STATE OF PRACTICE IN NATURE-BASED/INSPIRED SOLUTIONS FOR COASTAL EROSION[1]

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ABSTRACT: Nature-based Solutions (NbS) are imperative now, in view of the resulting effects of climate change and man-made alterations in coastal areas. The perspective to address coastal solutions may not be possible to be limited exclusively to ecological solutions. This article, based on a literature review, focuses on hybrid solutions for coastal erosion control. The review highlights examples from around the World that can be applied to islands, having Puerto Rico (PR) as a typical scenario. It presents a summary of how gray infrastructure commonly applied in the past decades can be re-designed and adapted to integrate natural solutions. This article provides significant facts about the merits of structural, ecological, and economical aspects that should be considered on NbS projects. This article helps understand the state of practice and possible solutions that can be implemented, especially, in tropical and sub-tropical regions.

Keywords: coastal erosion, nature-based solutions (NbS)

ESTADO DE LA PRÁCTICA EN SOLUCIONES BASADAS/INSPIRADAS EN LA NATURALEZA PARA EROSIÓN COSTERA

RESUMEN: Las soluciones basadas o inspiradas en la naturaleza (NbS) son imperativas en estos momentos, considerando los efectos del cambio climático y las alteraciones hechas por el ser humano en áreas costeras. Las perspectivas para utilizar NbS es posible que no puedan ser limitadas exclusivamente a soluciones ecológicas. Este artículo, en base a una revisión de la literatura, enfoca soluciones híbridas para el control de erosión costera. La revisión utiliza ejemplos de distintas partes del Mundo que pueden ser aplicados en islas, como ejemplos de escenarios típicos. Se presenta un resumen de cómo la infraestructura gris comúnmente utilizadas en las pasadas décadas puede ser re-diseñada y adaptada para integrar soluciones basadas en la naturaleza. La literatura provee los hechos relevantes sobre aspectos estructurales, ecológicos y económicos que pueden ser considerados en proyectos NbS. Este artículo ayuda a entender el estado de la práctica y posibles soluciones que pueden ser implementadas, especialmente, en áreas tropicales y sub-tropicales.

Palabras claves: erosión costera, soluciones basadas en la naturaleza

INTRODUCTION

Nature-based Solutions (NbS) are responsive actions that promote sustainable management of ecosystems using nature to provide societal benefits (IUCN, 2016). These solutions include the restoration, modification, adaptability, and integration of natural ecosystems to address an ecological problem. This concept has been applied globally following trackable standards adopted by non-government organizations, the federal government, and the scientific community (IUCN, 2020). This article focuses on NbS concept applied to coastal erosion problems which can be defined as the loss of sediments or a substrate in coastal areas. Erosion is highly associated with climate changes (e.g., precipitation patterns, sea level rise (SLR), wave action) affecting directly coastal areas, causing loss and modifications of the natural and built infrastructure (Department of Defense (DoD), 2021). The expected SLR is considered a high priority for studying causes of coastal erosion.

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The expected sea-level rise, considering an intermediate scenario, for 2050 in the Caribbean region is 0.28 meters with the associated expected social and economic impacts and implications (Sweet et al., 2022). The SLR trends for San Juan, Puerto Rico (PR) are currently 2.10 mm/yr and it is expected to increment up to 3.10 m by the year 2100 (Puerto Rico Climate Change Council (PRCCC), 2022). Hurricanes Irma and María (2017) over the Caribbean exacerbated extreme coastal erosion calling the attention of coastal communities and corresponding authorities dealing with coastal hazards for the urgent need to implementing NbS.

Islands are highly exposed and vulnerable to coastal erosion. Sediment loss and instability are frequently affecting coastal communities' economy and wellbeing. Puerto Rico (PR) State of Climate Change (2022) states that *"Future investments in infrastructure must consider adaptation to climate change in design, but also in operation and maintenance"* (Puerto Rico Climate Change Council (PRCCC), 2022). Most of the critical infrastructure in PR is located at coastal zones facing coastal erosion problems and other hazards (Barreto et al., 2021). PR has been mentioned in journals as one of the most affected countries by climate change (Cruz-Mejías, 2021; Martyr-Konaller et al., 2021). As an effort to mitigate the problem, new actions are in progress by diverse professional and scientific sectors.

The nature beneficial impacts in terms of economic and societal impacts have already been published, and the NbS practices implemented by the non-government organizations (NGO's), have established a base for inmediate actions. One step ahead has been the fund allocation on NbS by government agencies. For example, the Federal Emergency Management Agency (FEMA) has allocated significant funds to coral reef restoration (TNC, 2021). Also, the USA Department of Defense (DoD) invests in natural and hybrid infrastructure at their installations (Bridges et al., 2014; DARPA, Reefense, 2021; DoD, 2021). The Nature Conservancy (TNC) created a guidebook on the opportunities of FEMA funding on NbS through Hazard Mitigation Assistant (HMA) grants (TNC, 2021). Coalitions between public and private sectors are more frequent nowadays, to assure that hydraulic infrastructure is designed with societal and environmental benefits (Slinger and Vreugdenhil, 2020). Traditional infrastructure has altered the natural ecosystem services in the past century (Slinger and Vreugdenhil, 2020), then, a need for new or re-designed approaches to address coastal erosion problems is urgent. An optimum strategy to protect communities and the environment from coastal hazards is a great challenge (Maiolo et al., 2020).

APPROACH

This article focuses on identifying and compiling current published solutions for coastal erosion problems applying nature-based practices. It is a review of actions relative to different ecological units (e.g., mangroves, wetland, coral reefs). It will provide a starting point to evaluate effective erosion control practices related to reducing wave action, promoting sediments retention, and enhancing vegetation growth. A search of peer reviewed NbS with two primary mechanisms are implemented, namely, (1) identifying solutions in prior literature reviews and compiling referenced materials, and (2) searching standard bibliographic resources (i.e., Google Scholar) with relevant keyword searches such as "nature solutions + erosion", "mimic nature + coastal erosion", and "coastal erosion + ecosystems approach". This literature evaluation contributes to identifying the best standard of practices in NbS, simultaneously with other techniques that can be implemented in the Caribbean region.

FINDINGS

Man-made structures like seawalls or rocks addition have been considered an erosion control solution for decades (Barreto et al., 2021; Salgado K. and Martínez M.L, 2017), although some solutions may cause geomorphological changes (Barreto et al., 2021). Dikes, for example, are hard engineering structures without integrated ecological concepts (Scheres B. and Schüttrumpf H., 2019). But the integration of new approaches attracts the allocation of funds in retrofitted structures. An example is DoD funded resilience studies including structural, non-structural, and natural approaches (DoD, 2021). A summary of strategies has been compiled demonstrating the capabilities to adapt gray infrastructure into NbS (EWN, 2022). This reference effectively addressed the hybrid and habitat restoration approaches for coastal erosion issues. A summary of some selected best practices is presented in the following.

Hybrid approaches

Hybrid solutions can be defined as Nb techniques combined with gray infrastructure (TNC, 2021). Diverse terms are in use for hybrid solutions, for example, working with nature, ecological engineering, engineering with nature, among others (Slinger and Vreugdenhil, 2020). NbS have been categorized by Scheres and Schüttrumpf (2019) in four groups: "fully natural solutions", "managed natural solutions", "hybrid solutions that combine structural engineering with natural features", and "'environment-friendly' structural engineering".

Scheres and Schüttrumpf (2019) discussed the dike slope effect on materials and nature emphasizing the opportunity to reduce slopes creating a "green" pavement effect. They demonstrated the influence of vegetation cover on dikes efficiency, including grass or wood vegetation. In some cases, trees are considered a starting point for controlling erosion. Others consider root systems as a soil stabilizer. Alternative methods and their limitations for dikes are presented in Table 1 which is adopted here from Scheres and Schüttrumpf (2019). Hybrid structures, such as a dike with a foreshore natural barrier (coral reef, mangrove or sand dune), can reduce the flooding risks and increase the stability of the structure. These options depend on the structure location, whether it is in front of the water or backward (in a position behind the structure). Also interlocked vegetation can be considered as an alternative. Rivillas-Ospina and collaborators (2020) point out that man-made infrastructures like groins, dikes, and rock armors are a major factor influencing coastal erosion. As alternatives, they proposed coral reefs construction, transform rock armors into living dikes, restore mangroves, plant dunes vegetation, and create sediments traps (Rivillas-Ospina et al., 2020). For example, living dikes can be considered as a hybrid solution helping to reduce the reflection wave coefficient. Also, the authors suggested a combination of dunes in front of a rock-dike to protect coastal infrastructure.

Table 1: Methods for ecological enhancement of dikes and their limits/challenges.
Adopted from Scheres and Schüttrumpf (2019)

Dike component	Common Design	Ecological Enhancement	Limitations/Challenges
Foreshore	Not directly integrated in dike design	Ecosystem engineering (e.g., marshes, reefs, etc.) or NbS (artificial reefs)	Litter experience concerning establishment and management. Uncertainties concerning (constant) coastal protection function
Slope Inclination	Slope design as compromise between dike stability and material consumption/ footprint	Milder seaward slopes for positive effects on nature, recreation and coastal processes	Increased dike footprint, additional habitat loss/alteration

Dike Roads	Asphalt roads	Alternative vegetated fortified paths (e.g., vegetated geocellular containment systems)	Litter experience, mainly pilot projects. Assurance of stability and functionality
Revetment	Gray revetment (riprap, placed blocks, etc.)	Vegetated or colonized revetments	Litter experience, mainly pilot projects. Assurance of stability and functionality
Vegetated Dike Cover	Dense grass covers, no woody vegetation	Adaptation of seedling mixtures towards more ecologically valuable vegetation	Assurance of consistent erosion resistance

Within the same concept, Oderiz et al. (2020) study looked for a viable way to reduce erosion by a dual approach. They tested a reinforced vegetated and unvegetated sand dune by an inner rocky structure. They covered dunes with *Ipomoea pescaprae* plants and tested the two approaches under storm conditions. Plants turned out to be highly effectives at the initial stage of surges. Depending on the position of the plants, for example, if they are located at the leeside, it minimized and slowed down the impact of the over-wash. However, an inner rock structure prevented dune damage at the final surge stage. Oderiz et al. (2020) included hydrodynamic, morpho-dynamic, wave run-up, over-wash and reflected wave energy analyses in their study. They suggested a hybrid solution after weighed the economics and ecological costs of a project in Mexico.

On the other hand, *Reefense* (DARPA, 2021), a program sponsored by the DoD, integrates ecological concepts and mimic-nature solutions using man-made structures. This hybrid approach includes a seawall but mimicking nature relief. Rigid structures are part of the hazards built in the last decades (Maiolo et al., 2020; Rangel-Buitrago et al., 2017) and can be discussed from different points of view. It can be evaluated from an ecological perspective, leading to the creation of novel ecosystems with modified services and functions in the short term. The ecosystem changes can be explained by correlations between ecological complexity and ecosystem services optimization; where new and novel ecosystems turn to a high level of ecosystem transformation, but a lower optimization of ecological services is developed (IUCN, 2020). In the long run, NbS seek the lower possible transformation reaching the natural services provided by the complexity of the ecosystem. It optimizes services such as sediments traps, waves dissipation, and coastal erosion reduction.

Hybrid solutions can be interpreted as NbS. For example, the next project can be presented as a hybrid solution. Maiolo and collaborators (2020) mentions five common strategies to address coastal erosion problems, namely, doing nothing, management realignment, holding the line, move seawards, and limited interventions. The latter been the most popular when time to mitigate the hazard is limited (Rangel-Buitrago et al., 2017). The authors summarized the coastal defense measurements and their main effect using gray infrastructure and nourishment, promoting the last one as a soft defense (as NbS). This beach restoration has been implemented at the Mediterranean Sea coast (Calabaia Beach) after applying bathymetry, granulometric survey, wave climate, and hydrodynamic studies (Maiolo et al., 2020). The approach included several interventions moving groins and submerged breakwaters before nourishment. After the use of infrastructure, sea meadows of *Posidonia oceanica* were planted at different depths with the purpose of reducing waves and current effects and extending the infrastructure durability. The success of this Italian project uses a hybrid approach before implementing a NbS.

Another interesting example is a case implemented in San Diego, California which is considered a living shoreline (TNC, 2021). There they created a sand dune over gray infrastructure, using pre-existent riprap and revetment and planting native vegetation for stabilization. It can be a typical scenario in Puerto Rico to stabilize and mitigate coastal erosion as an example to be considered for future applications, where it may apply. Rock revetment and concrete dikes are commonly used to reduce surge waves, especially at industrial ports. Verhagen (2019) analyzed an alternative sea dike with a mangrove belt in front of it to reduce infrastructure costs. In Verhagen study, hydraulic and wave calculations were modeled using Simulating Waves Nearshore software (SWAN model and SWANONE, a SWAN interphase) (The SWAN Team, 2023), including the presence of mangroves scenario. Some of the data included in the models are average total height of the trees in the forest, mangroves density (taller > 1 meter), and the forest canopy cover. It resulted in a transmission and reduction coefficient and the wave height for the different scenarios. The cost of the dike construction with and without mangroves were calculated demonstrating the financial benefits of using mangroves. Verhagen concluded that adding mangroves reduces costs by at least 25 percent, even not considering the ecological benefits of mangrove systems.

After a brief look at hybrid solutions, the following presents the benefits of natural ecosystems and their restoration. As a summary, Narayan and collaborators (2016) presented the percentage of wave height reductions by different ecosystems (31% for mangroves, 36% for seagrasses, 70% for coral reefs and 72 % for saltmarshes) demonstrating the restoration value.

Habitat Restoration

Sun and Carson (2020) showed the economic value of wetlands protection after analyzing 88 storm events in the south and east coasts of the USA. Their results demonstrated that protective effect represents \$1.8 million USD/Km^2/per year with a median value of \$91K USD/Km^2. They estimated that hurricane Irma property loss in Florida would have been reduced by \$430 million USD if 500 Km^2 of wetlands still existed (by 2010). The researchers presented the marginal value of coastal wetlands for storm protection, per county for the east and south coast of the USA (Sun Fanglin and Carson Richard T, 2020).

Following the economic aspect, software based on economic analysis can be applied for evaluating the impact analyses and planning as suggested in the literature (Edwards et al., 2013). The researchers applied ‘Impact Analysis for Planning’ (IMPLAN) software to estimate the economic impact of habitat restoration in the Great Lakes area (IMPLAN® model, 2013 in Edwards et al., 2013). While Murti and Buyck (2014) stated that every dollar invested in coastal habitats in Barbados could reduce \$20 USD in hurricane loss which can be translated to other Caribbean Islands. They applied the Economics of Climate Adaptation methodology, was created by an international partnership in 2009, as a quantitative strategy for nature values (Mueller and Bresch, 2014). Another study summarizing the costs of NbS vs. engineering structures was published in 2016 by Narayan and collaborators (Narayan et al., 2016).

Wetland’s restoration and rehabilitation must meet FEMA criteria, namely, risk reduction/resiliency effectiveness, future conditions, and population impacted. A mangrove swamp, saltwater/freshwater marshes and seagrasses are considered different types of wetlands. This practice results in coastal flooding reduction and sediments traps to mitigate coastal erosion problems. Doa et al. (2020) explored the use of bamboo brush-fences in shallow waters at the Mekong Delta. They applied fences and mangroves as a current dissipator and sediments traps avoiding erosion. They proved a drag coefficient and turbulent friction coefficient relationship with this approach. In this case, they tested the hydraulic gradient using brushwood fences of bamboo as the main material. The fence’s porosity and their configuration influence the Reynolds numbers and bulk drag coefficient. This approach could be tested at estuarine areas where mangroves restoration is being implemented. The addition of renewable material (e.g., bamboo) can be considered as an option for mangrove establishment as a technique to reduce mangrove mortality at the initial stage of restoration projects. Mangroves and salt marshes are up to five times cheaper than breakwaters (Narayan et al., 2016). In the same way, the USA Department of Defense (DoD), implemented the living shoreline concept at MCAS Cherry Point North Carolina facilities (Defense Visual Information Distribution Service, 2021). They created a living shoreline with salt marshes and oyster reefs to promote seagrass and reefs growth. Also, they expand the living shoreline to riverine areas. In salt marshes, the wave reduction that can be related to erosion processes and its effect is highest with vegetation close to the water level (Narayan et al., 2016).

Coral reefs and salt marshes have the highest potential to reduce coastal flooding and erosion (Narayan et al., 2016). Efforts in coral reef restoration are ongoing around the World, recovering fragments from storms and grounding events and growing fragments inland and *in-situ*. In PR the NOAA Coral Restoration Center, the Institute of Socio-Ecological Research, HJR Reefscaping and "Sociedad Ambiente Marino" are leading the coral reefs restoration projects (Puerto Rico Climate Change Council (PRCCC), (2022). Narayan (2016) summarized coral reefs parameters for wave reduction and established that "the most effective reefs are at least twice as wide as the wavelength and located at depths that are at most half the incoming wave height". They estimated the median cost of $115.62 USD per m^2 on coral reef restoration based on 19 projects. Storlazzi et al. (2021) and collaborators estimated the risk reduction of re-building "restore" coral reefs in PR and Florida state in $272.9 million USD in economic activity (). This study focused on flooding risk during storms, but it can be applied to erosion problems caused by wave impacts. In 2021, the Puerto Rico Department of Environment and Natural Resources (DNER) requested proposals to apply FEMA Cost Analysis Tool for San Juan coastal areas to enhance the barrier reef as an alternative for coastal mitigation hazard projects (DRNA, 2021).

Reguero et al. (2018) studied the linkage between reef conditions and coastal protection in Granada Island. They applied the shoreline equilibrium model setting coral reefs as a wave refractory and diffraction obstacle like a breakwater or gray infrastructure. The authors used the wave energy flux integrated into a coastal modeling software (described in González et al., 2007) and retrieved the diffraction patterns from satellite imagery. The sediment transport component, beach profile, bathymetry and currents were considered in the study. They proposed the design of an artificial coral reef to mitigate coastal erosion and proved how engineering approaches can be implemented in natural systems. Likewise, the Engineering with Nature (EWN) group from the Engineer Research and Development Center (ERDC) of the US Army Corp of Engineers worked on three alternative designs of what they called the Reefmaker Ecosystem Wave Attenuator (Bryant and Provost, 2022). The project evaluated three configurations of size/shape and height at different depths and wave conditions. They showed that structure's porosity improved the attenuation, and the system configuration can reduce the wave height. These prototypes were tested at the Engineering Research and Development Center (ERDC) Coastal and Hydraulics Laboratory using scale-model testing at the 5 ft flume facility simulating estuarine conditions.

The algorithms and concepts applied to the design and construction of an artificial reef could be similarly adapted and applied to mangrove and other nature base solutions analysis. (Bryant et al., 2022) studied wave energy and the key factors influencing hydrodynamics in mangroves (*Rizophora mangle*) areas. They modeled the system in a closed flume under 72 different conditions. The main components included drag coefficient, Manning's roughness and damping coefficient. Although the objective was focused on flooding, it could be expanded to coastal erosion problems. The elements evaluated into hydraulic drag included tree density and spacing, bending stiffness, and root structure (primary roots, root height above the ground, root length and diameter) among other ecological parameters. The study evaluated water surface elevation, velocity measurements, hydrodynamic conditions, linear dispersion relation and drag coefficient analysis. In terms of the wave height attenuation, it presented a big range from 13 % to 77 %, depending on hydrodynamic parameters. The US Army Corps of Engineers designed a mangrove reefs wall tested in Florida (USA) for mimicking mangroves root (Bridges et al., 2021). These walls are created with urban and human disturbed areas in mind. Their construction is based on concrete mixed with oyster, silica flume and microfiber making them ecofriendly (Bridges et al., 2021). Similarly, to Bryant work with Reefmaker project, (Dao et al., 2020) stated that an increase in porosity (which is related to the structure arrangement), promotes a decrease on drag coefficient. This coefficient implies the resistance of a cylinder mimicking vegetation. Similarly, hydraulic modeling can be applied to help understand sand dunes restoration needs in projects that are in progress.

With the support of the National Fish and Wildlife Foundation (NFWF), "Vida Marina" team leads a dune restoration effort on the north coast of Puerto Rico (Dobson et al., 2020). This effort is managed by the University of Puerto Rico-Aguadilla to work at 21 sites, covering 10 acres of land. The project included wooden boardwalks for beach access, educational activities and boards, wooden fences and re-vegetation with native plants (*Canavalia rosea*, *Coccoloba uvifera, Calotropis gigantea, Conocarpus erectus, Ipomea pes-caprae*) promoting sand deposition and mitigating erosion (Dobson et al., 2020). The area is considered part of the coastal resilient hubs in the Island, and it is monitored by drones. In this case, the organization ("Vida Marina") received the support of a USACE for their sediments flow analyses (Mayer et al., 2018). In term of the costs, the project requires minimal maintenance and repairs and can be supported by several organizations or agencies (e.g., FEMA Hazard Mitigation Grant Fund, USFWS Coastal Program, National Fish and Wildlife Foundation, USACE, Department of Interior, National Oceanographic and Atmospheric Administration). Multiple sectors from the community can benefit from dune restoration. The authors suggested combining coral reefs, seagrasses and dune restoration efforts to minimize the wave action and promote dune stabilization.

In summary, the main goal of applying NbS alternatives to control coastal erosion is to mimic nature ecosystems. In tropical islands around the Caribbean, these principal components of the ecosystems are mangroves, coral reefs, seagrasses, and sand dunes, among others. On the other hand, common practices based on grey infrastructure are dikes, groins, ripraps, breakwaters, seawalls and others are practices that have been widely implemented. Table 2 shows the degree of efficacy and functionality of gray infrastructure applied in various ecosystems. In general, a high level of efficacy may rely on the functionality and lifespan of the alternative, while lower levels of efficiency mean a short lifespan which is affected by the wave impact and a low effect on sediments retention. For example, ripraps are highly affected by waves action, SLR, showing the effects on scoring and erosion. NbS act as wave breakers reducing erosion and promoting accretion.

Table 2. Common NbS for island nations to address coastal erosion problems.

Ecosystem (NbS)	Common Engineering Practice	Degree of efficacy (gray infrastructure)	Functionality
Mangroves/ saltmarshes	Dikes, channels & water pumps	Medium	Sediment's retention, wave reduction
Coral reefs	Groins, riprap, breakwaters	Low	Provides sediments, wave breakers/reduction
Seagrasses	Breakwaters	Low/medium	Sediment's retention, wave reduction
Sand dunes	Seawalls, groins	Medium	Sediment's retention, wave reduction

FROM POLICY AND SCIENCE TO PRACTICE

Based on FEMA definition NbS is "the sustainable planning, design and environmental management and engineering practices that wave natural features or processes into built environment to build more resilient communities" (FEMA, 2020). The Nature Conservancy (TNC, 2021) summarized FEMA agency's grants and supporting information. It provides three types of grants, two Pre-disaster (identified as Building Resilient Infrastructure and Communities, and the Flood Mitigation Assistance), and one post disaster (identifies as Hazard Mitigation Grant Program). In terms of the coastal flooding that also help mitigating erosion; FEMA can support culverts upgrades, waterfront parks, tidal circulation, living shorelines, channels restoration, beaches and dunes planting (not nourishment or re-nourishment), coral reefs, marshes and mangroves restoration, shellfish reef restoration and land conservation (TNC, 2021). The application of NbS requires to apply hydrodynamic models to simulate coastal processes. Some recommended models for coastal engineering are ADCIRC, STWAVE, XBEACH, MIKE21 (2D) and DELFT3D (3D) (TNC, 2021). Also, NbS projects can be supported by desktop analyses (e.g., tools like ArcGIS, Google Earth, FEMA flooding maps), economic models (FEMA-BCA Tool, HAZUS, BEACH-Fx, HEC-FDA) and environmental models (EDYS, HGM Approach, SLAMM) (TNC, 2021). Chapter 4 (in TNC, 2021) summarized qualitative and quantitative benefits of NbS projects in coastal areas not only preventing or mitigating erosion but also reducing risks on lifelines.

The design criteria for NbS included (1) economical, society and ecological interactions, (2) interventions across sectors, (3) and the risk identification and management (IUCN, 2020). Following the statement of the Coastal Resilience Evaluation for Puerto Rico (around 99% of the PR's coast) but, most specifically the east coast of the Island shows a high potential for NbS project development (Dobson et al., 2020). This region presents spots with a high index of community exposure to storms, erosion, flooding, loss of habitat and multiple stressors.

In a wide context, not all Latin American and Caribbean countries (LAC) have laws that regulates Coastal Zone Management (Barragán Muñoz, J. M., 2019). Puerto Rico is considered "in transition" for some topics related to the Integrated Coastal Zone Management and "in developing" in most of them, comparable with Belize and Brazil. This fact is positioning Puerto Rico at the top of the list for the LAC region having an advanced system for coastal management. However, we are still facing coastal erosion problems with a limited perspective towards NbS and implementing them effectively.

Coastal protection is an expensive activity as an initial investment. However, the return value increases in the long run through NbS approaches designed for long term goals considering SLR and accelerated projected coastal erosion scenarios. EWN provides the tools to integrate research and implement ecological concepts on hybrid solutions. Some of these concepts motivate to focus our attention back on earth and environmental sciences.

The archipelago of Puerto Rico and other tropical islands, cannot rely on adopting strategies from areas with extensive tide amplitude environments. Scientists must think about productive coastal ecosystems that support society wellbeing, food chain, and economic development (e.g., touristic activities) (PRCCC, 2022; Hernández-Delgado et al., 2018a, 2018b). The presence of seagrasses and coral reefs right in the shoreline limits the possibilities to extend a beach by nourishments. But at the same time, it creates the opportunities to increase living systems and use nature as a coalition. It must be seriously considered moving back from the shoreline and preparing the coastline for a sea-level rise adopting retreat strategies. Hybrid solutions represents an opportunity to work with coastal erosion problems and enhance ecosystems services. Moreover, when the Caribbean countries and other countries do not have the political organization and structure or mechanisms to face the challenges of coastal zone hazards.

CONCLUDING REFLECTIONS

The following are concluding reflections the reader should keep in mind:

1. In the long term, coastal restoration efforts increase the positive perception and recreational uses by the community, enhance the natural biodiversity, and improve the coastal protection which promote the green and blue economic development at the region.

2. Coastal erosion is one of the most important aspects influencing coastal activities (e.g., tourism activities around the Caribbean) due to the loss of sand beaches and increasing costs to keep the waterfronts, hotels, and critical infrastructure. This issue can be mitigated by using nature-based solutions and implementing hybrid approaches to stabilize the coastal environment, improve the development of natural ecosystem, and enhance safe economic and touristic activities which will safely promote economic development within a blue-green economy framework.

3. Hybrid solutions have been proven to be effective around the world providing opportunities to improve impacted ecosystems. These should be evaluated on a case-by-case basis to promote the recovery of deteriorated natural ecosystem services and the creation of new/novel ecosystems.

4. The feasibility of applying engineering practices to protect coastal environments must require the application of appropriate coastal engineering hydrodynamic modeling to determine the coastal hydraulics and sediments transport dynamics before NbS implementation to optimize the expected benefits of the alternatives implemented.

5. Coastal zone policies and regulations should be aligned with NbS concepts, strategies, and benefits promoting NbS simultaneously with the application of gray/hard engineering approaches.

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