NNBF

International Guidelines on Natural and Nature-Based Features for Flood Risk Management

Reefs

Puerto Rico I May 2022

12

Reefs

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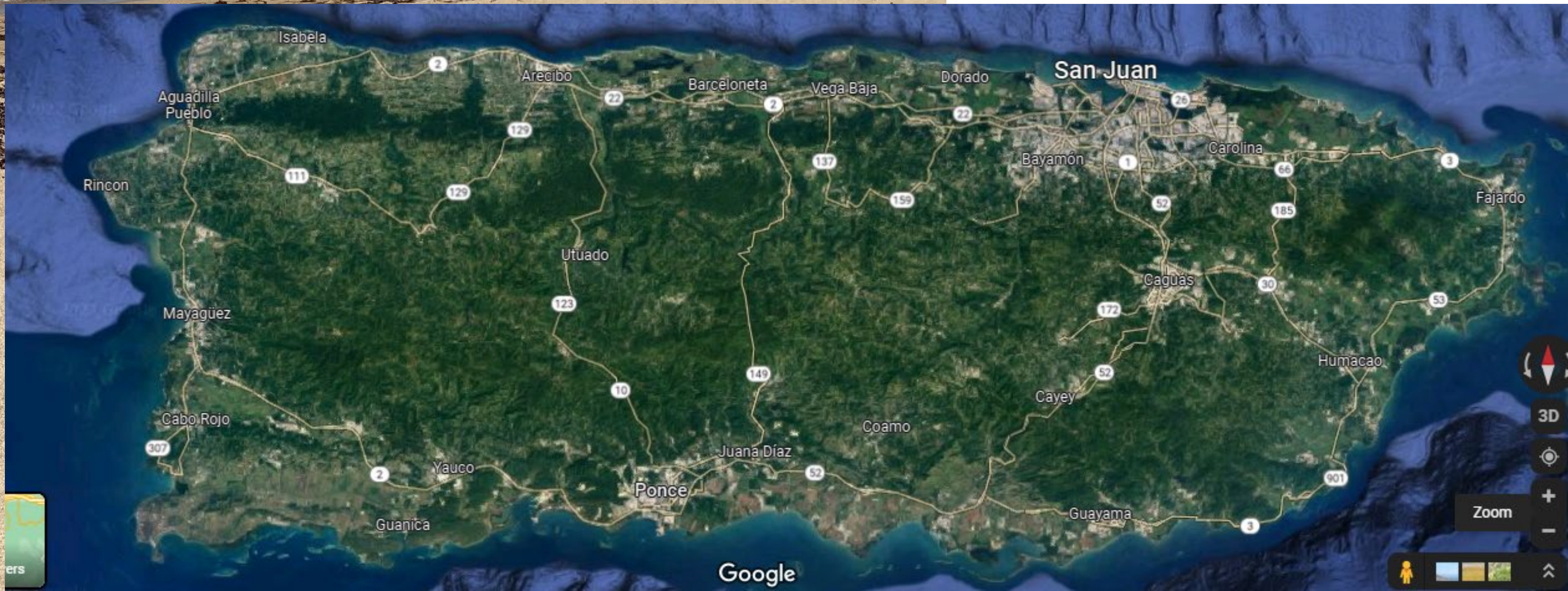
Introduction

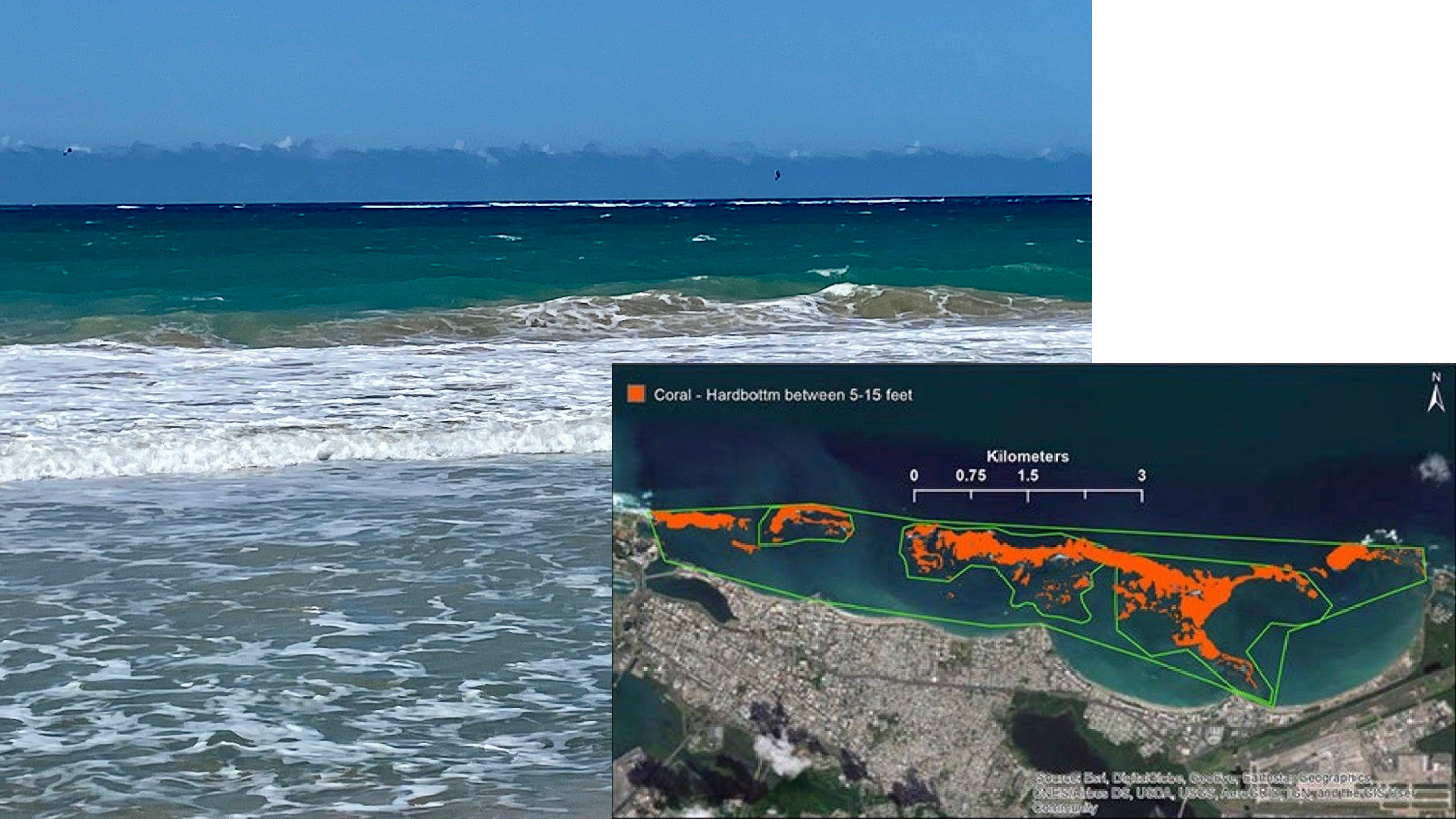
- Types of reefs
- Use of reefs for flood and erosion risk management
- Key reef building organisms

Coral reefs

Shellfish reefs

Artificial and hybrid reefs

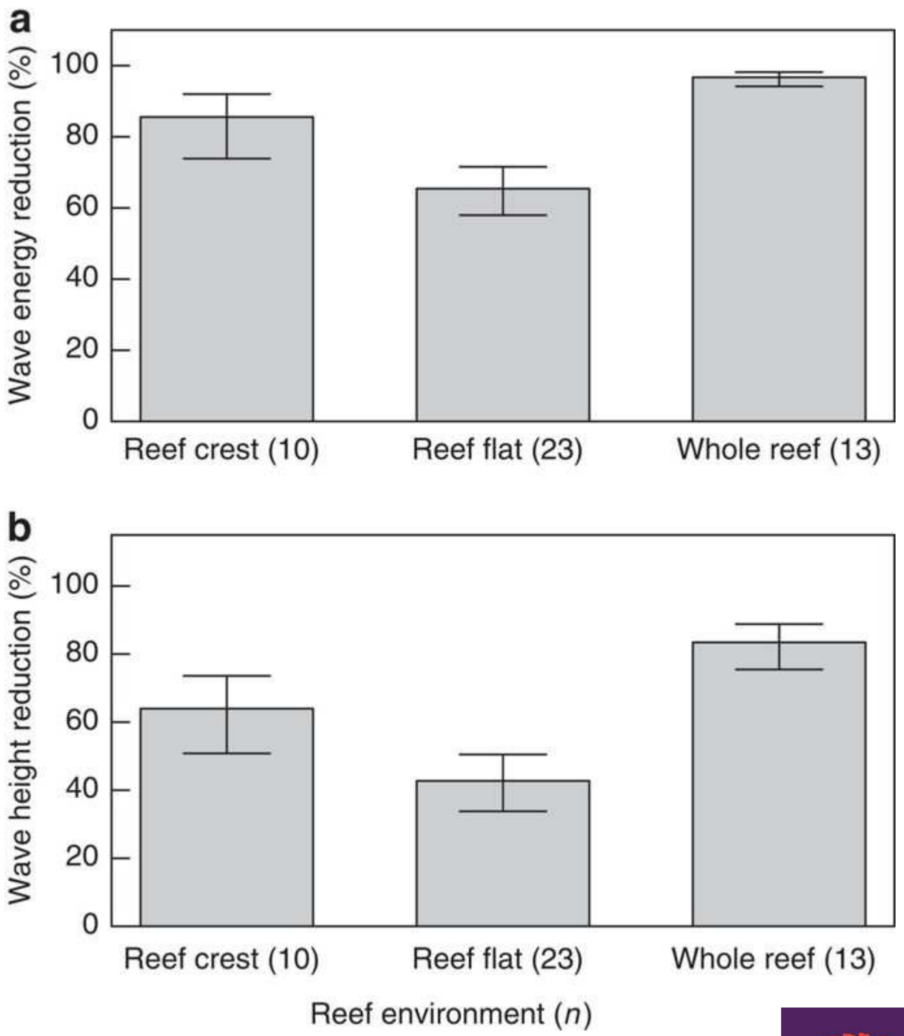

Isabela
Arecibo
Barceloneta
Vega Baja
Dorado
San Juan
Aguadilla Pueblo
Bayamón
Carolina
Rincon
Fajardo
Utuado
Caguas
Mayagüez
Humacao
Cayey
Cabo Rojo
Coamo
Juana Díaz
Yauco
Ponce
Guanica
Guayama
Google
Zoom
3D


Coral - Hardbottm between 5-15 feet
N
Kilometers
0
0.75
1.5
3

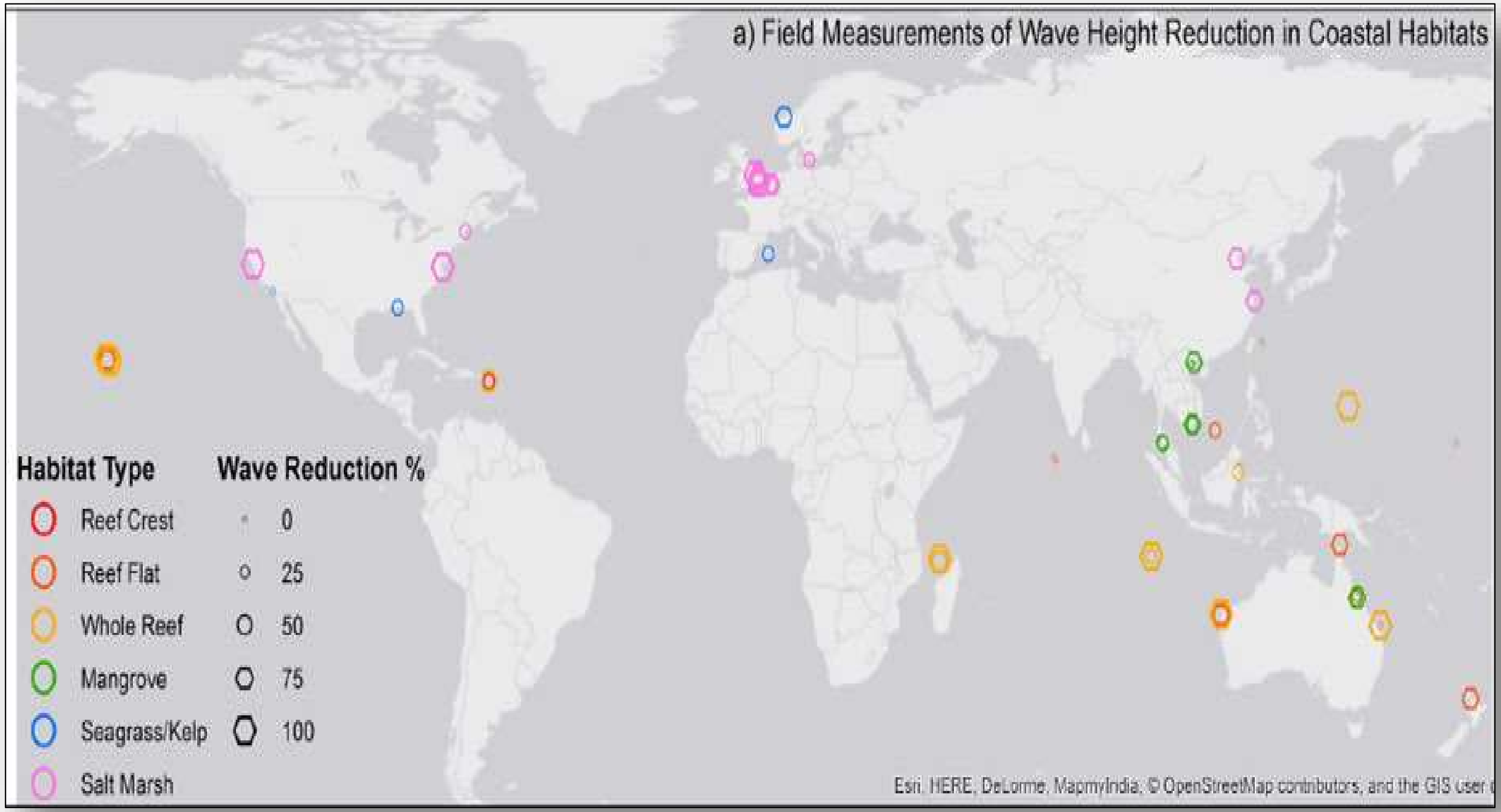
Why use reefs?

- Reefs act as the first line of defense
  - reduce the wave energy and wave-driven coastal flooding (often by >90%; Ferrario et al. 2014)
  - Reduce coastal erosion
  - Shoreline stabilization

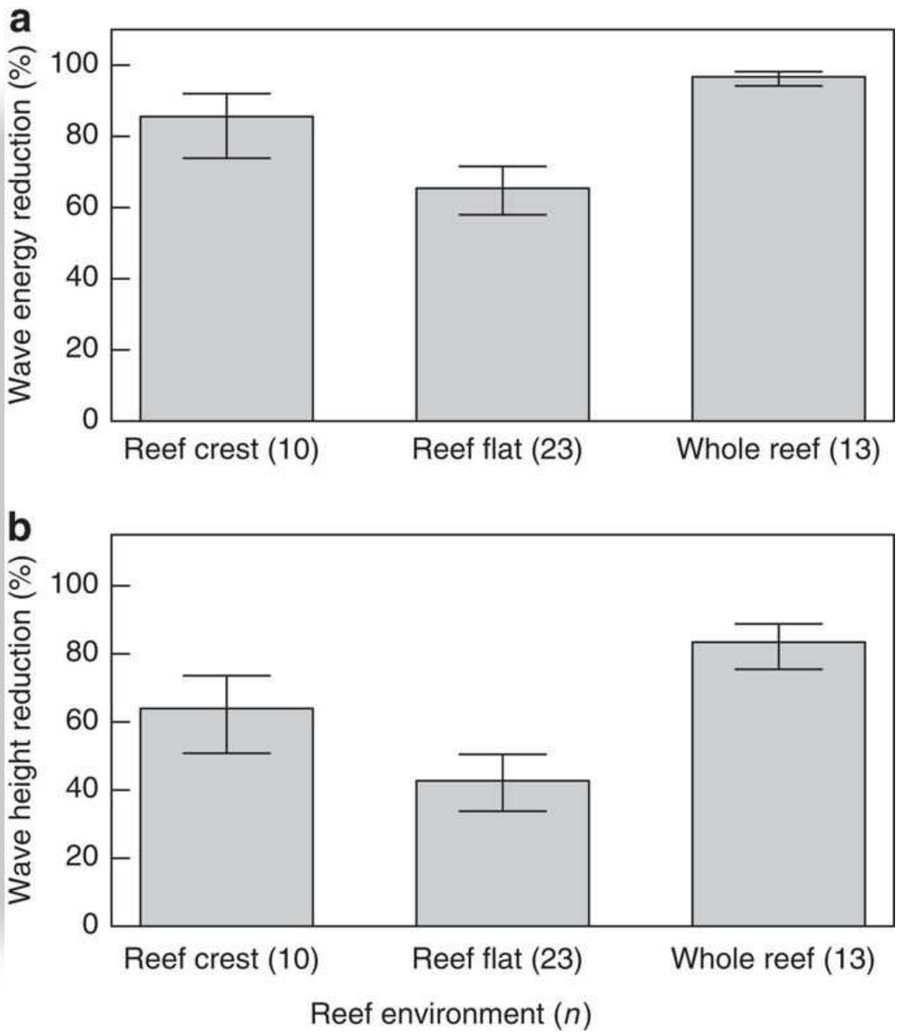
- Co-Benefits
  - food, spawning and nursery grounds for commercially-important fish
  - Improve water quality
  - compounds for medicines
  - tourism
  - fishing, and recreational activities
  - cultural value



Wave Energy and Wave Height Reduction

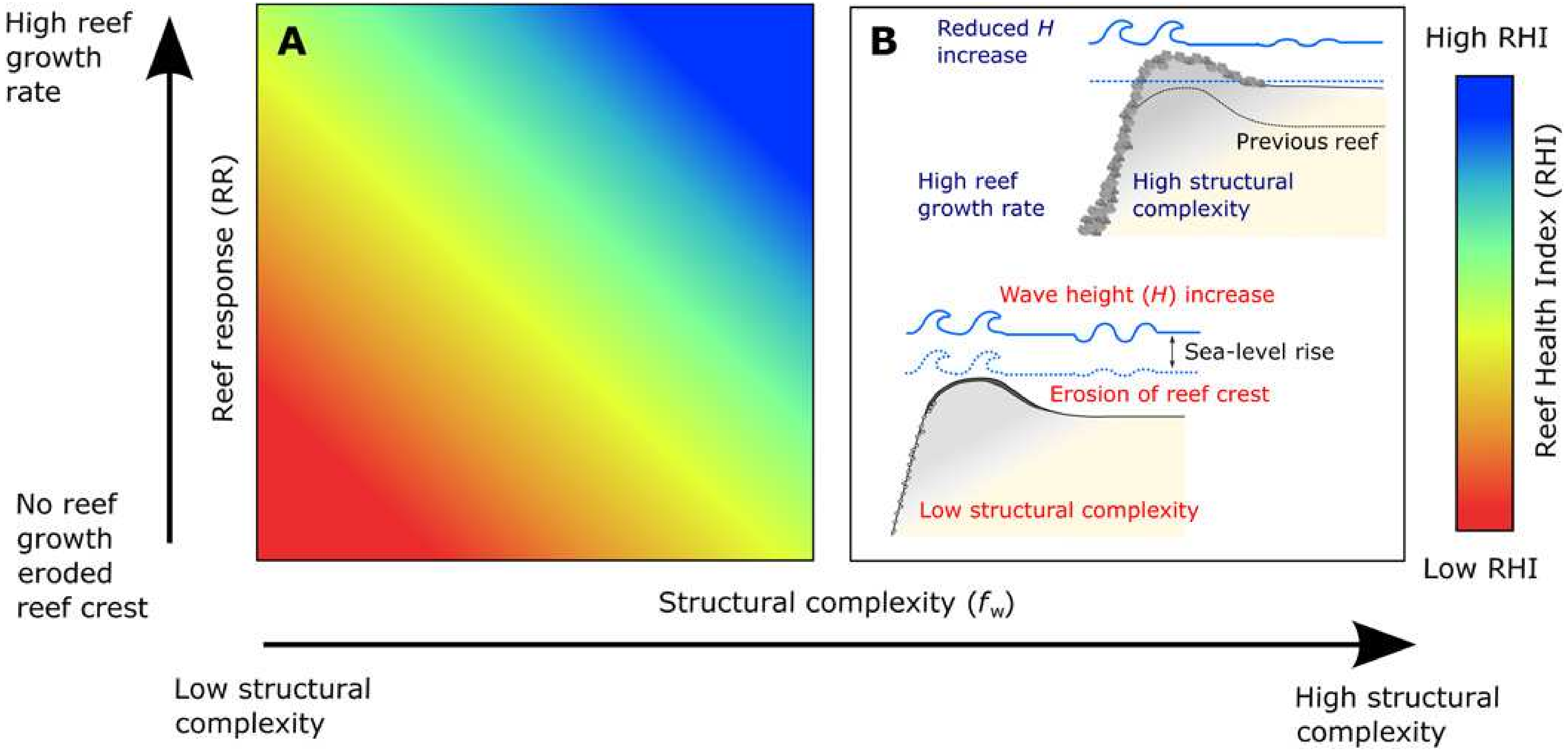


Narayan et al. 2016



Ferrario et al. 2014

Reef Complexity Impacts Wave Height



Harris et al. 2018

How reefs deliver flood and coastal erosion risk reduction

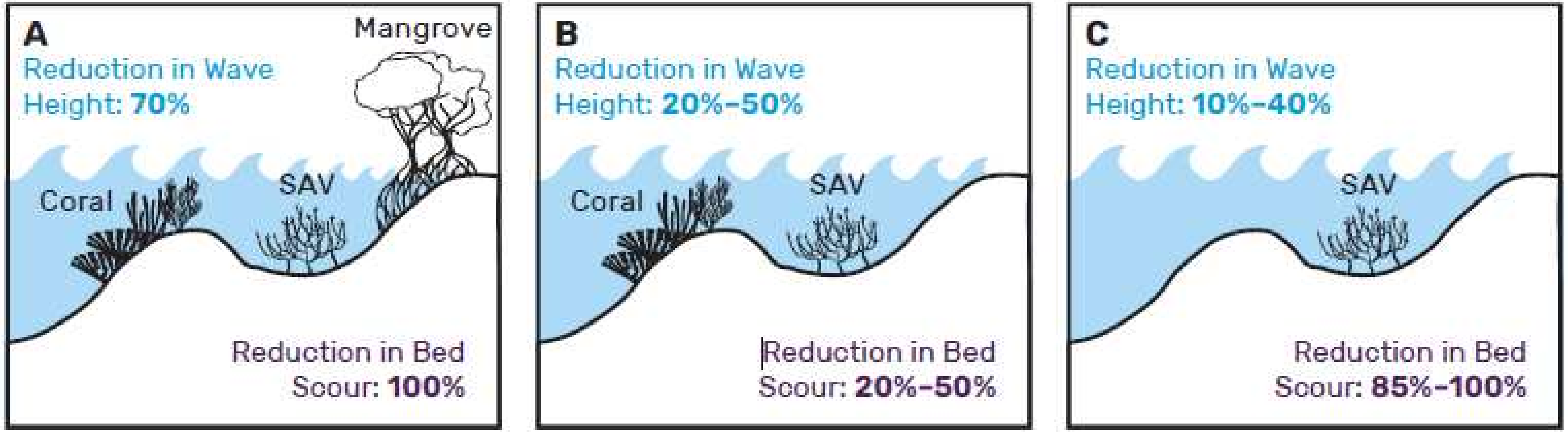
Effects	Performance factors	Potential Co-Benefit	Example
Wave energy dissipation	Elevation relative to water level, proximity to shore, width/height of reef, surface roughness/porosity, coral species (large branching corals vs. smaller weedy corals)	Reduce flood risk, reduce erosion, reduce damage of coastal infrastructure during storms	Fringing coral reefs in the tropical Indo-Pacific and Caribbean
Shoreline creation	Sand production, sand/sediment trapping	Coastal tourism	coral reef islands, coral atolls
Shoreline stabilization	Bathymetric configuration, surf zone, current, and sediment transport patterns	Coastal tourism through beach protection	oyster reefs adjacent to coastlines
Erosion reduction	Ability to reduce/shift wave energy Ability to reduce/shift currents Ability to stabilize shoreline	Reduced damage of coastal infrastructure during storms	Reduction of erosion during tropical cyclones (e.g. Cuttler et al. 2018)

Ways that reefs reduce coastal flooding and erosion

- Reefs are effective at reducing wave-driven coastal flooding
- Wave attenuation by wave breaking and reef roughness
- Reefs can mitigate erosion stabilize shorelines
- Can act synergistically to enhance other NNBF (e.g. wetland growth)

	Reduce erosion	Nuisance Flooding	Short wave attenuation	Reduce force and height of medium waves	Storm surge
Oyster/Bivalve Reef	+	Data gap	+	~	~
Coral Reef	+	Data gap	+	~	~

Benefits of combined NNBF solutions



Note: Strategies that incorporate multiple NNBF measures provide more effective shoreline and storm protection.

Effectiveness of reefs to protect coastlines

- Wave attenuation depends on:
  - ✓Reef dimensions
  - ✓Elevation (esp. of reef crest)
  - ✓Location relative to shore
  - ✓Roughness and porosity
  - ✓Waves + water level conditions
- Reef degradation can reduce ability to protect coastlines

Reef NNBF Project goals and objectives

Objectives should be:

Specific

Measureable

Achievable

Relevant

Timebound

Guiding Principals:

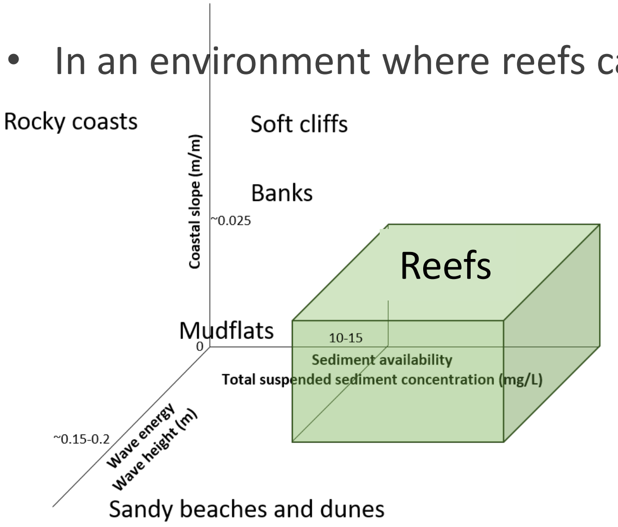
1. Reefs are complex physical systems
2. Reefs are complex ecological systems
3. Reefs are part of a complex socio-economic system
4. Reefs are evolving systems that may require adaptation

Examples of metrics to evaluate objectives

Objective	Metric
Coastal protection performance	Reef depth profile Coral cover (roughness) Wave attenuation Reef width (distance to shore) Angle of reef with dominant wave energy direction Shoreline change (erosion/accretion)
Ecological performance	Coral/oyster cover (richness and diversity) Fisheries production

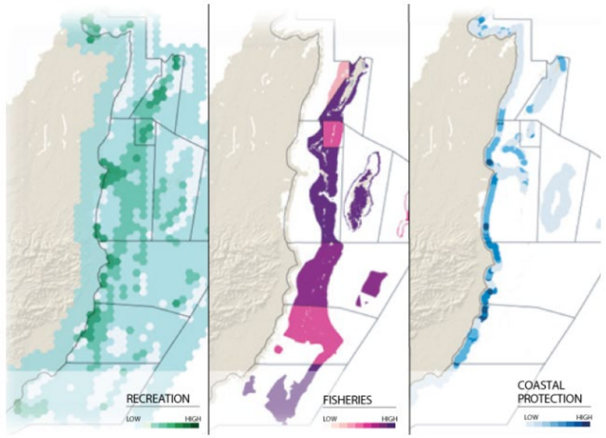
In what context do reefs make sense?

- In an environment where reefs can persist



These boundaries are not rigid.

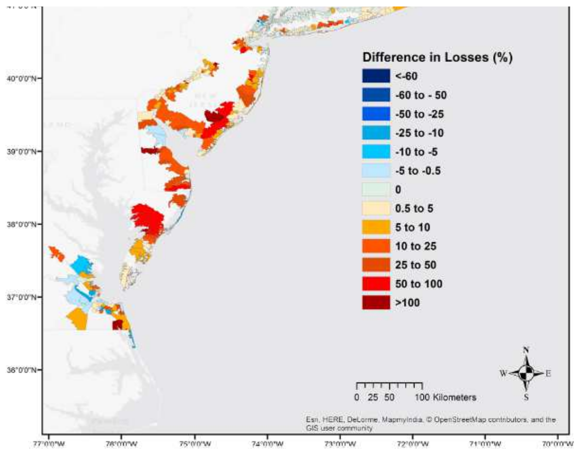
- Where they can provide the desired co-benefits



InVEST documentation

Co-benefits are not uniformly produced at all locations.

- Where they can provide the required engineering performance



Reefs in some areas can reduce erosion but may increase it in others.

from Narayan and Beck 2017

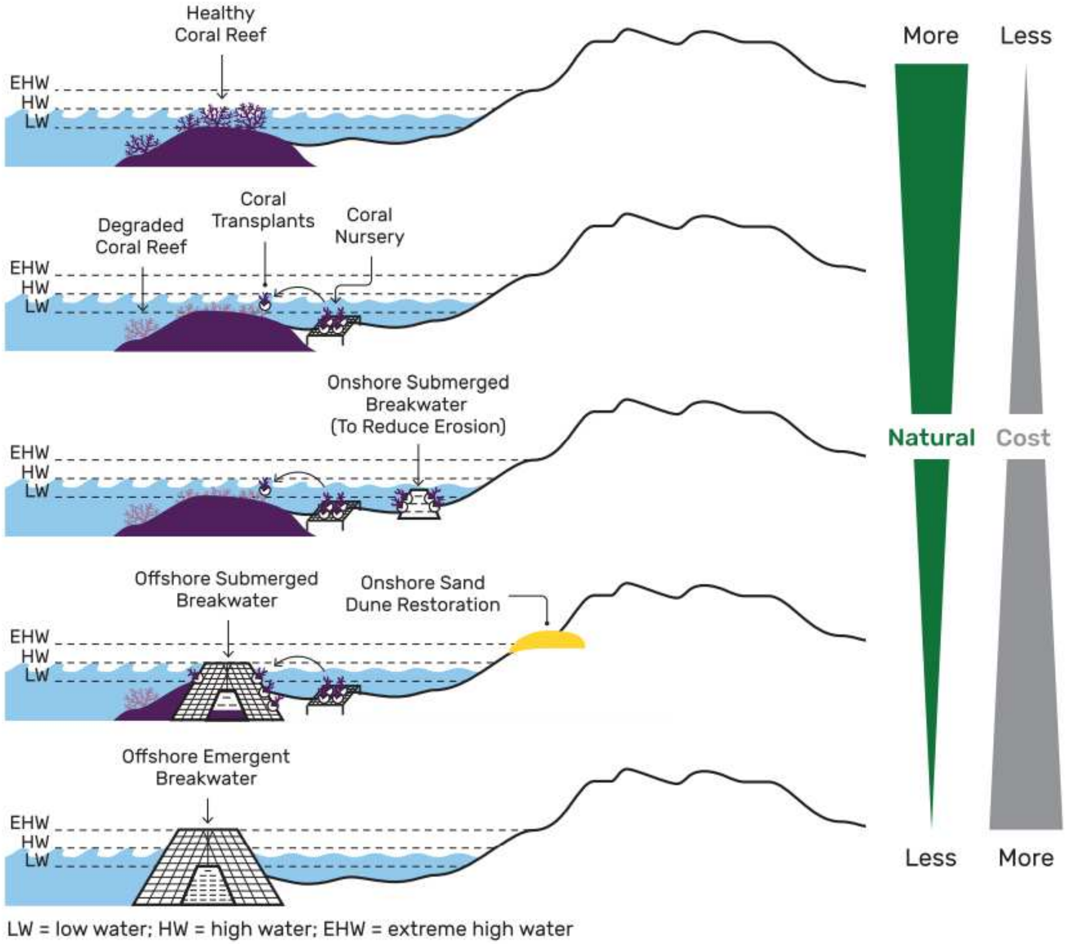
- Where they are accepted

Education, outreach, and guidance are required to ensure reefs are accepted.

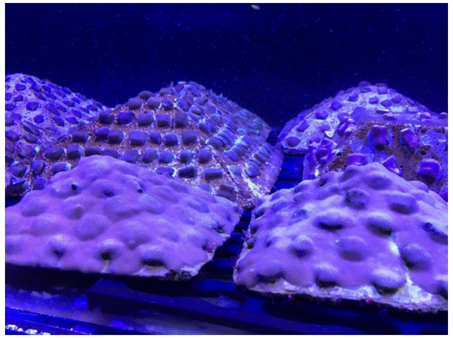
from TNC *Mangroves for Coastal Defence: Guidelines for coastal managers & policy makers*

Designing the reef

- Site selection and problem formulation
- Hydrodynamic performance and engineering design
- Design tools and models
- Ecological performance (designing the living layer)
- Evaluating costs and benefits of different options and stakeholder engagement



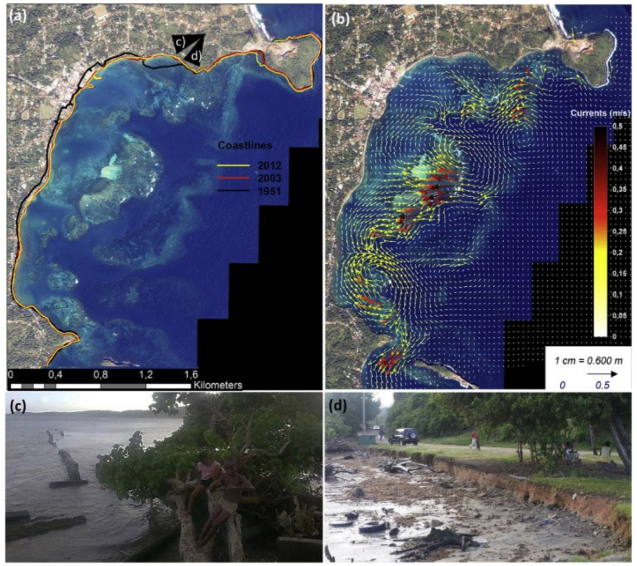
Adapted from Kramer, in World Bank (2016)



Division of Aquatic Resources, Hawaii

General Reef Design steps

Define offshore wave climate and sea levels → Assess coastal hydrodynamics at site → Quantify effects of reef structure on hydrodynamics → Calculate coastal flooding and sediment transport



Temporal resolution

DATA

Purpose

Geographic scale

Spatial resolution

Example Design tools

Spatial scale	Intended use	Representative resolution	Hydrodynamics	Erosion
Large scale assessment	Scoping flooding and erosion risk	~100 m to kms	Regional phase-averaged wave models with empirical wave runup formulations	Empirical beach erosion models
Local scale	Assessing coastal responses to reefs (coastal flooding and erosion mitigation)	~10-100 m	Wave models that account for breaking, refraction and diffraction For example: REFDIF and mild slope, Xbeach, SWASH, Boussinesq	Morphological models Examples: Xbeach
Detailed reef design	Conducting detailed structural design for e.g. artificial reef structures	<1 m	Computational Fluid Dynamics (CFD) models for detailed hydrodynamic load and performance predictions For example: RANS (e.g. OpenFOAM), Smooth Particle Hydrodynamics (SPH)	N/A

Reef construction and monitoring performance

- Choosing materials
- Construction techniques
- Monitoring and adaptive management

Source: Shellfish Reef as Shoreline Protection in the Netherlands; Ysebaert. Wageningen Marine Research.

Construction Considerations

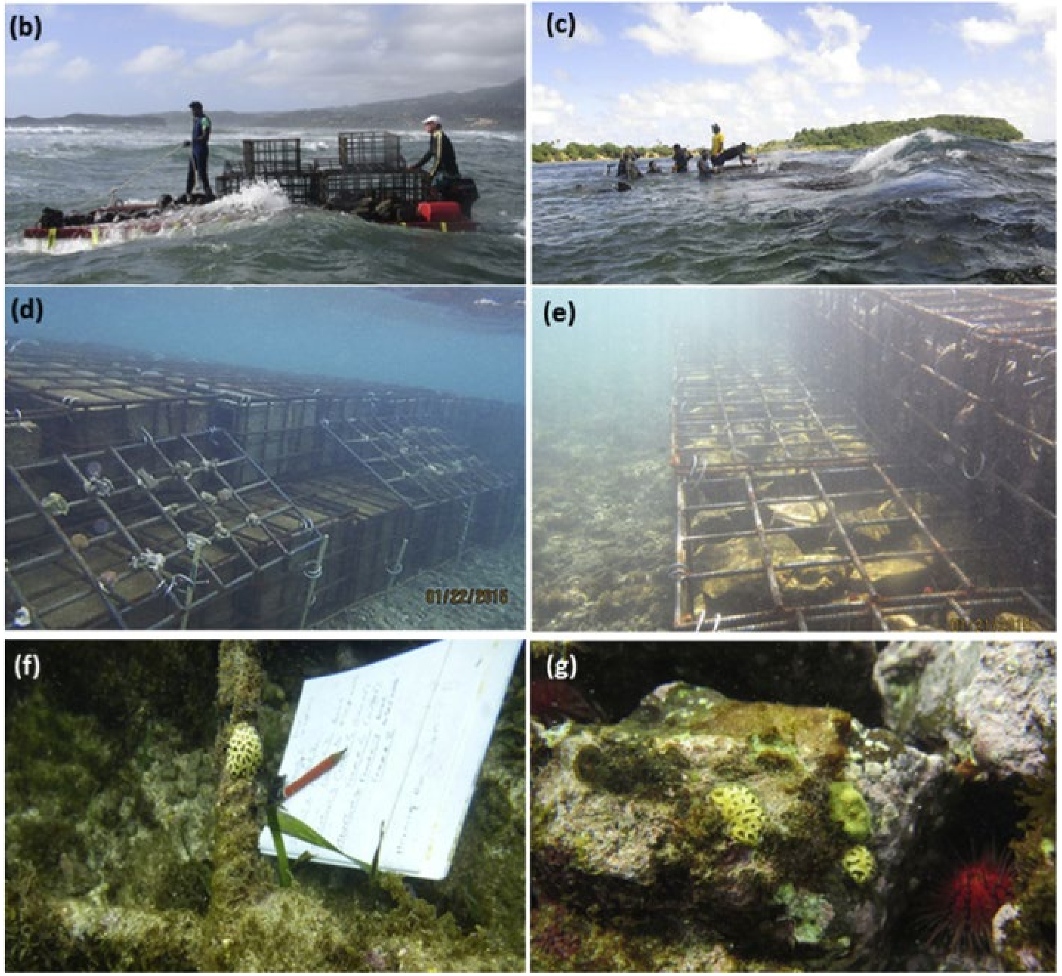
Natural materials

Artificial materials

Reef type

EcoReef

Reef Balls



Steel gabions, Reguero et al. 2018

Monitoring and Maintenance

Geomorphic components

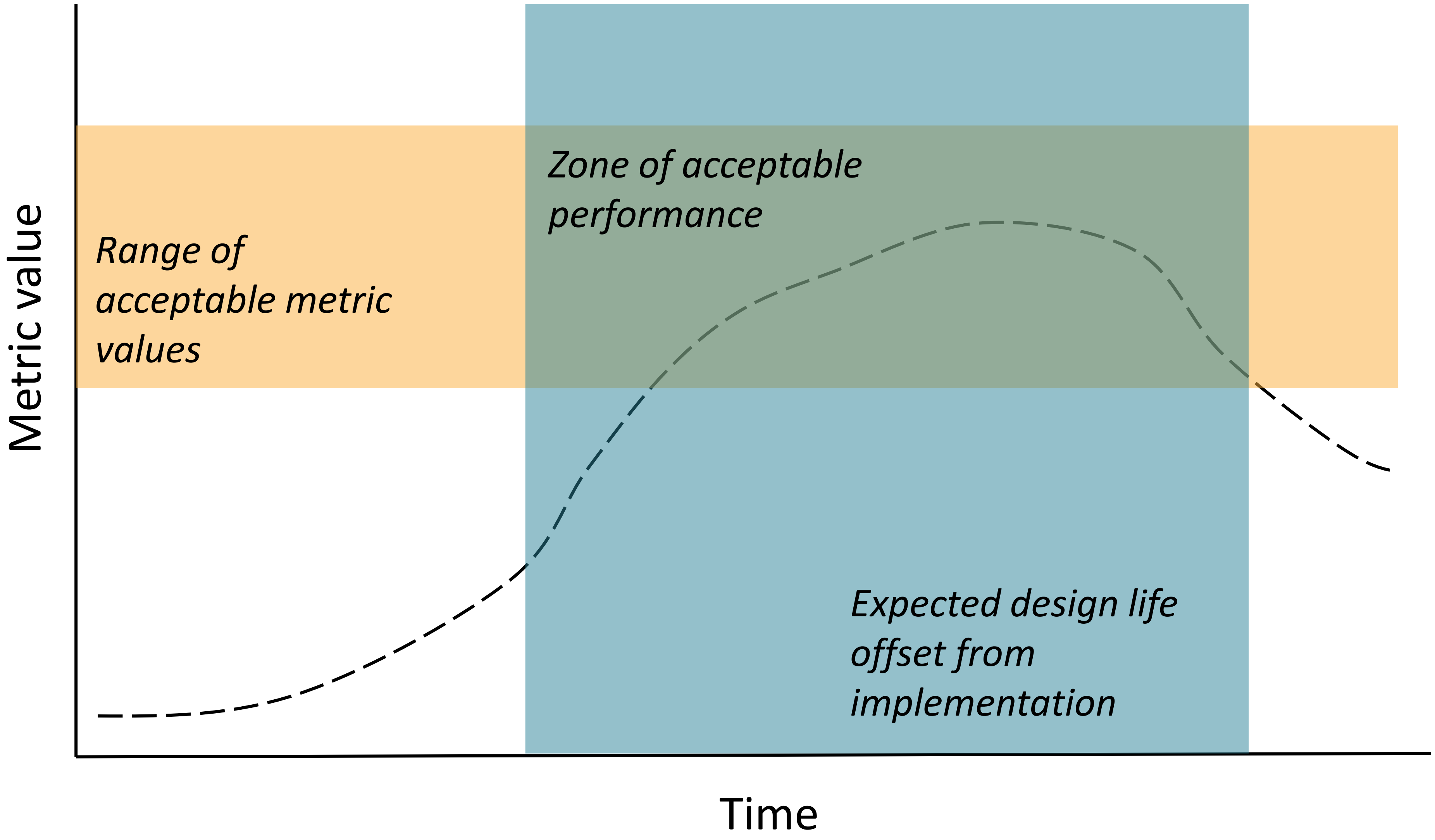
Monitoring Parameter	Metric	Performance Criteria	Frequency of Monitoring
Wave energy before reaching reef and leeward of the reef	Sea-swell wave conditions (heights, periods and directions) Low frequency wave motions Wave setup	Decreased wave frequency Decreased wave energy (-)increased (long waves) surf beat (-)increased low frequency wave resonance reduced swell	Annually in years 1-5 after implementation
Nearshore currents	Mean currents in the lee of reefs	Nearshore current patterns conducive to beach accretion (rather than erosion)	Annually in years 1-5 after implementation
Shoreline creation (sediment accretion)	shoreline loss/gain	should exceed minimum accepted design criteria	
Shoreline erosion		should be stable or decreasing relative to reference sites	

Monitoring and Maintenance

Biological and longevity components

Monitoring Parameter	Metric	Performance Criteria	Frequency of Monitoring
Reef sustainability	reef aerial dimension species survival	increase in spatial footprint water quality parameters in range for species survival	Dependent on reef type and biologic growth rates
Coral reef sustainability	coral density coral size coral survival rate	increase in coral density increase in coral size maintain or exceed design survivorship successful recruitment of new corals disease resistance	Decadal timescales
SAV, mangrove, and marsh enhancement leeward of reef	vegetation cover	increase in vegetation	

Monitoring and adaptation

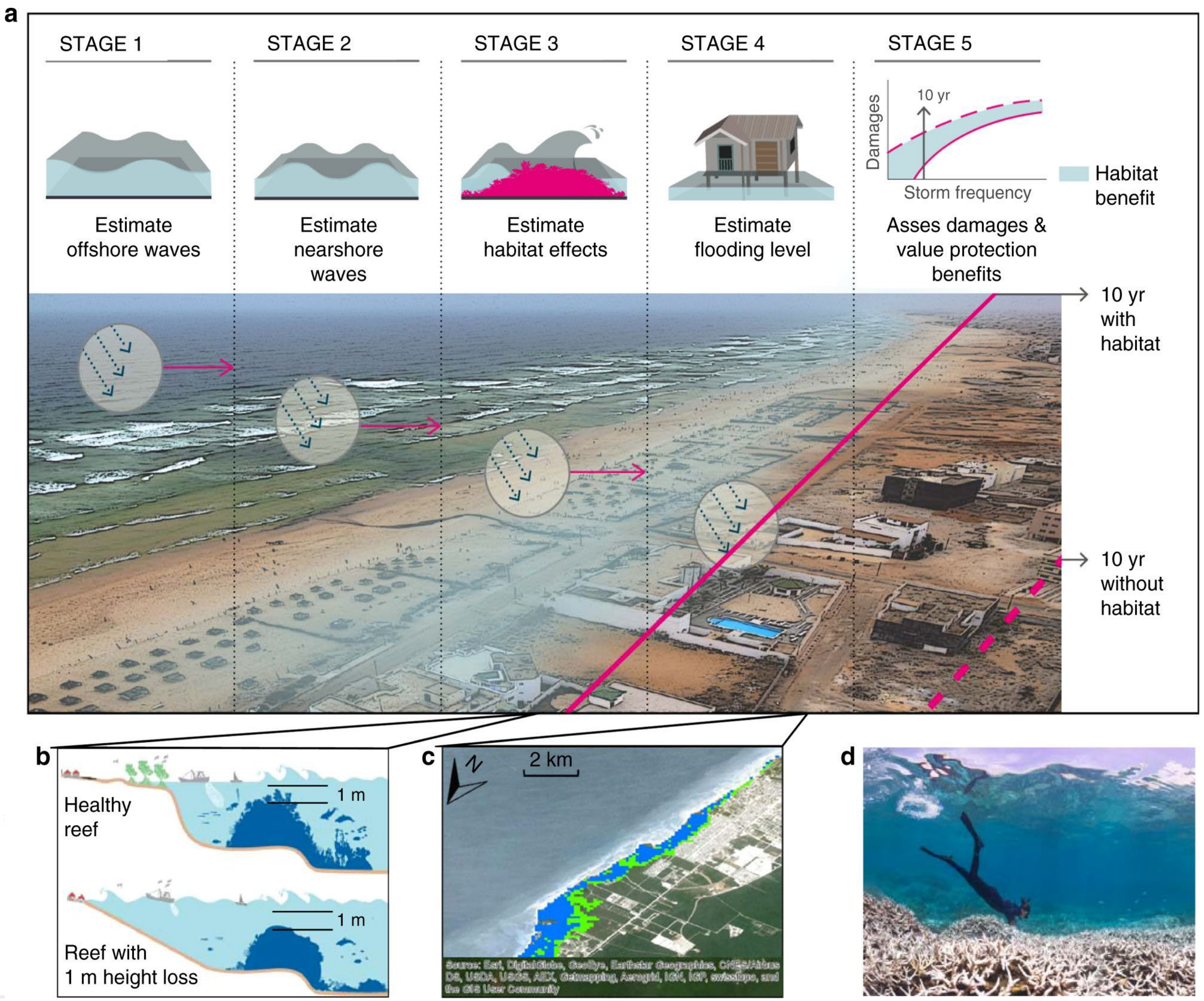


If at any time in design life acceptable performance is not achieved, adaptive actions must be taken.

Costs/Benefits

Mean Building Cost

- Tropical breakwater : $456 to $188,817 per meter (median ~$20K)
- Structural coral reef restoration project: $20 to $155,000 per meter (median $1300)



The global flood protection savings provided by coral reefs

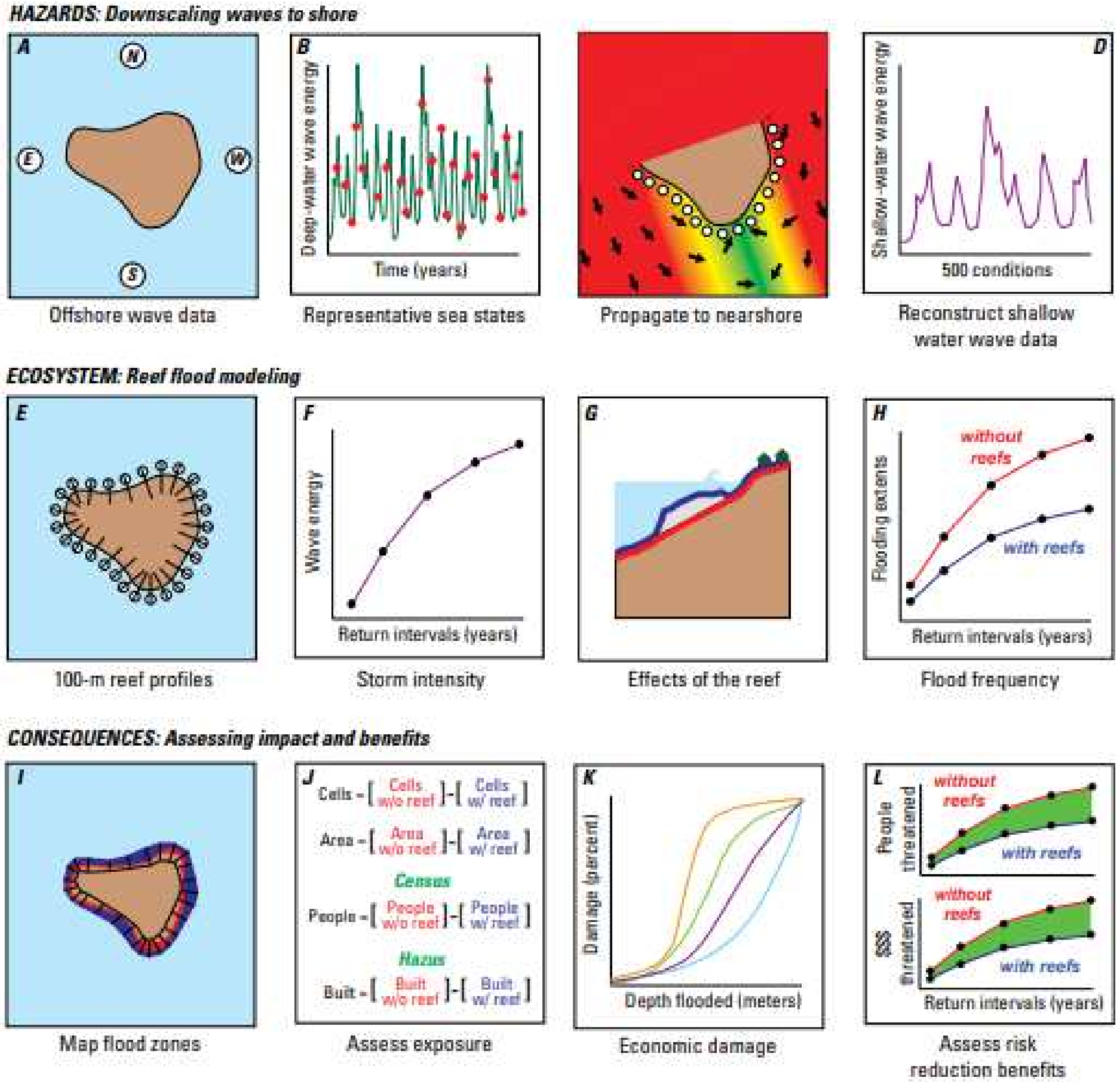
Michael W. Beck, Iñigo J. Losada, Pelayo Menéndez, Borja G. Reguero, Pedro Díaz-Simal & Felipe Fernández

Nature Communications 9, Article number: 2186 (2018) | Download Citation

Cost/Benefits

Annual protection provided by U.S. coral reefs:

- Avoided flooding to more than 18,180 people
- Avoided direct flood damages of more than $825 million (>5,600 buildings)
- Avoided flooding to more than 33 critical infrastructure facilities,
- Avoided indirect damages of more than $699 million in economic activity of individuals and more than $272 million in avoided business interruption.

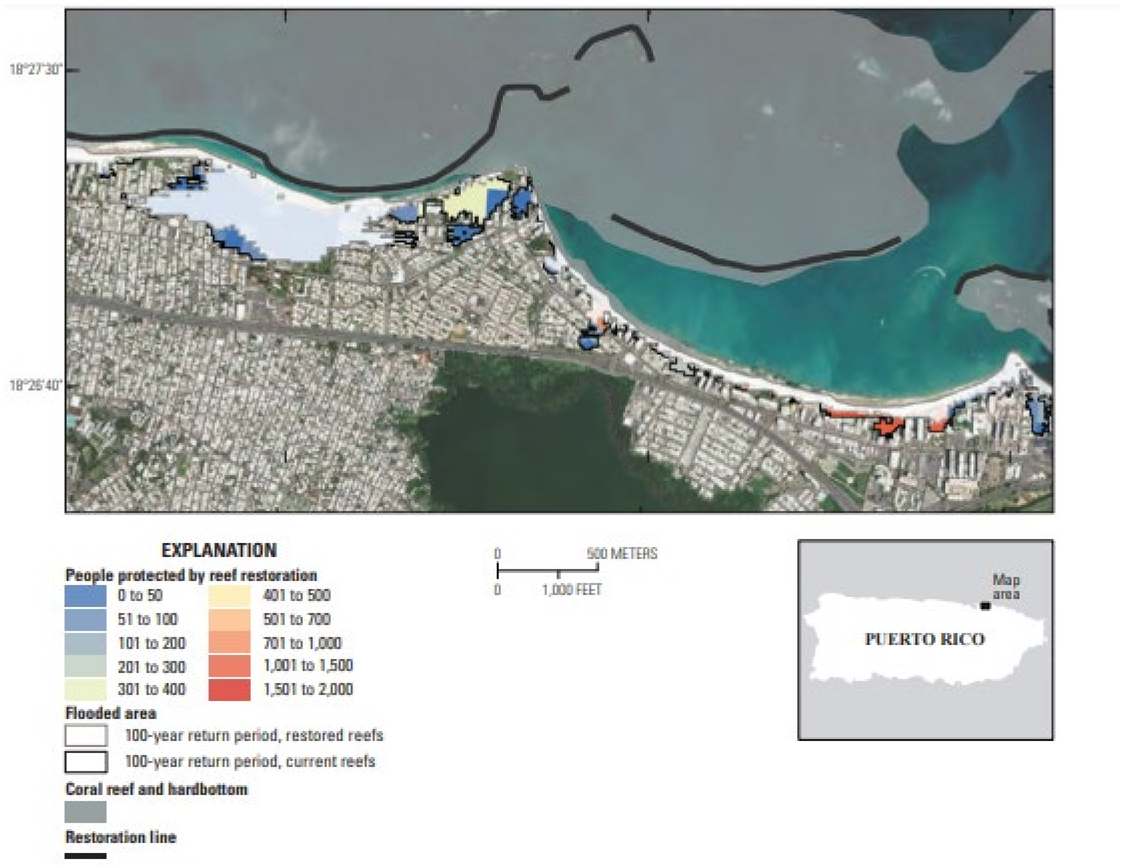


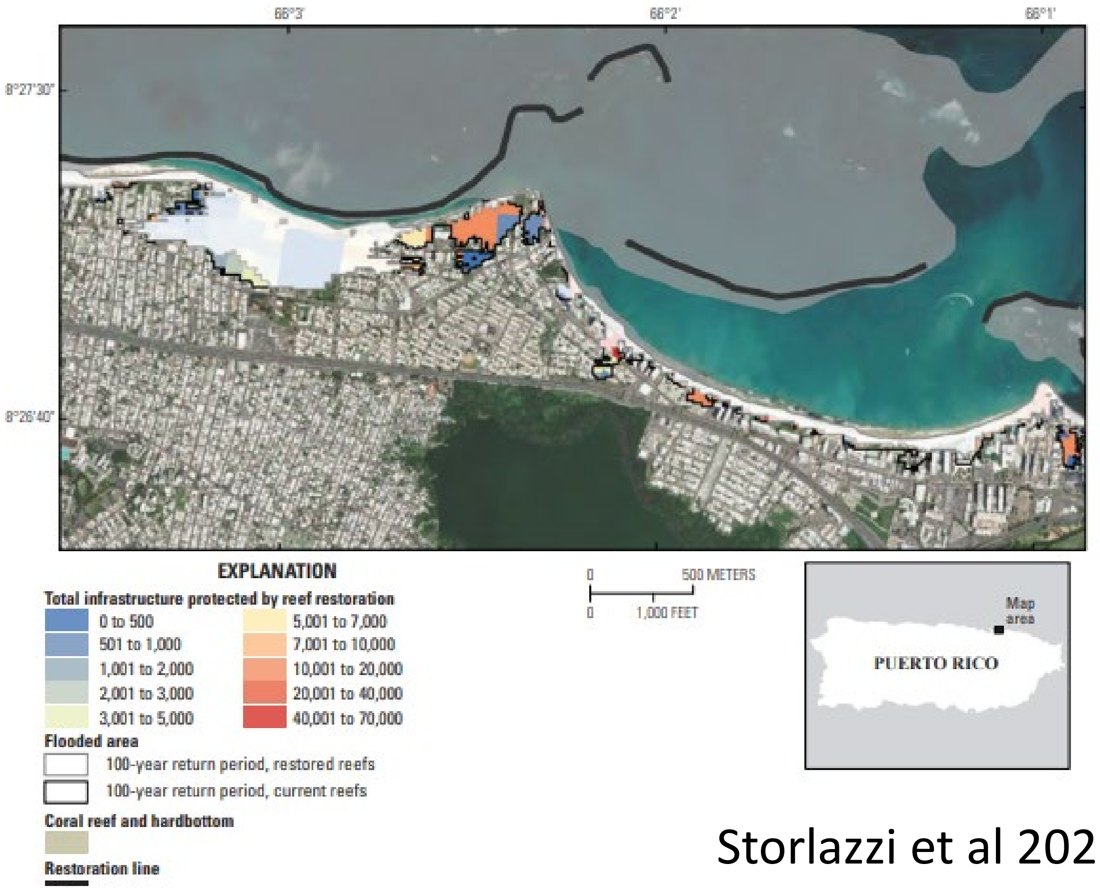
Storlazzi et al 2019

Cost/Benefits

Annual protection provided by U.S. coral reefs off Florida and Puerto Rico more than **9,800 people** and **$859 million**

Reef restoration and NNBF in Florida and Puerto Rico: adds more than **3,100 people** and **$272.9 million**



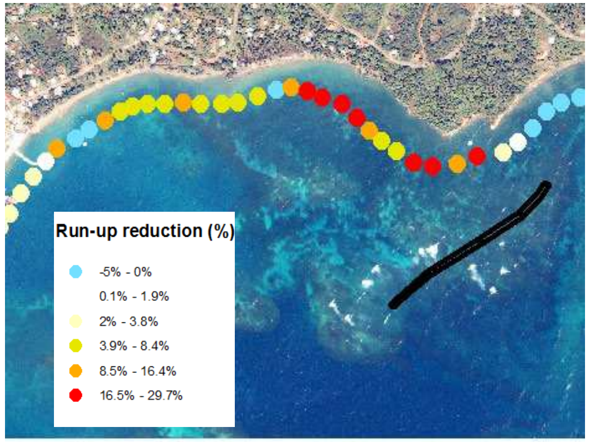


Storlazzi et al 2021

Case study

Hybrid reef in Grenville Bay, Grenada

- Goal: reduce coastal flooding / erosion + support biodiversity
- Community built hybrid reef to raise the degraded reef crest
- Outplanted corals to aid reef establishment
- Post-deployment monitoring



Source: The Nature Conservancy & Borja Reguero

Concluding thoughts

- Natural and nature-based reef structures provide comparable coastal protection to conventional engineered structures
- Reefs provide additional benefits (fisheries, tourism, water quality improvement)
- Unlike engineered structures, natural reefs can be self-sustaining (keep pace with SLR when healthy)

Questions?

EngineeringWithNature.org

Download

- Executive Summary (70 pages)
- International Guidelines on NNBF for Flood Risk Management (1,000 pages)