protective benefits to people and enhancing successful seedling growth behind the front line. A number of mangrove restoration projects combine grey or hybrid infrastructure, such as reed fences or cement planters, to promote mangrove growth; reed fences can slow initial erosion which would impede mangrove growth and cement planters can improve the establishment of mangrove trees on the front-line.

Restoration efforts should incorporate support for the ongoing management of mangrove forests. For example, regular maintenance of roads, such as clearing broken branches, can help maintain hydrological flows that are important for mangrove health. Ultimately, the ongoing management of a mangrove forest will decrease its likelihood of sustaining extensive damage in the event of a storm.

Finally, any mangrove management project should place some emphasis on greater ecosystem management and reporting. A joint report published by the International Union for Conservation of Nature and TNC (McLeod, 2006) listed seven factors for ongoing mangrove management success, which are shown in Figure 2.

Access to a healthy supply of propagules, either internally or from adjacent mangrove areas.

Limited anthropogenic stress.

Strong mangrove recruitment indicated by the presence, variety, and abundance of established mangrove propagules.

Unimpeded or restored hydrological regime.

Close proximity and connectivity to neighboring stands of healthy mangroves.

Control of common threats such as dredging and filling, conversion to aquaculture ponds, construction of dams, roads, and dikes that disrupt the hydrological regime.

Access to sediment and freshwater.

Figure 2
Identified Factors for Ongoing Mangrove Management Success.
Source: McLeod, Elizabeth and Rodney V. Salm. (2006). "Managing Mangroves for Resilience to Climate Change," IUCN, Gland, Switzerland: pp. 64.

Opportunities for a Mangrove Insurance Product

Given that mangrove forests create significant protective value for coastal communities, there is likely an opportunity to insure these natural assets, as in the case of coral reefs. Initially, we focus on opportunities to insure mangrove forests from damage incurred during storm events. Assessing the potential for a mangrove insurance product covering storm events is logical given that it is more straightforward to assess the fragility of mangroves to wind speed or storm surge—common characteristics of a storm event—than other more nuanced ecological stressors, such as precipitation and sea level rise. At the end of this section, we highlight potential opportunities for a mangrove insurance product outside of storm events.

Identifying the Appropriate Insurance Product

A key decision when setting up a mangrove insurance product is what type of insurance product to use. For the coral reef insurance product discussed above, a parametric insurance product was implemented where insurance payouts were made based on the recorded wind intensity of a storm. In the case of mangroves, as with coral reefs, there are key characteristics of parametric insurance that make it likely to be the best candidate for an insurance product.

Parametric insurance payouts can be made in as little as 10 working days of the damage occurring. This fast payout schedule is because parametric insurance, unlike traditional property indemnity insurance, is not tied to a specific asset but rather to a specific triggering event. As soon as the triggering event occurs, the pre-defined payout can be made to the insured party. With parametric insurance, there is no need to wait for an insurance assessor to come to the property and assess the amount of damages incurred and what will and will not be covered by insurance. This quick payout could be beneficial where a rapid post-disaster response to mangrove restoration may be necessary to ensure the long-term viability of the mangrove forest. In many cases, rapid restoration action may be less critical for mangroves per se than it is for coral reefs. However, rapid payouts that help provide restoration jobs in local communities could be socially beneficial, which could have indirect and long-term benefits for ecological recovery.

A parametric insurance policy would cover a defined geographical area, which identifies the mangroves included in the insurance policy. Estimated restoration costs would form the basis to calculate the required amount of insurance coverage. Several recent studies address the relationship between wind speed and mangrove destruction (Imbert, 2018; Tallie et al., 2020; Tomiczek et al., 2020). Another issue is the likely cost of restoration if there is both mangrove loss and extensive hydrological alteration (e.g., extensive erosion or sedimentation). It is likely that restoration costs may increase non-linearly with wind speed because of these hydrological/topographical impacts.[3]

In the case of parametric insurance, an important decision-point is the triggering event. In the case of the coral reef insurance product in Mexico, the trigger point was recorded wind speed in a given area; payouts started when wind speeds of 100 knots or more were recorded and maxed out when wind speeds of 160 knots—equal to a category five hurricane—or more were recorded. When insuring mangrove forests using a parametric insurance product, it would be important to decide what the appropriate trigger point for payouts would be, with wind speed being the most likely trigger point.

In deciding on the triggering event and trigger point for a mangrove insurance project, careful thought will also need to be given to the associated basis risk (defined as the imperfect correlation between index and individual loss). In designing a parametric insurance product, the triggering event, index, and trigger point must reflect the insured risk as accurately as possible. Basis risk refers to the degree to which the insurance index under or overestimates the damage following a triggering event. In the case of a mangrove insurance product, basis risk would occur, for example, if a triggering event that was linked to wind speed did not match up closely with the expected damage sustained to a mangrove forest during a storm event. For one, a mangrove forest may be in the lee of a storm and even though the wind speeds exceed the trigger point the mangroves sustain limited to no damage. Conversely, a mangrove forest could sustain damage even if a storm's wind speeds do not exceed the trigger point. Thus, when deciding on the appropriate triggering event and trigger point for a mangrove insurance product, careful thought needs to be given to factors that affect mangrove forests, how their impacts on mangrove forests can be measured, and the vulnerability of mangrove forests to those factors. Ideally, historical storm events serve as the ground for assessing the historical damages and losses which allows for an accurate structuring of the trigger point and mitigates the challenge with basis risk.

> Ideally, historical storm events serve as the ground for assessing the historical damages and losses which allows for an accurate structuring of the trigger point and mitigates the challenge with basis risk.

Mangrove forests could also potentially be insured following a more traditional property indemnity insurance model. In contrast to parametric insurance, with property-indemnity insurance, the size of the payout would be based on ex-post assessments of mangrove damage. In this example, mangroves could be rolled into corporate insurance where, for example, a company that restores and/or maintains a mangrove forest of a specified size and location could then qualify for a reduction in insurance premiums. It is open to question whether it may be feasible to develop a similar model with private home insurance, with verification as one of the practicalities that would have to be addressed.

Alternatively, a combined parametric-indemnity insurance product could be created. In this case, a percentage of the payout could be paid out immediately post-storm through the parametric portion and a remaining portion could be paid out at a later date based on assessed damage.

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[3] Non-linearity in restoration costs/efforts was also assumed with coral reef insurance.

Mark Godfrey/TNC @ The Nature Conservancy. Boats used by the local shrimp cooperative of Salto de Agua lay at rest in the coastal wetlands and mangrove forest of the La Encrucijada Biosphere Reserve of Chiapas, Mexico.

Identifying the Appropriate Insurance Customer

The second decision when setting up mangrove insurance focuses on identifying the primary customer. Ultimately, the identified customer will be location-specific and depend on the assets that are being protected by a specific mangrove forest. In areas where mangrove forests protect residential houses, individual private citizens may wish to purchase a mangrove insurance product. Similarly, in areas where mangrove forests protect commercial properties – such as hotels – private businesses may wish to purchase a mangrove insurance product.

For both residential and commercial insurance, there are complications that could arise in developing an individual insurance product. In any mangrove insurance product, one needs to understand what area of land is protected for a given parcel of mangrove forests. If a given parcel of mangrove forest protects multiple properties, whether they are residential or commercial, then any one property holder taking out mangrove insurance will end up inherently benefiting

multiple property owners. On the flip side, if all benefiting property owners took out their own mangrove insurance policies the logistics of aggregating and disbursing payouts for mangrove restoration could quickly become cumbersome and a hindrance to the post-storm restoration of the mangrove forest.

Multiple schemes may be used to get around this collective action problem. As in the case of the coral reef insurance in Mexico, a trust fund could be created. In the Mexico example, all benefiting property owners agreed to pay into the trust fund. Alternatively, a composite insurance policy could be used (Sanderman, 2018). With composite insurance, individual property owners are insured under a single insurance policy where their payments into the policy are a function of the relative protective benefits received from the mangrove forests. Finally, the mangrove insurance product could be purchased directly by an insurance company to cover regions where a portfolio of insured properties has extensive coastal exposure.

A mangrove insurance product could also be purchased by the public sector, such as a national government, which would avoid this collective action problem. Mangroves often provide critical coastal defenses to important public infrastructure. Ports, airports, wastewater treatment and energy transfer facilities were built in the lowest lying open areas near urban centers, which often meant over mangroves. A national or local government could opt to purchase a single mangrove insurance plan to reduce storm damage in specified regions with the intent of protecting many of its different stakeholders, including private citizens and companies. Due to the protection gap, the costs of storm relief and recovery efforts are typically covered by governments. In many cases, maintaining mangrove forests is a cost-effective means of mitigating storm damage affecting sea walls and other grey infrastructure (Bell and Lovelock, 2013). Consequently, a government could find that purchasing mangrove insurance is a cost-effective means of ensuring that mangrove forests within a given area are maintained sufficiently to maximize protection to inland communities from storms. Additionally, mangroves are often on public land and governments may already be committing millions of dollars to restoring mangroves. There is the possibility that a publicly-oriented mangrove insurance product could also be of interest to local or global humanitarian and/or disaster risk-reduction organizations as either a stand-alone product or integrated into other product offerings.

> A national or local government could opt to **purchase a single mangrove insurance plan to reduce storm damage in specified regions** with the intent of protecting many of its different stakeholders, including private citizens and companies.

Opportunities for Mangrove Insurance Beyond Storm Events

Up until now, we have focused on the benefits of insuring mangrove forests in order to prevent or reduce damage to physical assets from a storm event. As discussed above, however, mangroves are subject to additional ecological stressors outside of storm events. Mangrove forests also provide many other benefits to neighboring communities beyond property protection (Barbier, 2011). When considering mangrove insurance, it may be feasible to develop an insurance product that focuses on one of these other benefits or stressors. One possible alternative mangrove forest benefit to consider for an insurance product relates to carbon storage.

Mangrove forests are considered one of the most carbon-dense ecosystems in the world – the carbon storage benefits of marine habitats, including mangroves, is commonly referred to as blue carbon. Mangrove forests are able to store carbon not only in their biomass but also in the soil, acting as long-term carbon sinks, and making them incredibly effective environments for carbon storage (Sanderman, 2018). The Caribbean is home to mangrove forests that store a significant amount of carbon and many of these countries have lost soil carbon at notably high rates since 2000 (Sanderman, 2018). Although insurance for carbon credits is fundamentally different from the mangrove insurance discussed above, it is still possible to develop a mangrove insurance product related to carbon storage (Bell and Lovelock, 2013). Insurance Facilitators in Australia, for example, launched one of the first insurance products to cover sequestered carbon from forests, which works in collaboration with major accredited carbon offset projects (Insurance Facilitators). A similar product could be developed for mangrove forests. Alternatively, the development of a mangrove insurance product could potentially be expedited if insurance companies were able to count the carbon sequestration benefits of insured mangrove forests as carbon offsets.

A mangrove insurance product could also theoretically be linked to non-storm related ecological stressors, such as precipitation or temperature changes. Assessing the fragility of mangroves with respect to these stressors, however, is likely to be much more difficult than assessing the fragility of mangroves with respect to different intensities of storm events. For one, the impact of precipitation and temperature changes on mangrove forests is much more location-specific than the impact of storm events on mangroves, with some regions experiencing expansion of mangrove forests as rain events increase and/or temperatures increase, while other regions experience the opposite effect. Thus, any insurance product focusing on these ecological stressors would potentially need to construct dozens of different fragility curves specific to the region and stressor – an enormously time-intensive pursuit. While feasible, it's much more likely that any cost-effective mangrove insurance product would focus on the impact to mangroves from storm events. Funding from any storm-related insurance product would then have to be utilized efficiently to resolve any other compounding factors that threaten mangroves.

Tim Calver @ The Nature Conservancy. Community planted mangroves grow along the shore in Caracol, Haiti.

Benefit-Cost Analysis of Mangroves in the Caribbean

In order to identify which locations to focus on for mangrove insurance in the Caribbean, we begin with a high-level country analysis. For any local analysis, we'll need to consider both supply-side factors and demand-side factors. Supply-side factors refer to whether insurance providers show interest in developing a product and have the ability to do so. The demand-side factors refer to the process of identifying the recipients of mangrove protection, and other services (e.g., residential, commercial, or government), and how much they would be willing to pay to insure the mangrove forest, which in turn, is a function of the amount of benefits received. From an economic perspective, mangrove insurance will be feasible in areas where mangrove forests exist, where mangrove forests provide protective, and other benefits, and where it is cost-effective for the beneficiaries to restore or protect the mangrove forest.

Government agencies and the world's biggest (re-)insurers are considering how their funds could be invested in habitat restoration to reduce future risk and build resilience. For example, the US Federal Emergency Management Agency (FEMA) has indicated that they can fund restoration with storm recovery funding if it can be shown in their benefit-cost analysis that such projects achieve benefit-cost ratios (B:C) greater than 1. Likewise, the insurance industry and ecologists are developing tools to estimate where resilience insurance could be used to pay for restoration up front based on reduced risk and premiums later (Reguero et al., 2020). To realize these opportunities, we must provide critical information on mangrove benefits and restoration costs to build the B:C maps that can guide cost effective mangrove conservation and restoration.

Erik Kruthoff @ The Nature Conservancy. Sunset over a saltwater tidal creek and mangrove forest on the island of Eleuthera, the Bahamas.

Methods

We have developed benefit-cost maps based on **(i) recently published work that measures the benefits of mangroves for flood risk reduction globally** (Menéndez et al., 2020), **(ii) new data on the costs of mangrove restoration**, and **(iii) the assessment of mangroves as a 30-year coastal asset.** The core assessment considers coastal flood risk and the value of mangroves for reducing this risk.

To measure and value the coastal protection benefits provided by mangroves, we follow the Expected Damage Function approach (Figure 3) commonly used in engineering and insurance sectors and recommended for the assessment of coastal protection services from habitats (World Bank, 2016). The flood protection benefits provided by mangroves are assessed as the flood damages avoided to people and property by keeping mangroves in place. We couple offshore storm models with coastal process and flood models to measure the flooding that occurs with and without mangroves under different storm conditions. These flood extents are used to estimate the averted flood damages to people and property and hence the expected benefits of mangroves in social (people protected) and economic terms (value of property protected). These methods have been applied in a number of prior projects to assess the value of coral reefs for coastal protection globally (Beck et al., 2018a), and to assess the value of mangroves for coastal protection in the Philippines, Jamaica, and globally (Losada et al., 2017; Menéndez et al., 2018; Menéndez et al., 2020; Beck et al., 2019a).

Our estimates are based on a set of global process-based models, applied to the Caribbean region, that identify the annual expected benefits of mangroves for flood risk reduction (Menéndez et al., 2020). We use a set of hydrodynamic and economic models to identify the area and depth of flooding (i) for mangrove coastlines, (ii) in model runs with and without mangrove, and (iii) for four storm return periods, 1 in 10, 25, 50, 100-year driven by local storm data. We first develop and validate these models in the Philippines, a country with over 36,000 km of heavily populated coastlines, at high risk from cyclones, and more than 200,000 hectares of coastal mangroves (Menéndez et al., 2018). We use these models to develop a dataset of several thousand simulations to statistically describe the physical relationships between (i) tropical cyclones and offshore wave climate; and (ii) offshore wave climate, mangrove parameters, and extreme sea level in coast. This dataset is then used to build regression models and interpolation tables to estimate how mangroves modify extreme water levels at the shoreline. Finally, for every kilometer of mangrove shoreline globally, we overlay the resulting coastal flood maps on economic asset information downscaled to 30 x 30 meters and assessed by flood depth to identify flood damages (risk) and avoided damages (mangrove benefits).

The values that we have provided for both mangroves and coral reefs (Beck et al., 2018a; Menéndez et al., 2020) are the first global estimates of flood risk reduction benefits provided from process-based models for any coastal or marine ecosystem. This work represents a state of the art in global flood risk and benefits assessment and has been shown to provide better estimates than replacement cost approaches (Barbier et al., 2015; World Bank, 2016). We have chosen this approach over others because it is (i) quantitative in contrast to other approaches, which use indicator (expert) scores to assess shoreline vulnerability (e.g., Silver et al., 2019), (ii) it uses the methods and tools of risk agencies, insurers, and engineers (Narayan et al., 2016; Narayan et al., 2017; Reguero et al., 2018), (iii) it is consistent with approaches for national accounting (World Bank, 2016), and (iv) it accurately captures impacts of extreme cyclone events that are typically underestimated in global studies.

We measure the flood protection benefits of mangroves all over the world for coastal flooding from extreme water levels at the shoreline. Following this approach, the role of mangroves in coastal protection is examined by measuring the economic impacts of coastal flooding on people and property under two scenarios: with and without mangroves. The "without mangroves" scenario assumes complete loss of the habitat and the consequent erosion of the intertidal area into a smooth sandy surface.

Our global study covers 700,000 km of mangrove-inhabited coastline that includes more than 141,000 square km of mangroves. The models require a huge amount of data and high computational effort, so a four-level subdivision of the world is made to organize data and modeling efforts (see Figure 4). The first level is the division into five macro-regions, corresponding to the five ocean basins of tropical cyclone generation (Knapp et al., 2010). The second level divides the 700,000 km of coastline into 68 sub-regions considering coastline transects of similar coastal typology (e.g., islands and continental coasts) and similar ecosystem characteristics. The third level of disaggregation involves local scaling, taking units with 20 km of coastline and extending up to 30 km inland and 10 km seaward, with the aim of providing local results. The fourth, and final, subdivision is the coastline profiling of every kilometer.

Offshore Dynamics

Nearshore Dynamics

Habitat

Impact

Consequences

IMPACT WITH HABITAT

IMPACT WITHOUT HABITAT

Offshore

Nearshore

Onshore

▶

Figure 3
Key Steps and Data for Estimating the Flood Protection Benefits Provided by Mangroves.

Step 1. Offshore dynamics: Oceanographic data are combined to assess offshore sea states.
Step 2. Nearshore dynamics: Waves are modified by nearshore hydrodynamics. Step 3. Habitat: Effects of mangroves on wave run-up are estimated. Step 4. Impacts: Flood heights are extended inland along profiles (every 1 km) for 1 in 10, 25, 50, 100-yr events with and without mangroves to estimate impacts. Step 5. Consequences: The consequences to land, people and built capital damaged under the flooded areas are estimated (adapted from Beck et al., 2019a). ©PuntoAparte
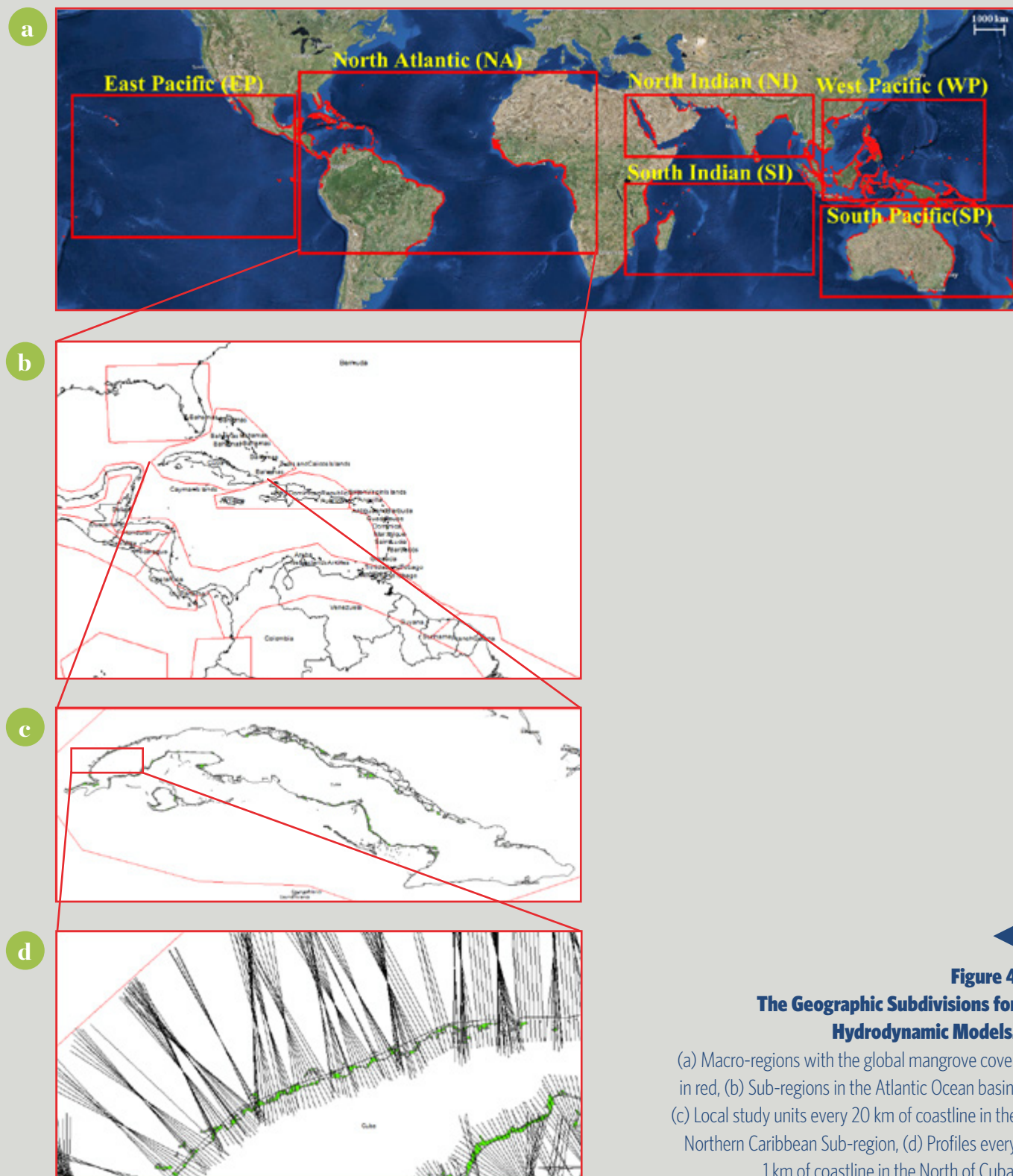
Figure 4
The Geographic Subdivisions for Hydrodynamic Models.
(a) Macro-regions with the global mangrove cover in red, (b) Sub-regions in the Atlantic Ocean basin, (c) Local study units every 20 km of coastline in the Northern Caribbean Sub-region, (d) Profiles every 1 km of coastline in the North of Cuba.

First, we define cross-shore (i.e., seaward to landward) coastal profiles every 1 km for all mangrove coastlines globally and group them into 20 km study units. The 700,000 global coastal profiles are grouped and classified using a library of 750 pre-existing cross-shore, 1-D profiles that were developed based on data from the Philippines. Each profile contains the following information: (i) profile slope (i.e., from mean water depth along the profile at multiple distance intervals from offshore to shoreline), and (ii) total height and width of mangroves.

Then, we follow a multi-step framework:

1 **Estimate offshore dynamics.** Produced from tropical cyclones and regular climate conditions. This measures the flood protection service of mangroves all over the world for two climatic conditions: (i) Cyclonic, i.e., the conditions of high-intensity extreme waves and storm surge induced by tropical cyclones; and (ii) Non-cyclonic, i.e., the "regular" waves generated by low-intensity local storms. The data sets on tropical cyclones and waves are global and provide locally specific information from more than 7,000 historical cyclones (Knapp et al., 2010) and 32 years of data on waves and sea level.

2 **Estimate nearshore dynamics** produced by non-cyclonic and cyclonic conditions. Once we resolve offshore dynamics, we obtain waves and storm surge on the seaward side of each cross-shore profile. Waves interact with the sea floor and other obstacles (e.g., islands) as they approach the coast and modify height and direction through shoaling, refraction, diffraction, and breaking processes. Regular climate is propagated following a hybrid downscaling. The 32-year long series, from 1979 to 2010, includes 280,000 sea states (one sea state is a 1-hour record of wave height, peak period, and total water level). Considering the 700,000 coastal profiles and the 280,000 sea states results together is an unmanageable number of cases. Therefore, we reduce the number of sea-state propagations by considering only the 3,787 non-repeated combinations of wave height, peak period and total water level (SS+AT+MSL) and, then, applying the Maximum Dissimilarity Algorithm (MDA) to obtain 120 sea states to be propagated to shore following with Snell's law and the shoaling equation. Tropical cyclone nearshore hydrodynamics are estimated using a previously derived regression model (see Menéndez et al., 2020). We apply regression models in each profile, and we obtain the same parameters as for regular climate.

3 **Estimate the effects of mangroves on flood reduction.** This consists of pro-
pagating ocean hydrodynamics over mangrove forests which dissipate wave and surge
energy, and, consequently, reduce flood height. Flood height is a function of mean sea
level, astronomical tide and wave runup. Mangrove dissipation takes place by means of
breaking and friction processes. Given the large scale of this analysis, we follow a simpli-
fied approach for vegetation modeling. We use the model developed in the Philippines
to infer the flood height (output) given mangrove forest width, significant wave height,
peak period, and total water level (inputs). Then, we apply the statistical reconstruction
technique RBF (Radial Basis Functions) to calculate the complete historical flood height
time series at each profile. Next, we carry out an extreme value analysis. First, we se-
lect maximum values on a variable threshold (minimum, 1-in-5-year event). We adjust
these selected values to a Generalized Pareto-Poisson distribution, and we obtain the
flood height vs return period curves for both scenarios: with and without mangroves.

We determine **flood
damage** using **depth-
damage curves,** which
identify the flood damage
that would occur at
specific water depths.

4 **Estimate the land flooded (impact)** due to extreme water levels
along the shoreline by intersecting the flood height with topography.
We use a global GIS model to calculate the extent and height of inland
flooding due to the flood height at the shoreline with and without man-
groves, from tropical cyclones and regular climate.

5 **Calculate the (averted) flood damages to people and property.** We use global
datasets and GIS models to estimate the damages to property (economic) and people (so-
cial) from flooding due to tropical cyclones and regular climate, with and without mangroves.
We determine flood damage using depth-damage curves, which identify the flood damage
that would occur at specific water depths. Two sources of information have been used to
obtain these damage curves: the EU Joint Research Centre (JRC) (Huizinga et al., 2017) and
US Hazus (Scawthorn et al., 2006). Hazus is based only on US collected data but frequently
extrapolated for use in other geographies. Whenever possible, we used the new curves from
JRC, which used an extensive literature survey to develop damage curves for each continent
with some additional differentiation between countries to establish maximum damage values.

Data and Model Assumptions

Population Data

Global exposure data for people was obtained from the Socioeconomic Data and Applications Center (SEDAC) fourth version of Gridded Population of the World at a 1 km spatial resolution (http://sedac.ciesin.columbia.edu/data/collection/gpw-v4). SEDAC is freely available, and includes a map viewer to see the global distribution of different socio-economic assets (http://sedac.ciesin.columbia.edu/mapping/viewer/).

Residential and Industrial Property Data

This study uses data from GAR15 (Desai et al., 2015) on the economic value of the residential and industrial building stock, which is based on 2010 economic data from the World Bank (World Bank, 2011; De Bono and Chatenoux, 2015). Throughout this report, we use stock and property interchangeably to mean the physical buildings. The GAR15 provides a global exposure database with a standard 5 km spatial resolution and a 1 km detailed spatial resolution on coastal areas, estimating the economic value of the exposed assets, as well as their physical characteristics in urban and rural agglomerations. The variables included in the database are number of residents, and economic value of residential, commercial and industrial buildings (De Bono and Chatenoux, 2015). The GAR15 database follows a top-down approach using the geographic distribution of population and gross domestic product (GDP) as proxies to distribute the rest of the socio-economic variables (population, income, education, health, and building types) where statistical information including socio-economic, building type, and capital stock at a national level are transposed onto the grids of 5x5 km or 1x1 km using geographic distribution of population data and GDP as proxies (UNISDR, 2015). We downscaled residential and industrial stock data from the GAR15 using the population raster (from WorldPop, 100m resolution).

Gross Domestic Product

World Development Indicators from the World Bank (https://datacatalog.worldbank.org/dataset/world-development-indicators) were used to obtain GDP data for each country involved in this study (World Bank, 2017). GDP information is available from 1960 to 2016. Additionally, World Bank databases were used to validate other data-sources: population from SEDAC and residential and industrial stock from GAR15.

Damage Functions

Global flood depth-damage functions are needed to evaluate damages for different flood levels. A new report from the EU Joint Research Centre (JRC) collected data from Africa, Asia, Oceania, North America, South America and Central America and proposed damage functions for residential and industrial stock, commerce, transport, infrastructure and agriculture (henceforth, JRC damage) at each location (Huizinga et al., 2017). These damage functions are a new alternative to damage curves from Hazus databases (Scawthorn et al., 2006). JRC damage functions are intended to address flooding effects on property globally, developing a consistent database of depth-damage curves.

Limitations and Adjustments

Our efforts represent state of the art process-based assessments of flood risk and mangrove benefits globally. For most countries with mangroves, these represent the best data and models for mangrove benefits, and for many countries the best national level estimate of flood risk. For this study, we have developed a dataset of several thousand simulations to describe how mangroves modify extreme water levels at the shoreline, for every kilometer of mangrove coastline in the world. This approach is computationally highly efficient and allows us to estimate coastal flood risk for new scenarios of mangrove presence and extent. However, for local scale analyses, it is sometimes possible to obtain higher resolution data for example for bathymetry, topography, and assets.

This approach is computationally highly efficient and allows us to estimate coastal flood risk for new scenarios of mangrove presence and extent.

Based on prior work and our own sensitivity analyses, the greatest sources of uncertainty in coastal flood risk assessments are estimates of topography (Menéndez et al., 2019). Given that flooding and damage from tropical storms are among the greatest risks to people and property, better elevation and depth data is urgently needed. Fortunately, in the past decade, there has been a substantial increase in the availability of high-resolution coastal elevation data through the widespread use of LIDAR. Nearshore bathymetry, however, remains a major gap, though there are advances in remote sensing that could help.

Our coastal flooding analyses have several significant, combined improvements over other recent global flooding analyses including downscaling to 30 m resolution; consideration of hydraulic connectivity in the flooding of land; the use of 30 years of wave, surge, tide, and sea level data; reconstruction of the flooding height time series and associated flood return periods. Our flood risk models also include ecosystems for the first time, which represent critical advances in the assessment of flood risk. Major remaining constraints for global coastal flooding models include the consideration of flooding as a one-dimensional process and the difficulty in adequately representing flooding on smaller islands.

Our preliminary review of the results from the global analysis identified that a handful of countries had very high values of benefits per hectare (up to millions per hectare). To be conservative, we assumed that these values were too high and represented outliers. Two measures were taken to address these outliers. First, countries with less than 100 hectares of mangroves were excluded from the analyses as there were too few mangroves in these countries to reliably estimate benefits from a global model. This excluded a total of 15 countries including Bahrain, Singapore, and Benin as well as eight Caribbean Small Island Developing States.

Once we excluded the countries above, there were 7 more countries including the US, China, and Vietnam with benefits per hectare that were considered exceptionally high. For these countries, we capped the estimated benefits per country from our global model at $50,000 per hectare. This value was based on the maximum benefits per hectare from high resolution flood risk and mangrove benefits that we calculated using the best insurance industry risk models and capital exposure datasets (see for example Narayan et al., 2017). Specifically, in work done with Risk Management Solutions (RMS), a leading insurance risk modeling firm, we found the benefits of Florida mangroves during Hurricane Irma to be as high as $47,000 per hectare at the county level (Narayan et al., 2019).

It is certainly possible to design specific mangrove restoration projects to deliver very high flood protection benefits (i.e., much greater than $50,000 per hectare). Examples of high value restorations could be a few hectares of mangroves placed in front of airports, port facilities, bridges or high value homes and condos. However, for the purposes of these analyses across 20 km stretches of coastline, a cap of $50,000 per hectare represents a conservative estimate of benefits. The purpose of this study was to identify areas with benefit to cost ratios greater than one (B:C>1); all coastal study units with benefits at $50,000 per hectare had very high B:C ratios.

We found the **benefits of Florida mangroves** during Hurricane Irma to be as high as **$47,000 per hectare at the county level.**

Assessing Costs of Mangrove Restoration

We gathered published data on the costs of mangrove restoration across the wider Caribbean region. We also identify factors that are particularly important in determining the costs of mangrove restoration projects. In total, we assess data from 137 mangrove restoration projects world-wide, including 72 projects implemented in the Caribbean (Narayan et al., 2019). These data are obtained through a systematic literature review of the reported costs of mangrove restoration projects in Jamaica and the Caribbean region, and the costs of coastal protection structures in Jamaica, using Google, Google Scholar, Web of Science, and Scopus search engines. We extend and build on the data provided by the comprehensive review conducted by Bayraktarov et al. (2016) and Narayan et al. (2016). All cost data were combined with information on project areas to obtain a cost per hectare. In addition to the literature review, we reached out to relevant government and other institutions in Florida, Jamaica, and the wider Caribbean for information on any site-specific factors that would influence these costs including project areas, restoration techniques, and individual project costs.

Restoration costs across the wider Caribbean are generally comparable and vary from around $23,000 per hectare in countries like Guyana to around $14,000 in Grenada (Figure 5). The costliest location in the Caribbean region for mangrove restoration is Florida, with median costs of $45,000 per hectare and extreme variability. We also report on restoration costs in other regions, which primarily represents data gathered from SE Asia where restoration can be cheaper than in the Caribbean (see Figure 5).

Costs per hectare are typically lower for larger restoration projects. In general, the factors influencing the costs of mangrove restoration projects are four-fold: (i) the costs of land and permits; (ii) the costs of obtaining and transporting the material; (iii) the costs of designing and constructing the project, and; (iv) the costs of monitoring and maintaining the project post-construction (Narayan et al., 2019). Since mangrove restoration happens in the inter-tidal zone, the availability and price of land and the necessary permits are an important factor influencing costs. Another factor that influences costs is the restoration technique. Restoration by planting mangrove saplings manually can be cheap if these projects make use of local, voluntary labor. Projects involving hydrological restoration can be more expensive due to the need for specialized equipment, labor and the purchase and transportation of sediment. Maintenance and monitoring are other important cost components, though often not reported in restoration projects. We find that specific maintenance actions, such as fencing restoration sites to reduce disturbance can significantly add to overall project costs (Narayan et al., 2019).
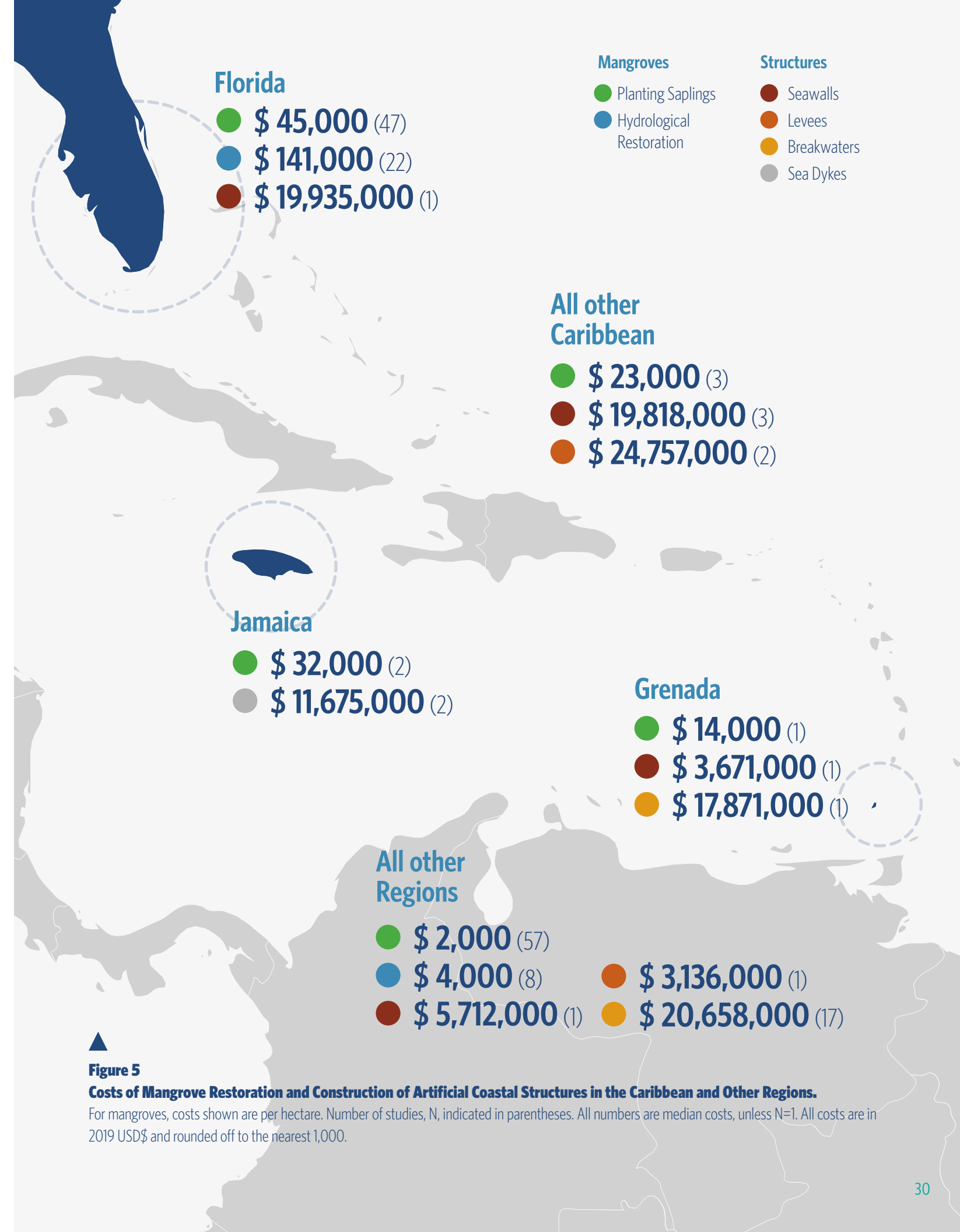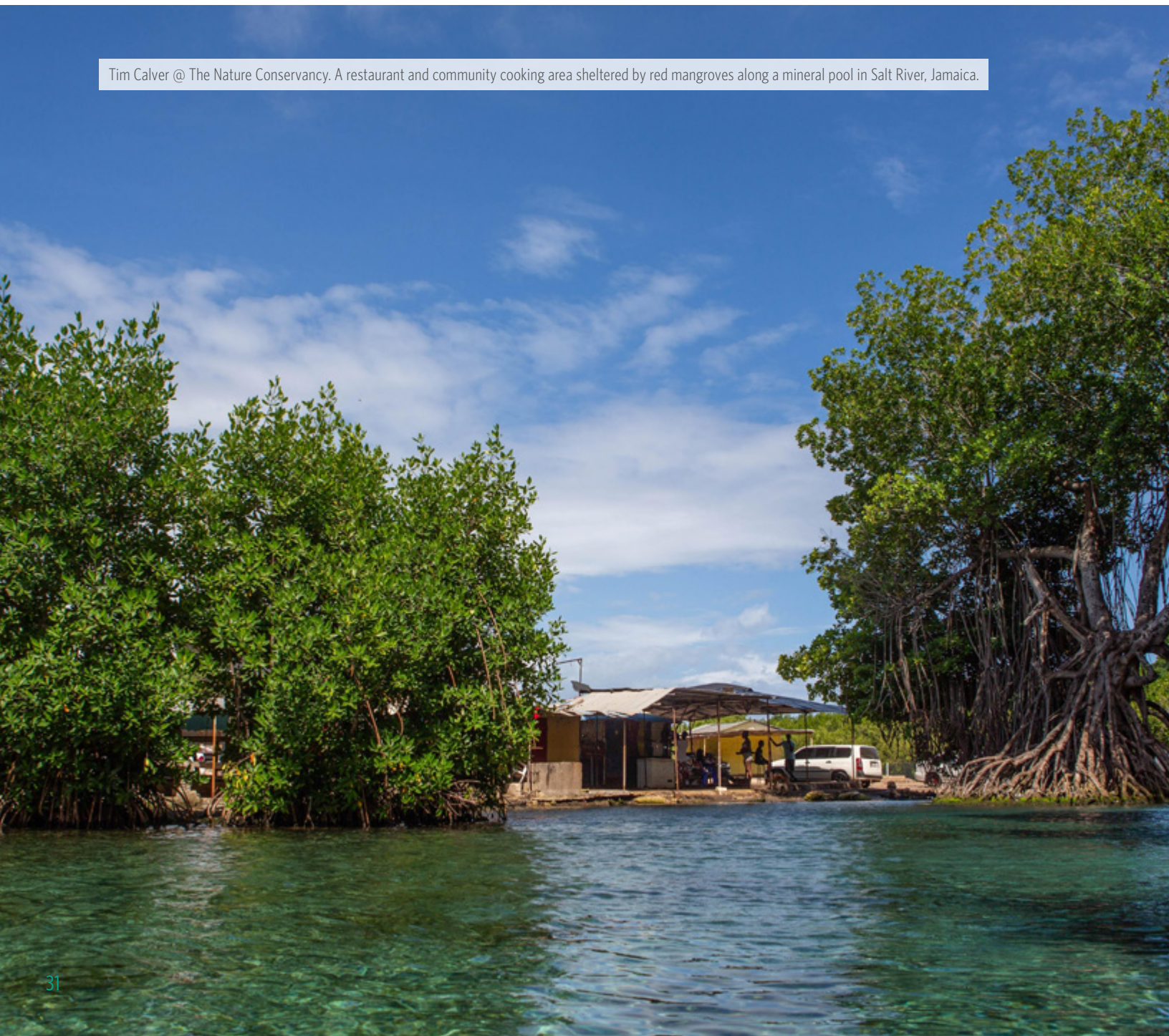

Mangroves
● Planting Saplings
● Hydrological Restoration

Structures
● Seawalls
● Levees
● Breakwaters
● Sea Dykes

Florida
● $ 45,000 (47)
● $ 141,000 (22)
● $ 19,935,000 (1)

All other Caribbean
● $ 23,000 (3)
● $ 19,818,000 (3)
● $ 24,757,000 (2)

Jamaica
● $ 32,000 (2)
● $ 11,675,000 (2)

Grenada
● $ 14,000 (1)
● $ 3,671,000 (1)
● $ 17,871,000 (1)

All other Regions
● $ 2,000 (57)
● $ 4,000 (8)
● $ 5,712,000 (1)
● $ 3,136,000 (1)
● $ 20,658,000 (17)

Figure 5
Costs of Mangrove Restoration and Construction of Artificial Coastal Structures in the Caribbean and Other Regions.
For mangroves, costs shown are per hectare. Number of studies, N, indicated in parentheses. All numbers are median costs, unless N=1. All costs are in 2019 USD$ and rounded off to the nearest 1,000.

Restoration costs vary by region, given the variation in the costs of project components. Restoration in the US is considerably more expensive than across the wider Caribbean, partly due to the higher costs of land, equipment, labor, and permits.

Thus, in our benefit to cost ratio analyses, we used two different average costs of restoration. For projects in the US, we assumed an average cost of restoration per hectare of $45,000. For projects across the rest of the Caribbean, we used an average cost of $23,000 per hectare.

Tim Calver @ The Nature Conservancy. A restaurant and community cooking area sheltered by red mangroves along a mineral pool in Salt River, Jamaica.

Benefit-Cost Ratios

Our B:C analyses combine information from (i) annual expected flood risk reduction benefits ($) provided by mangroves in each 20 km coastal unit; (ii) total hectares of mangrove in each unit; and (iii) average costs of restoration per hectare.

Using data on mangrove benefits and restoration costs, we calculated benefit-cost ratios for each coastal unit. In our analyses, we assume that restoration means the return or recovery of mangrove habitat into areas where they once occurred. In addition, we calculated benefits per mangrove hectare for each coastal segment. We mapped the data in ArcGIS to visualize spatial differences in B:C ratios and benefit value per hectare.

To estimate B:C ratios, we assume that future restoration benefits per hectare will be similar to current flood risk reduction benefits per hectare within each coastal unit as measured in Menéndez et al. (2020). Mangroves in areas with significant storms and high economic exposure offer more benefits per hectare than areas with fewer storms and less economic exposure.

Mangroves in areas with significant storms and high economic exposure offer more benefits per hectare than areas with fewer storms and less economic exposure.

We assume that mangrove restoration projects represent a 30-year coastal infrastructure asset (i.e., a 30-year project lifetime). We apply two different discount rates across this project lifetime: 4% and 7%. Four percent is consistent with values for project assessments with the World Bank. Seven percent is the required discount rate for projects assessed/supported by FEMA in the US.

Results

The results identify that there are cost effective opportunities for mangrove restoration across the Caribbean. There are 20 territories and countries in the region that have sections of coastline (i.e., ~20 km coastal study units) with cost effective opportunities for mangrove restoration (Figure 6). In total, we identified more than 180 coastal units (i.e., > 3,000 km of coastline) that have cost effective opportunities for mangrove restoration at a 4% discount rate. Cuba (37), Bahamas (23), and Florida (23) have the most study units with cost effective opportunities for mangrove restoration. The additional territories and countries rounding out the top 10 with the highest numbers of cost effective coastal study units (i.e., lengths of coastline with cost effective opportunities for mangrove restoration) were, in order, Mexico, Venezuela, Puerto Rico, Belize, the Dominican Republic, Jamaica and Guyana.

Results are robust to changes in discount rates. For mangroves, there are only 15 (8%) coastal study units that drop below the cost-effective threshold at a 7% discount rate (Figure 8) as compared to 4% rate.

Restoration project benefits per hectare varied widely across the Caribbean (Figures 7 and 9). These benefits per hectare results (Figures 7 and 9) identify where to find the expected break-even costs for mangrove restoration across the Caribbean; e.g., all areas in orange could achieve 1:1 B:C ratios for projects if restoration costs were $10,000 per hectare. The highest potential average restoration project benefits per hectare are in Antigua and Barbuda, the Dominican Republic, Saint Kitts and Nevis, and the British Virgin Islands.

Shane Gross @ The Nature Conservancy. Mangroves in Alligator Creek, Cat Island, Bahamas.
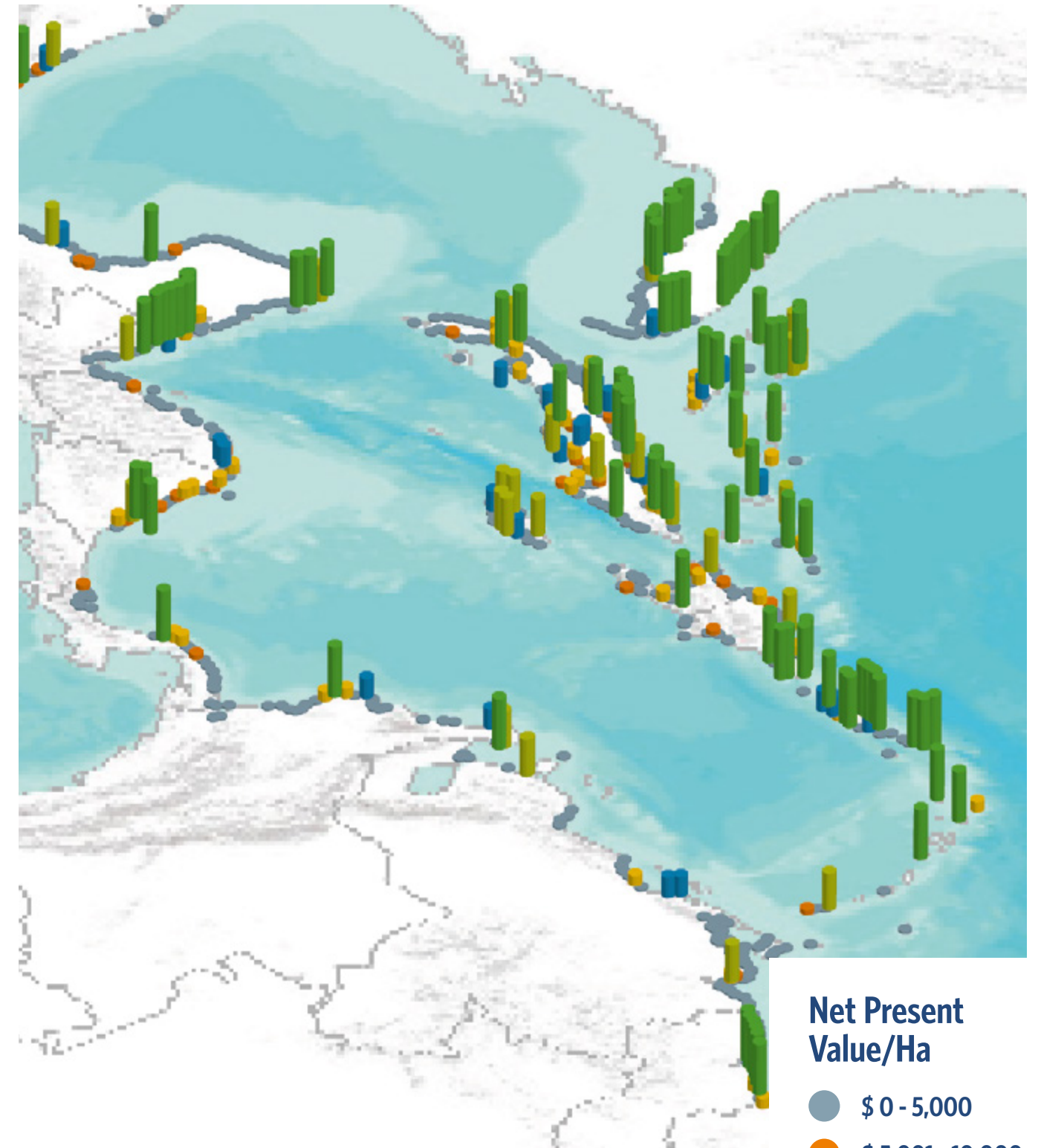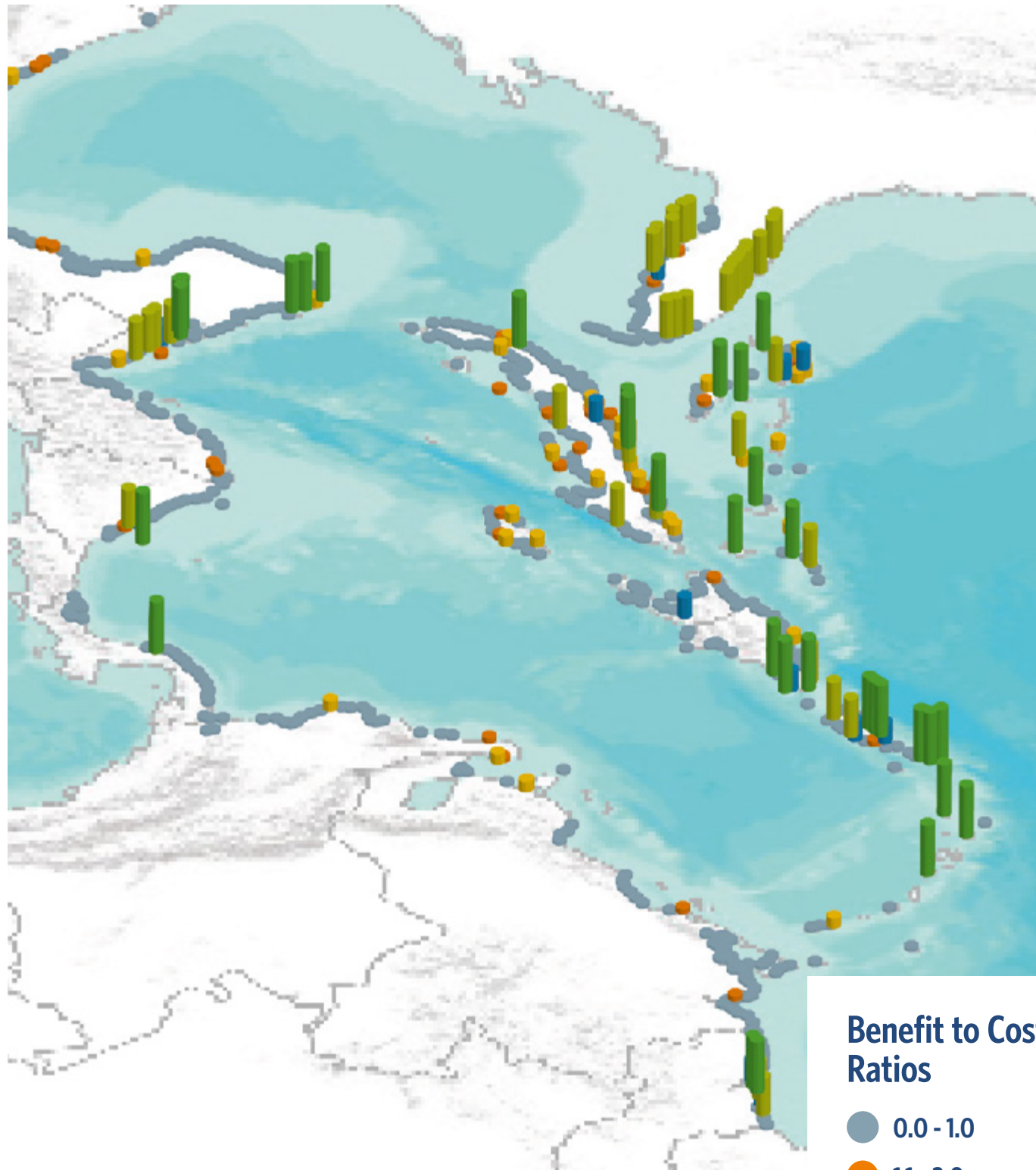
▲
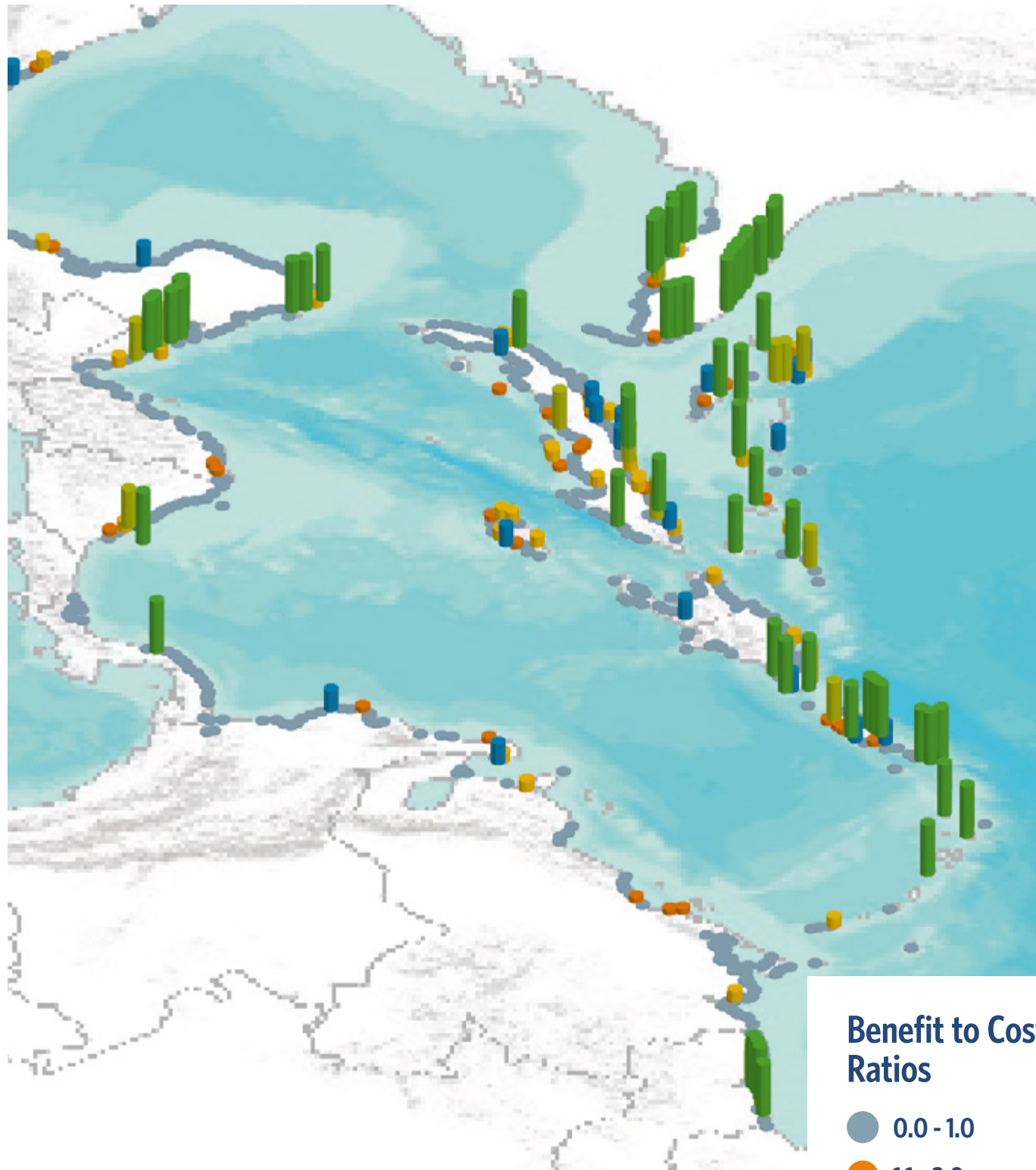
Figure 6
Benefit to Cost Ratios for Mangrove Restoration across the Caribbean at 4% Discount Rate.
Values are the net present value of restored mangroves as an infrastructure asset assuming a 30-year project
with a 4% discount rate. Benefit values are based on Menéndez et al. 2020. We assume a restoration cost
of $45,000/ha for projects in the US and $23,000/ha across the rest of the Caribbean. The B:C ratios are
summarized in coastal study units or blocks which cover approximately 20 km of coastline (see methods).

**Benefit to Cost
Ratios**

- 0.0 - 1.0
- 1.1 - 2.0
- 2.1 - 4.0
- 4.1 - 8.0
- 8.1 - 15.0
- > 15

▲

Figure 7
Benefits of Mangrove Restoration per Hectare at 4% Discount Rate.
The values are summarized in coastal study units which cover approximately 20 km of coastline. We use the
spatially explicit, annual expected flood risk reduction benefits for each coastal unit from Menéndez et al.
2020 and divide by the total hectares of mangrove in each unit. We then calculate the benefits of the asset
over a 30-year time period at a 4% discount rate.

**Net Present
Value/Ha**

- $ 0 - 5,000
- $ 5,001 - 10,000
- $ 10,001 - 25,000
- $ 25,001 - 50,000
- $ 50,001 - 100,000
- >$ 100,000

▲
Figure 8
Benefit to Cost Ratios for Mangrove Restoration across the Caribbean at 7% Discount Rate.
Values are the net present value of restored mangroves as an infrastructure asset assuming a 30-year project with a 7% discount rate. Benefit values are based on Menéndez et al. 2020. We assume a restoration cost of $45,000/ha for projects in the US and $23,000/ha across the rest of the Caribbean. The B:C ratios are summarized in coastal study units or blocks which cover approximately 20 km of coastline (see methods).

Benefit to Cost Ratios

● 0.0 - 1.0
● 1.1 - 2.0
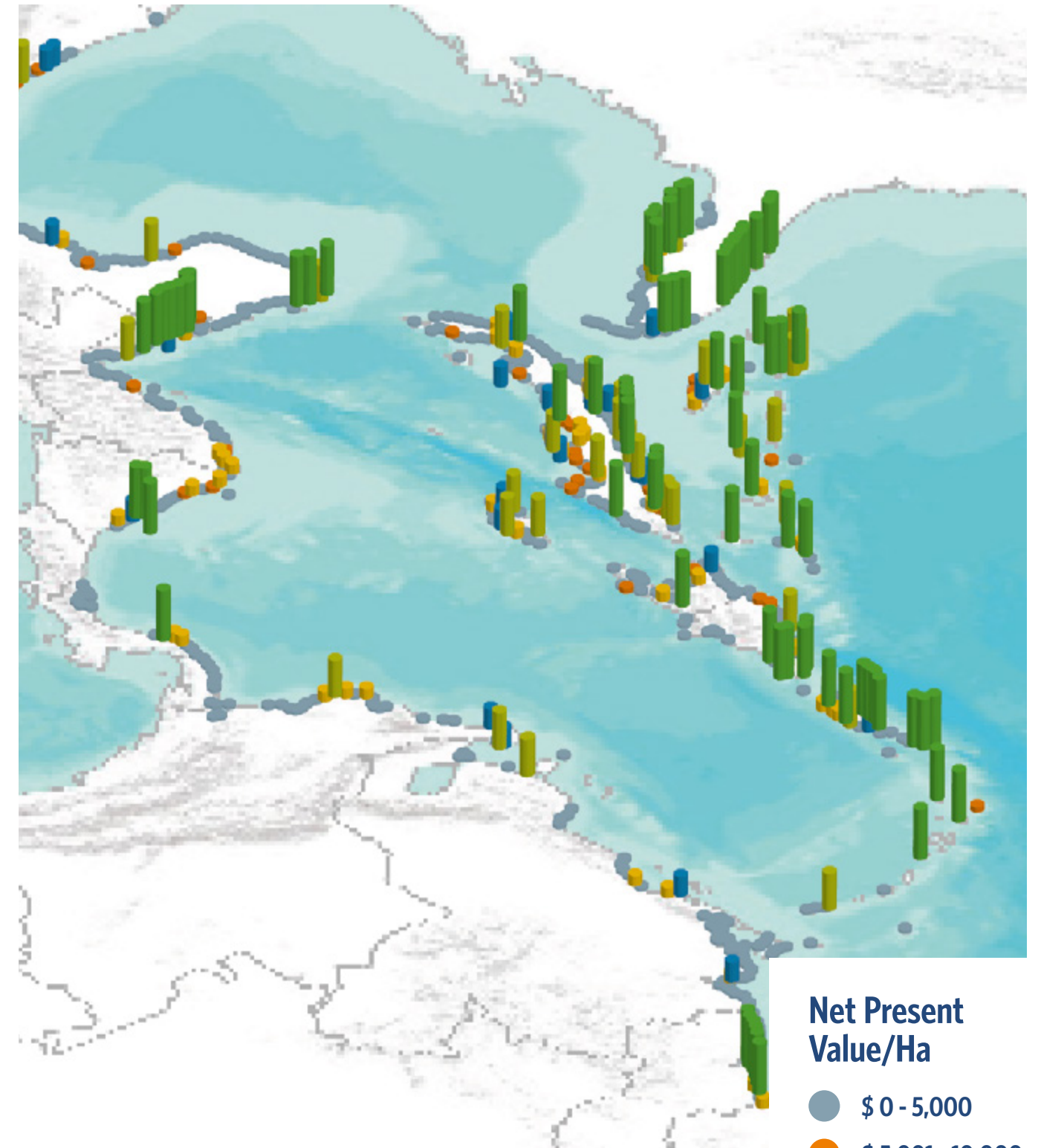● 2.1 - 4.0
● 4.1 - 8.0
● 8.1 - 15.0
● > 15

▲
Figure 9
Benefits of Mangrove Restoration per Hectare at 7% Discount Rate.
The values are summarized in coastal study units which cover approximately 20 km of coastline. We use the spatially explicit, annual expected flood risk reduction benefits for each coastal unit from Menéndez et al. 2020 and divide by the total hectares of mangrove in each unit. We then calculate the benefits of the asset over a 30-year time period at a 7% discount rate.

Net Present Value/Ha

● $ 0 - 5,000
● $ 5,001 - 10,000
● $ 10,001 - 25,000
● $ 25,001 - 50,000
● $ 50,001 - 100,000
● >$ 100,000

Benefit to Cost Ratios

- 0.0 - 1.0
- 1.1 - 2.0
- 2.1 - 4.0
- 4.1 - 8.0
- 8.1 - 15.0
- > 15

▲
Figure 10
Benefit to Cost Ratios for Private Property Benefits of Mangrove Restoration.
This map considers only the flood reduction benefits in averted damages to private property across the Caribbean. Values are the net present value of restored mangroves as an infrastructure asset assuming a 30-year project with a 4% discount rate.

Benefit to Cost Ratios

- 0.0 - 1.0
- 1.1 - 2.0
- 2.1 - 4.0
- 4.1 - 8.0
- 8.1 - 15.0
- > 15

▲
Figure 11
Benefit to Cost Ratios for Public Property Benefits of Mangrove Restoration.
This map considers only the flood reduction benefits in averted damages to public property across the Caribbean. Values are the net present value of restored mangroves as an infrastructure asset assuming a 30-year project with a 4% discount rate.
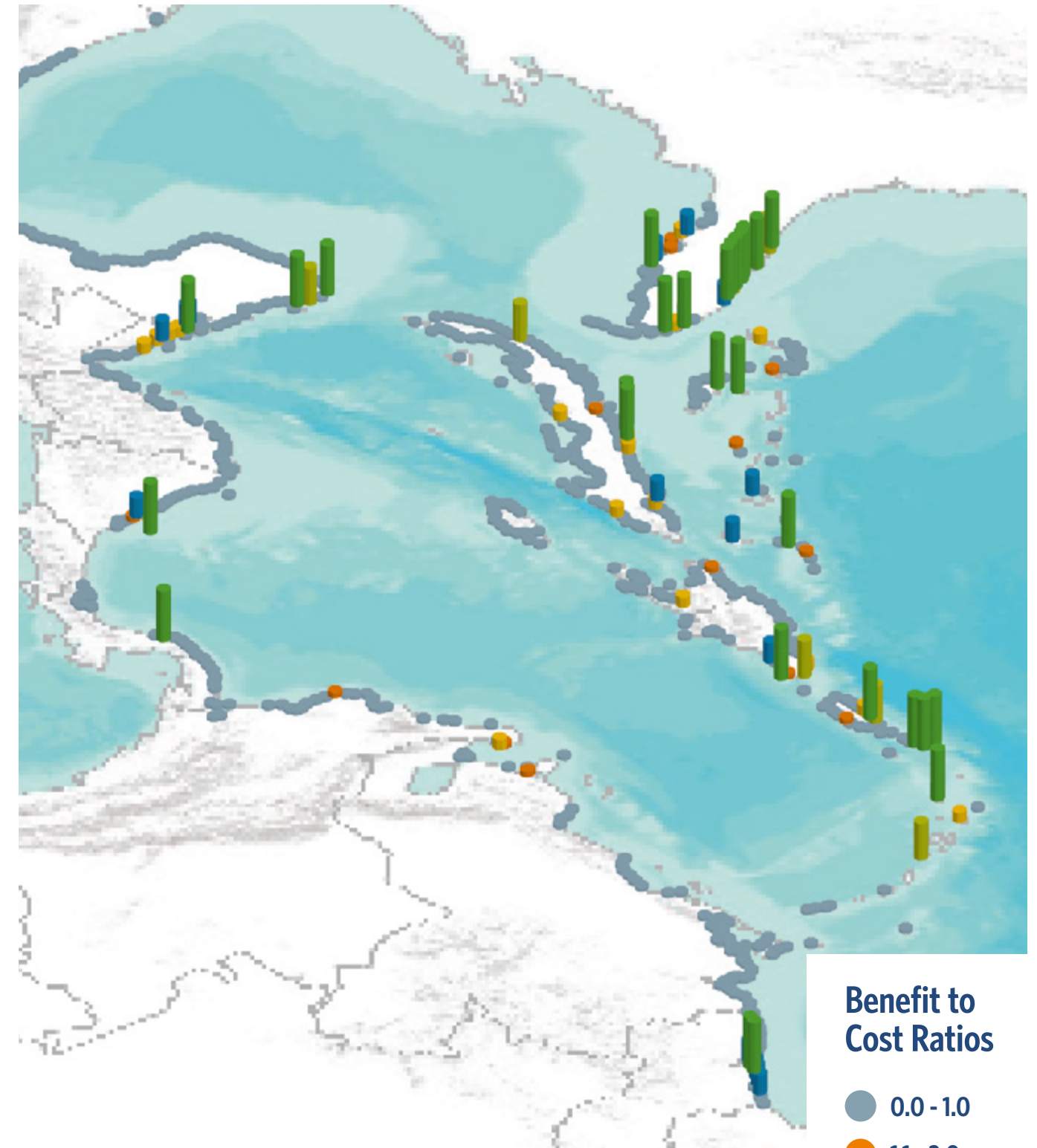
Insurance Product Analysis

Some market analysis will need to be location specific but for this review, we focus on seven countries (the Bahamas, Belize, Cuba, the Dominican Republic, Jamaica, Mexico, and the United States) with some of the greatest opportunities for mangrove insurance in terms of benefit to cost ratios for restoration and market forces. These seven countries include three of the countries with the highest number of cost-effective opportunities, based on 20 km study units, for mangrove restoration (Cuba, the Bahamas, and the United States). The four additional countries included (Belize, the Dominican Republic, Jamaica, and Mexico) also have numerous cost-effective opportunities for mangrove restoration.

For these seven countries we consider relevant country-level demand-side factors. This initial high-level analysis will rule out countries that do not currently possess the right customer base, adequate governance or economic infrastructure to support a mangrove insurance product. For each country, we assess three specific factors: (i) governance indicators, (ii) current size of the insurance market, and (iii) macroeconomic indicators. The governance indicators will tell us how likely a mangrove insurance product is to succeed given a country's current political state, including the regulatory environment and level of corruption. The insurance market information will tell us how widespread insurance currently is in the country and will give us a sense of the likelihood of adoption of a mangrove insurance policy. Finally, the macroeconomic indicators will give us a sense of the level of funds available to support a mangrove insurance policy in a given country. In addition, we can use the macroeconomic indicators to get an initial sense of the potential customers for a mangrove insurance policy.

I — Governance indicators

II — Current size of the insurance market

III — Macroeconomic indicators

Bahamas

	Score	Percentile Rank
● Political Stability & Absense of Violence/Terrorism	0.87	79
● Governement Effectiveness	0.54	72
● Regulatory Quality	0.15	61
● Rule of Law	0.10	57
● Control of Corruption	1.13	83
● Average Score	0.56	

Belize

	Score	Percentile Rank
●	0.02	46
●	-0.59	30
●	-0.66	26
●	-0.82	20
●	-0.14	52
●	-0.44	

Cuba

	Score	Percentile Rank
●	0.65	68
●	-0.24	45
●	-1.46	6
●	-0.44	35
●	0.17	61
●	-0.27	

Dominican Republic

	Score	Percentile Rank
●	0.03	48
●	-0.40	39
●	-0.08	50
●	-0.40	39
●	-0.75	25
●	-0.32	

Jamaica

	Score	Percentile Rank
●	0.49	63
●	0.50	71
●	0.28	63
●	-0.24	46
●	-0.16	50
●	0.17	

Mexico

	Score	Percentile Rank
●	-0.57	26
●	-0.15	48
●	0.15	61
●	-0.67	27
●	-0.86	19
●	-0.42	

United States

	Score	Percentile Rank
●	0.48	62
●	1.58	92
●	1.58	92
●	1.45	89
●	1.32	88
●	1.28	

Legend:
- ● Political Stability & Absense of Violence/Terrorism
- ● Governement Effectiveness
- ● Regulatory Quality
- ● Rule of Law
- ● Control of Corruption
- ● Average Score

▲

Table 1
Country-Level Governance Indicators (2018).
Note: Scores range from -2.5 (weak) to +2.5 (strong).
Source: The World Bank, "World Governance Index," available at http://info.worldbank.org/governance/wgi/#home.

Table 1 displays five governance indicators for each of the seven countries. For each indicator, the table shows the country's raw score as well as its percentile rank across all 214 countries analyzed. The scores range from -2.5 to +2.5 with higher scores indicating stronger governance for that particular dimension. We've also included the average score across these five dimensions for each country. The Bahamas, Jamaica, and the United States are the only three countries to have an average score above zero although Mexico also scores fairly high in regulatory quality.
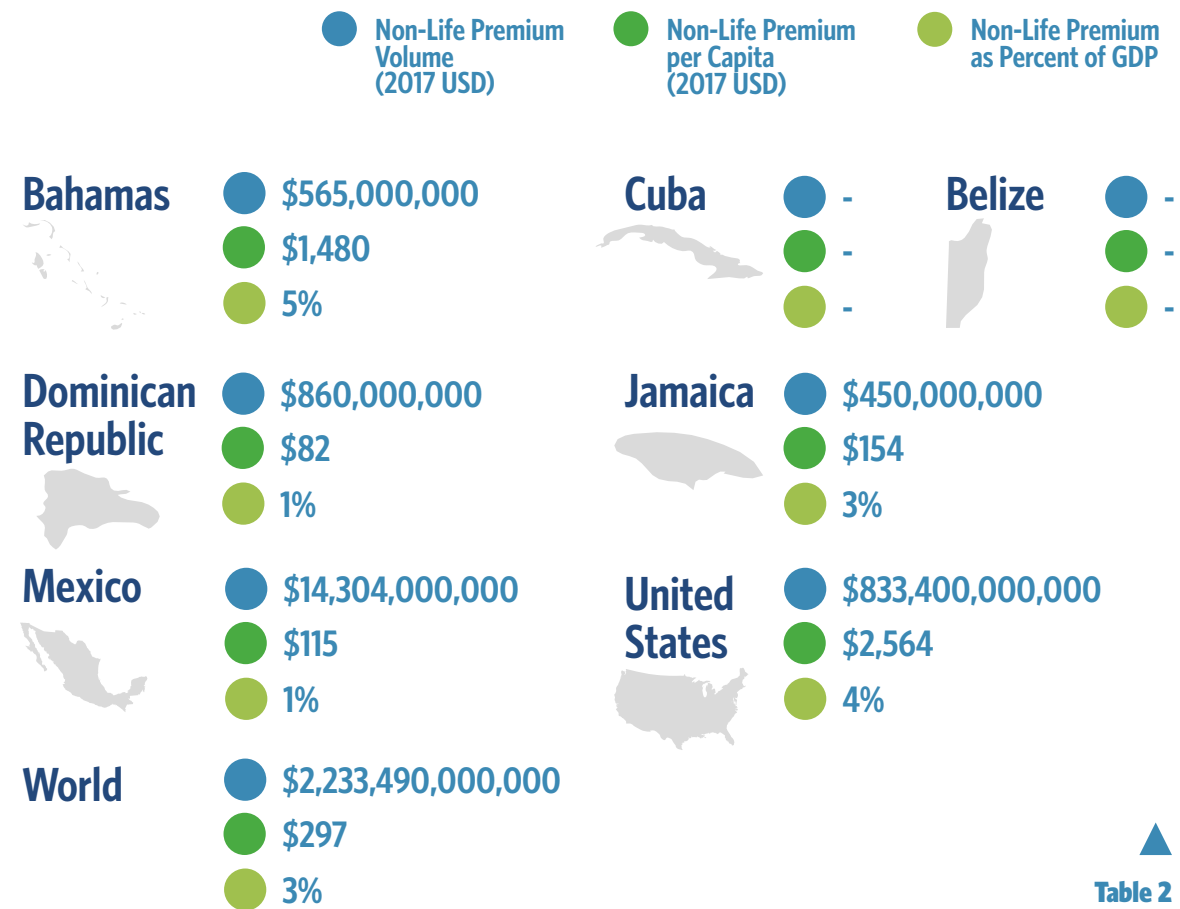
	Non-Life Premium Volume (2017 USD)	Non-Life Premium per Capita (2017 USD)	Non-Life Premium as Percent of GDP
Bahamas	$565,000,000	$1,480	5%
Cuba	-	-	-
Belize	-	-	-
Dominican Republic	$860,000,000	$82	1%
Jamaica	$450,000,000	$154	3%
Mexico	$14,304,000,000	$115	1%
United States	$833,400,000,000	$2,564	4%
World	$2,233,490,000,000	$297	3%

▲
Table 2
Country-Level Insurance Market Indicators (2017).
Note: Data not available for Belize or Cuba.
Source: Swiss Re Institute, "World Insurance: The Great Pivot East Continues," 2019,
available at: https://www.swissre.com/dam/jcr:b8010432-3697-4a97-ad8b-6cb6c0aece33/sigma3_2019_en.pdf.

Next, Table 2 shows the insurance market premium volume for five of the seven countries – insurance market data were not available for Belize or Cuba. For this dimension, we only consider non-life insurance premiums as mangrove insurance would not fall into any life insurance policy. In terms of non-life premium volume per capita, the Bahamas and the United States have significantly bigger insurance markets than the Dominican Republic, Jamaica, and Mexico, and both countries exceed the penetration rate of non-life insurance globally – measured as the non-life insurance premium volume as a percent of GDP. In comparison, Jamaica's insurance market is much closer to global penetration rates and Mexico's and the Dominican Republic's insurance market are smaller than global penetration rates. On the other hand, the penetration rate for insurance in the Bahamas is mainly driven by the small fraction of the population that is wealthy. The size of the market in terms of total premiums is largest in Mexico and the United States.

Carlton Ward Jr. @ The Nature Conservancy. Oysters grow on the mangrove coastline of Charlotte Harbor Estuary near Punta Gorda, Florida located on the Gulf of Mexico.

	Annual Number of International Tourists	Tourists as Percent of Population	Capture Fisheries Production (metric tons)	Capture Fisheries Production as percent of Total	GDP (millions 2015 USD)	GDP per Capita (2015 USD)	Total Population	Population Density (people/sq. km)
Bahamas	1,484,000	397%	11,307	100%	$11,752	$31,406	374,206	37
Belize	341,000	94%	97,523	96%	$1,724	$4,776	360,933	16
Cuba	3,506,000	31%	25,634	44%	$87,133	$7,694	11,324,781	109
Dominican Republic	5,600,000	54%	11,893	84%	$71,165	$6,922	10,281,680	213
Jamaica	2,123,000	73%	17,025	96%	$14,188	$4,908	2,891,021	267
Mexico	32,093,000	26%	1,479,563	87%	$1,170,565	$9,606	121,858,258	63
United States	77,773,520	24%	5,045,443	92%	$18,219,298	$56,823	320,635,163	35
Caribbean small states	6,437,000	89%	357,253	98%	$71,649	$9,921	7,222,212	18
World	1,206,215,744	16%	93,736,945	47%	$75,049,468	$10,224	7,340,548,192	58

▲

Table 3
Country-Level Macroeconomic Indicators (2015).
Note: Caribbean Small States include Antigua and Barbuda; The Bahamas; Barbados; Belize; Dominica; Grenada; Guyana; Jamaica; St. Kitts and Nevis; St. Lucia; St. Vincent and the Grenadines; Suriname; and Trinidad and Tobago.
Source: The World Bank, "World Development Indicators", available at: https://databank.worldbank.org/reports.aspx?source=world-development-indicators.

Lisette Poole @ The Nature Conservancy. A mangrove forest in Puerto Morelos, Mexico at sunset.

Finally, Table 3 shows key macroeconomic indicators for each country. For comparison purposes, we include the same indicators for a set of 13 Caribbean small states and for the World. This table provides us with three key takeaways. First, six of the seven countries (except Belize) receive over one million tourists a year suggesting that mangrove insurance tied to the tourism sector may be especially effective. Second, all of the countries except Cuba have fisheries production that is composed almost exclusively of capture fisheries—or the harvesting of naturally-occurring freshwater and marine living species—in comparison to a world average of slightly less than half. This observation suggests that given the strong reliance on marine ecosystems for fisheries production, there may be strong interest in protecting coastal ecosystems in these countries. Third, the Bahamas, Mexico, and the United States have the highest GPD per capita of all seven countries, with the Bahamas' GPD per capita being over three times that of Mexico, and the United States' GPD per capita being over five times that of Mexico, suggesting that capacity to pay for mangrove insurance may be highest in these three countries.

As an additional check on each country's potential interest in supporting a mangrove insurance product, we cross-check which of these countries are members of the Caribbean's Catastrophe Risk Insurance Facility (CCRIF). CCRIF was created in 2007 and operates as a regional parametric insurance product to limit the financial impacts to an individual country related to hurricanes, earthquakes, excessive rainfall or other catastrophic events.[4] Since 2007, CCRIF has made 41 payouts to 13 different member countries totaling over $152 million USD. Countries that are currently members of the CCRIF may be more likely to have a national government that would support the development and piloting of a mangrove insurance product. Of the seven countries assessed here, three are currently members of the CCRIF – the Bahamas, Belize, and Jamaica.

Since **2007,** CCRIF has made **41** payouts to **13** different member countries totaling over **$152 million USD.**

[4] For more information, see https://www.ccrif.org/.

Table 4 provides a summary of each of these demand-side factors for all seven countries.

Bahamas

Governance Status
Above or near 60th percentile in all dimensions; highest average score of 0.56.

Insurance Market Status
Current market penetration above global average.

Economic Status
Nearly 4x as many tourists/year as residents; exclusively capture fisheries production; high GPD per capita; low population density.

CCRIF Member
Yes

Belize

Governance Status
Poor regulatory and rule of law performance; moderate performance in control of corruption and political stability; lowest average score of -0.44.

Insurance Market Status
No data.

Economic Status
Nearly as many tourists/year as residents; almost all fisheries are capture fisheries; relatively low GDP per capita; low population density.

CCRIF Member
Yes

Cuba

Governance Status
Extremely low regulatory quality; above-average political stability and control of corruption score.

Insurance Market Status
No data.

Economic Status
Over three million tourists/year; less than half of fisheries are capture fisheries; moderate population density.

CCRIF Member
No

Dominican Republic

Governance Status
Moderate performance across all scores with the exception of control of corruption, where it ranks in the bottom quartile.

Insurance Market Status
Lowest non-life premium per capita across all five countries with data.

Economic Status
Over five million tourists/year; high population density.

CCRIF Member
No

Jamaica

Governance Status
Above or near 50th percentile in all dimensions.

Insurance Market Status
Current market penetration on par with global average.

Economic Status
Over two million tourists/year; almost all fisheries are capture fisheries; relatively low GDP per capita; extremely high population density.

CCRIF Member
Yes

Mexico

Governance Status
Poor political stability, rule of law, and corruption performance; moderate to high performance in government effectiveness and regulatory quality.

Insurance Market Status
Current market penetration below global average.

Economic Status
Over 32 million tourists/year; lowest share of fisheries is capture fisheries; moderate GDP per capita; moderate population density.

CCRIF Member
No

United States

Governance Status
Moderate political stability score; in the top 15% for all other indicators.

Insurance Market Status
Highest non-life premium per capita; over $833 billion in non-life premium volume.

Economic Status
Over 70 million tourists/year; highest GDP per capita.

CCRIF Member
No

▲
Table 4
Summary of Country-Level Demand-Side Factors.

Tim Calver @ The Nature Conservancy. An abandoned fish trap lays in the Red Mangrove roots in Baie Liberte, Haiti.

Nick Hall @ The Nature Conservancy. Kayaking among the mangroves in the mist at dawn in Biscayne National Park, Florida.

Implications and Recommendations

For the first time, we have created a spatially explicit benefit-cost analysis across an entire region to identify where mangrove restoration may be most cost effective for conservation and restoration. This work builds on the paper recently published by Menéndez et al. (2020) by adding information on restoration project cost and considering restored mangroves as 30-year assets.

The results identify that there are many opportunities for mangrove restoration across the Caribbean. There are 20 states, territories and countries in the region that have sections of coastline (i.e., measured in 20 km coastal study units) where the benefit-cost ratio of mangrove restoration exceeds one. In total, we identified more than 165 coastal units (i.e., more than 3,000 km of Caribbean coastline) where the benefits of mangrove restoration, in the form of coastal protection, exceed the costs of mangrove restoration using a 7% discount rate. When we use a 4% discount rate, there are an additional 15 study units (an additional 300 km of coastline) with cost effective opportunities for restoration.

Mangrove restoration in some areas may be more expensive than we estimate. In our analysis, however, there are many areas where the benefit to cost ratios exceed 2, 3 and even 10 times mangrove restoration costs. This high benefit-cost ratio means that even if restoration was twice as expensive, there would still be many coastal areas across the Caribbean where it is economical to restore and protect mangroves. Further, we expect that as mangrove restoration efforts grow across the Caribbean, restoration costs should reduce. That is, we expect economies of scale as the number and size of projects grow. This expectation is based on experiences elsewhere including in Southeast Asia where there are many large mangrove restoration projects with costs that are about an order of magnitude less than in the Caribbean.

The development of a mangrove insurance product would be a unique tool to protect mangrove forests and to ensure that they continue to provide coastal protection benefits. Although mangrove forests face many natural and man-made threats, it is most feasible that a mangrove insurance product would enable mangrove repair post storm. We note, however, that there are other potential opportunities for a mangrove insurance product related to, for example, carbon sequestration.

There are many beneficial opportunities for mangrove restoration **across the Caribbean.**

The most likely mangrove insurance product would be a parametric insurance product but there is also an opportunity to develop an indemnity product and/or some combination of parametric and indemnity insurance. Parametric insurance is unique in that it allows for the rapid disbursal of funds following the trigger event which, subsequently, would allow for the rapid repair of mangrove forests. Indemnity insurance could be implemented if there were aspects of the mangrove forest that do not require immediate repair. In the case of parametric insurance, wind speed remains the most likely triggering event but other triggering events, such as storm surge and precipitation could also be considered.

There is potential for any mangrove insurance product to be marketed to either private or public customers. In the short-term, however, a mangrove insurance product geared towards the public sector appears most feasible. With a mangrove insurance policy, local or national governments could use the insurance coverage to restore damaged mangrove forests with the aim of protecting communities and assets from storms, which could impact local food sources, local infrastructure, and local economies. A mangrove insurance policy designed for private customers is also possible but would require overcoming the collective action problem – whereby a single mangrove forest may protect multiple households and/or businesses. In addition, commercial modeling capabilities are currently not able to assess the protective benefits of mangrove forests at the granularity that would be needed for a private insurance product on smaller properties. In the short-term, the private sector can continue to demonstrate the protective value of mangrove forests for their properties to the point that insurance companies begin to encourage policyholders to invest in mangroves. Over time, these investments in mangrove forests could be compensated with a reduction in the cost of property insurance.

Finally, for seven of the countries with the largest amounts of mangrove coastline that would be cost-effective to restore, we consider whether these countries have sufficient market and economic conditions to support a mangrove insurance product. We note that the targeted mangrove insurance customer in any given area would differ based on who receives the most protective benefits; that is, whether it is residential, commercial, or public sector assets that are protected by the mangrove forest to a greater extent. We find that while the Bahamas and the United States have the strongest governance metrics and most robust insurance markets of all seven countries reviewed, other countries also show strong potential. For example, Jamaica has one of the highest population densities of all seven countries considered suggesting that mangrove insurance targeted to the public sector may be especially valuable there.

> With a **mangrove insurance policy,** local or national governments could use the insurance cover to **restore damaged mangrove forests** with the aim of protecting communities and assets from storms, **which could impact local food sources, local infrastructure, and local economies.**

Tim Calver @ The Nature Conservancy. Black Mangrove seedlings, soon to be transplanted to a nursery area, Haiti.

Before developing and piloting an actual mangrove insurance product, more assessment and analysis is required. Quantitative analyses will be needed to construct fragility curves and to understand the wind reduction benefits provided by mangroves; the analysis here only considers the flood reduction benefits of mangrove forests. The addition of wind protection benefits from storms will increase the value ($) of benefits and make restoration projects even more cost effective (i.e., higher B:C ratios). Fragility curves identify under what storm conditions mangroves are destroyed and/or fail during storm events. The construction of a fragility curve is essential for identifying (i) the storm conditions under which mangroves stop providing protection benefits, and (ii) the storm conditions under which payouts will be required to restore mangroves post-storm. Finally, additional ecosystem services could be included in the benefit assessment, such as recreation, erosion reduction, fish production, or carbon sequestration, which would only further the case for mangrove restoration and protection.

In addition, for any specific geographic location identified, a market analysis will be required in order to identify the appropriate mangrove insurance customer, assess their interest in purchasing such a product, and how best to structure a mangrove insurance product for this customer. The buyers and sellers of a mangrove insurance product may also be interested in much higher resolution flood models so that they can better define the benefits of local mangrove forests. Beginning the work on these next steps is paramount, given the large number of cost-effective mangrove restoration projects that currently exist in the Caribbean region.

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