



Coral reef restoration for coastal protection: Crafting technical and financial solutions

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ABSTRACT

Coastal erosion, aggravated by coral reef mortality is a major issue for Small Island Developing States. Traditionally gray infrastructure, financed by public budgets has been used to combat beach loss. We examined if three Nature-based Solutions (NbS): (i) coral restoration (green) (ii) restoration + limestone (hybrid) and (iii) restoration + 3D printed concrete (hybrid) could deliver positive outcomes for coastal protection and further incentivize cost sharing for reef conservation, with private beneficiaries. We modelled the impact of restoration on wave attenuation at two reefs off Barbados and simulated up-front and maintenance costs over a 25-year period. All solutions provide additionality when compared to gray infrastructure, especially in mitigating against Sea Level Rise. Restoration was the least costly with the highest risk of failure. The hybrid solutions, were less risky than the green as they provided immediate wave attenuation, alongside complementary services such as increased attractiveness due to the presence of reef fish. Their costs were however between +80% and +450% higher than gray solutions. While this might initially deter the use of NbS, blended finance and in some cases, Payments for Ecosystem Services, could provide options for governments and private beneficiaries to share costs, with ultimately greater benefits for themselves and coral reefs.

1. Introduction

Coral reefs are among the most productive and biodiverse ecosystems on the planet, providing a range of Ecosystem Services (ES) on which humanity depends. Unfortunately, reef health is declining on a global scale and increasingly, these ES are also decreasing (Eddy et al., 2021).

Coral reefs play an important role in protecting beaches from erosion by attenuating wave energy (van Zanten et al., 2014; Eliff et al., 2019; Zhao et al., 2019) with estimates of up to 97% wave dissipation being recorded (Ferrario et al., 2014). Additionally, these complex, three dimensional structures, and their calcareous algae, generate sediments that contribute to and maintain beaches (Harney et al., 2000).

Coastal erosion from high energy waves is a particularly onerous issue for Small Island Developing States (SIDS) with their small land-masses and reliance on coastal tourism (Cashman and Nagdee, 2017). Beach loss, flooding and reduced appeal of landscape aesthetics, are

some impacts, which can prompt major investments aimed at mitigation (World Bank, 2016; Rangel-Buitrago et al., 2018).

The two primary, reef related requirements for coastal protection are wave attenuation and growth, therefore actions aimed at improving the coastal protection ecosystem service should be effective at improving both (Brathwaite et al., 2021). Wave attenuation occurs primarily due to structure, as waves break on the reef framework (Monismith et al., 2015; Harris et al., 2018). Reef growth however, requires living corals to accrete, and produce positive carbonate budgets (Guannel et al., 2016; Perry et al., 2018; Ryan et al., 2019). Naturally derived coastal protection, therefore relies on healthy reefs (Sheppard et al., 2005; Quataert et al., 2015; Zhao et al., 2019) and stable populations of reef building corals, particularly the branching *Acropora* spp. and massive *Orbicella* spp. (Bruno et al., 2019; Estrada-Saldivar et al., 2019).

With the deterioration of coral reefs that provide natural defenses (De'ath et al., 2012; Jackson et al., 2014) and the concomitant increase in beach erosion, traditionally, gray infrastructure (e.g. breakwaters, sea

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walls, bulkheads) has been widely used for coastal protection (Liquete et al., 2013; Silver et al., 2019). These structures can be designed to bespoke parameters, aimed at delivering specific results, such as measurable impacts on wave attenuation and risk reduction, immediately. Typically, gray infrastructure is designed to withstand low frequency-high energy situations (e.g. storm surge) while improving wave attenuation for low energy, daily erosion events.

Gray infrastructure is effective when well designed, however many are: (i) expensive to build; (ii) rigid and unable to adapt to changing conditions such as increasing sea levels; (iii) unable to self-maintain and require costly maintenance; (iv) alter the natural character of a site in terms of both character and ecological processes and (v) might not be as conducive to the provision of other ecosystem services of coral reefs such as fisheries habitat and tourism (Fabian et al., 2013; Sutton-Grier et al., 2015). In addition, such infrastructure does little to improve the health of existing coral reefs, which originally provided the service.

There may however be a way of enhancing the ability of natural reefs to attenuate wave energy, using Nature based Solutions (NbS) such as reef restoration strategies. This type of green infrastructure is aimed at adaptively addressing challenges via protection and/or restoration of ecosystems thereby allowing their benefits to flow (Cohen-Shacham et al., 2016). With an overall goal of re-establishing sexually reproducing, genetically diverse populations, that can sustain themselves (Baums et al., 2019) reef restoration can assist in helping to maintain or recover key coral reef ecosystem services (Hein et al., 2020a, 2020b). With predominantly passive management (e.g. Integrated Coastal Zone Management) failing to significantly improve reef health, the addition of active measures, such as restoration has been suggested as a means of assisting the flow of ecosystem services (Ferrario et al., 2014; Roelvink, 2019).

The ability of green infrastructure to grow is especially important with the impending threat of Sea Level Rise (SLR). Sea levels exert major controls on coral growth, as the organisms attempt to maintain their position in the photic zone, by producing calcium carbonate (Dullo, 2005). Rising seas and major reductions of carbonate producers can result in corals “giving up” and drowning (Schlager, 2003). The IPCC Special Report on Global Warming predicts with high certainty, that a temperature increase of 1.5 °C could result in a global mean sea level rise of 0.43 m by 2100 (relative to 1986–2005), causing up to 90% loss of coral (Naueis et al., 2019). While the natural reef framework can be substituted by other rigid structures such as stone, which is often used in the construction of breakwaters (CIRIA, 2007), their ability to continue to provide the coastal protection service will depend on vertical reef accretion (Beetham et al., 2017; Perry et al., 2018).

Reef restoration is a fairly recent intervention, however there is a wide variety of methods described and a large body of peer reviewed literature that details best practices including (Fabian et al., 2013; Bayraktarov et al., 2016, 2019; Rinkevich, 2019). In this study, Boström-Einarsson et al. (2020) was used as our seminal document, as it is the most recent and extensive review reef restoration to date.

In addition to technical considerations, the financing of any intervention is a major consideration. Investment in NbS ought to at least triple in real terms by 2030 if the world is to meet its climate change, biodiversity and land degradation targets (United Nations Environment Programme, 2021). While public funding for NbS is essential, finding ways to unlock private sector financing for marine conservation would reduce the burden on governments (Salamon, 2014) and help close the conservation gap (Bos et al., 2015). Further, such mechanisms incorporate the private sector – that benefits from the service – in improving ecosystem health.

The west coast of the Caribbean Island of Barbados was chosen as the Pilot Site for investigation, due to its history of coastal erosion coupled with strong government interest in implementing interventions (Downstream Strategies, 2015; IHCantabria, 2019). Coastal erosion has been an enduring issue for Barbados, since at least the 1980's, leading to the formation of the Coastal Zone Management Unit (CZMU) in 1982.

Under this Unit and via an International Development Bank (IDB) loan, the Government of Barbados (GOB) spent over USD\$ 20 million to provide shoreline stability via breakwaters and beach nourishment in the Coastal Infrastructure Project between 2002 and 2010. This investment provided a reduction in coastal erosion and additional benefits from aesthetics, recreation and tourism have also been achieved (Banerjee et al., 2018). The work however has not, nor was it designed to improve the health of the coral reefs that originally provided this service. At the same time, coral health in Barbados severely declined due to a combination of local and global factors that include increasing levels of anthropogenic nutrients, unsustainable harvesting of reef fish and warming seas (Irvine et al., 2021).

Barbados is currently in an IMF restructuring programme with goals of reducing government spending, especially in cases where public services provide benefits for private entities. The recommendation has further been made, that the GOB consider “innovative” means of providing incentives for the private sector that would encourage them to take part in environmental activities (Schuhmann, 2019).

This paper therefore seeks to provide such incentive by strengthening the case for NbS as alternatives to fully built (gray) infrastructure for coastal protection and suggesting mechanisms with the private sector to finance the interventions.

In order to meet our objective, we will:

- Identify fringing reefs on the west coast of Barbados that are providing the coastal protection service
- Demonstrate the ability of restored reefs to increase wave attenuation under storm surge and Sea Level Rise (SLR) at these sites
- Discuss possible NbS restoration interventions for coastal protection
- Discuss cost implications and potential financing mechanisms for NbS interventions

2. Descriptions

2.1. Site characterisation – Barbados

Barbados, with a coastline of almost 97 km, is almost entirely surrounded by coral reefs (Fig. 1). The coastal area represents one of the largest economic assets, with approximately 95% of tourism activities (Corral et al., 2016) and more than 70% of hotels (Cashman and Nagdee, 2017). Barbados is a tourism “hub” with this industry contributing 13% directly and 40% indirectly to the GDP (Kemp-Benedict et al., 2020). Tourism relies heavily on the allure of wide beaches (Dharmaratne and Brathwaite, 1998), so the quality of beaches, and by extension coral reefs are of primary significance to this industry. Investments which target increasing the size of beaches are increasingly important (Banerjee et al., 2018).

Technical agencies in Barbados house extensive data sets on coastal processes, as a means to better manage coastal erosion, which has affected the tourism product. The west and south coasts are already heavily engineered, primarily at the expense of the GOB. The west coast has however seen the onset of a potential change in financing, with select west coast hoteliers contributing to funding for coastal engineering preliminary work in 2010. There is therefore a precedent that can build upon to provide a different funding mechanism for shoreline protection projects.

The west coast of Barbados is home to some of the island's best-developed fringing reefs, which typically extend from headlands, slope gently to 10 m depths and extend approximately 300 m from the beach (Stearn et al., 1977). Reef health is measured by a variety of indicators, with hard coral cover being primarily key to the provision of coastal protection (Graham and Nash, 2013; Harris et al., 2018) and so will be used in this paper as the indication of health. Fossil records indicate that *Acropora* spp. were once dominant on fringing reefs, regionally (Macintyre et al., 2007) and in Barbados, primarily colonized reef crests and inner swash zones (Lewis, 1984). A net decrease in hard coral cover on



Fig. 1. Coral reefs around Barbados. Red dot in inset is the island of Barbados (Source CZMU). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

west coast fringing reefs between 2007 and 2017 has been recorded (CERMES, 2018).

Beaches along the west coast of the island are typically coralline or mollusc in origin, narrow (35m max width and steeper in gradient than south east and east coast beaches (55m max width) (Baird, 2016a, 2016b). Average annual erosion rate is between 0.3 and 0.4 m/yr (Baird, 2015a, 2015b) and 20–50% loss of sand supply rates is predicted, if the least optimistic IPCC scenario (RPC8.5) is reached in the absence of mitigation (Baird, 2016a, 2016b).

2.2. Restoration design for coastal protection

From the range of restoration methods presented in the Bostrum et al. (2020) review we pre-selected (i) a green solution - coral gardening and (ii) two hybrid gray-green solutions - artificial reefs with cultivated corals from gardening (hereafter called artificial reefs). These are reported as the more extensively utilized and tested methods, with the greatest records of success at 66%. Coral gardening and artificial reefs comprise 48% and 21% respectively of the restoration studies found globally. The sexual propagation method of larval enhancement for example, while promising, has been used in only 6% of the studies. Direct transplantation, in addition, was discarded due to its requirement of harvesting corals from existing natural colonies (Boström-Einarsson et al., 2020).

Project goals for restoration are (i) reef growth, indicated by positive carbonate budgets (Perry et al., 2013) and (ii) increased wave attenuation (in either short or long terms) indicated by shallow depths. Shallow reef depths do not necessarily result in increased wave attenuation and the actual depth for wave breaking, depends on different factors,

including wave height (Scott et al., 2021). However as much of the critical wave breaking on Barbados west coast reefs in the past occurred in 1m or less (A. Rowe, pers comms, August 8th 2021), this is used as our restoration goal (Fig. 2).

2.2.1. Coral gardening (green solution – NbS1)

Coral gardening is at the foundation of any intervention due to our requirement for growth (Bowden-Kerby, 2001; Shaish et al., 2008; Rinkevich, 2019). It is two-step process with an initial nursery phase where coral recruits reach acceptable sizes, in preparation for the second step in which they are out-planted onto a reef. The core methods for coral gardening are the same, but a variety of techniques exist for growing and out-planting. In the absence of peer-reviewed literature assessing and comparing coral propagation methods in the eastern Caribbean, the method used by Seascope Caribbean (Jamaica) was investigated. This, to our knowledge, is the only eastern Caribbean operation in which corals are commercially grown and out-planted to re-populate reefs for coastal protection (Iberostar Group, 2020). It involves an in-situ nursery framework supporting a proprietary coral-to-nursery and coral-to-substrate combined device. Via this device, the coral nubbin remains in the nursery only for the period required to heal and to maximize its metabolic resources (head-starting), of usually 100days or less (Ross, 2016). This allows rapid throughput and minimal in-nursery investment per planted coral (A. Ross April 10th 2021 pers. comm.).

We chose to focus on *Acropora palmata* as our species of interest due to its: (i) importance as a structural builder on reefs (Graham and Nash, 2013); existing extensive use in restoration (Boström-Einarsson et al., 2020; Hein et al., 2020a, 2020b); fast growth and reproductive strategies adapted to the shallow, high energy environment in which they will be out-planted (Boulon et al., 2005; Roelfsema et al., 2018) and history as wave dampeners on Barbados reefs (Oxenford et al., 2021).

2.2.2. *y*-green hybrid – artificial reef – limestone (NbS2), Natrx™ (NbS3) + coral gardening

The hybrid consists of artificial reefs populated with coral outplants from gardening. As underwater structures that mimic natural reefs physically, and ecologically (Baine, 2001; Goreau and Trench, 2012), they can be used to structurally and functionally restore degraded reefs (Reguero et al., 2018). Further, while decreased wave energy and reef growth are primary goals, the enhancement of the substratum also allows for complementary secondary goals to be achieved, such as improved biodiversity habitat and aesthetics for tourism (Hein et al., 2020a, 2020b).

Wave breaking and friction occur as a result of the artificial reef structure itself, while its ability to maintain distance with the surface and keep pace with expected changes in SLR is dependent on coral growth (Perry et al., 2018); which itself relies on a variety of ecological parameters. Incorporating corals from gardening is therefore a key component of our hybrid solution, and the ability to attract natural coral recruits, highly desirable (Yanovski and Abelson, 2019). Concrete and stone have consistently been identified as appropriate for both wave attenuation and natural coral recruitment (Lukens and Selberg, 2004; Creed and De Paula, 2007; Burt et al., 2009; Foley et al., 2014) and are already in use in Barbados as breakwater material.

We propose for the hybrids (i) limestone as it is a natural material for coral recruitment and is found locally and (ii) concrete in the form of 3D printed concrete modules, with a patented design by Natrx™. They possess large surface areas (for natural recruitment) and internal void spaces to facilitate growth of organisms (Natrx, 2021).

2.3. Dimensions/design

In a real-life scenario, final designs will be made only after extensive modelling and examination of oceanographic conditions such as waves and water levels. The proposals suggested are at a conceptual level only,

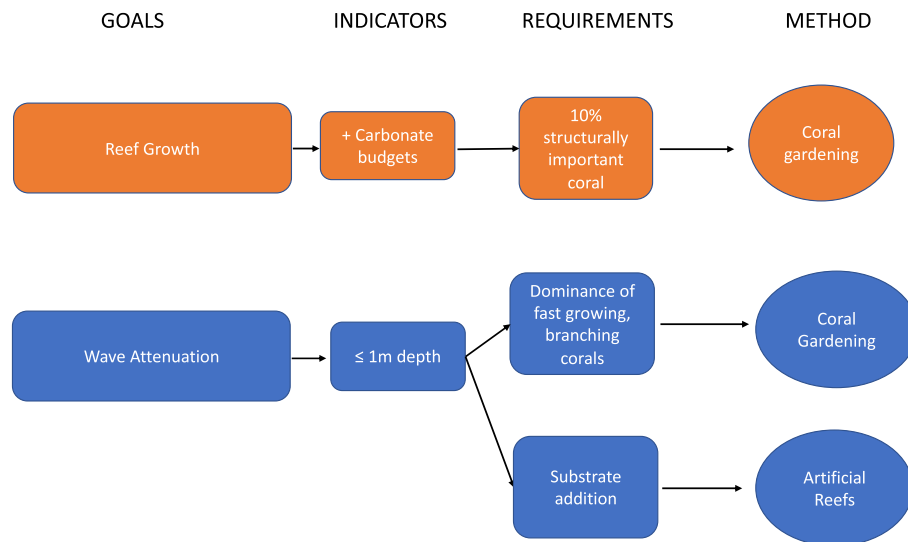


Fig. 2. Restoration project goals, indicators of success, contributing factors and methods for implementation.

and consist of one layer of stone on bare reef substrate.

Dimensions of 30m long and 12m width, equivalent to a 360 sq.m area were based on past breakwater construction work for similar projects in Barbados. These dimensions also fall within those modelled by Roelvink et al. (2021) (Section 3.2). Structures proposed were 1m in height, to be placed in 1.5m depth.

Acropora palmata is reported to grow on average 9–10 cm per year in the Caribbean (Gladfelter, 1984; Shinn et al., 1989; Dullo, 2005). We therefore used a ratio of 1 fragment transplanted per sq.m. for coral gardening, in order to reduce the chances of crowding.

The same dimensions were used for the green solution, as the authors were unable to locate data or guidelines on the reef area dimensions required for replanting in order to achieve similar wave attenuation as artificial breakwaters.

3. Methods

The protective functions of specified reefs were first demonstrated, then areas where restoration would be effective, identified, and the 3 NbS interventions then costed.

3.1. Identification of fringing reefs providing coastal protection

The following steps were taken to identify beaches where reefs could be credited with providing significant protective functions:

1. Google Earth™ maps were used to identify sandy beaches, fronted by natural fringing coral reefs (slope/crest, spur and groove).
2. The Shoreline Change Study (Baird, 2015a, 2015b), a coastal classification system based on 30 years of erosional trends was used to identify sections of these sandy coastlines categorized as Stable Coast (Natural), Accreting Coast (Natural) or Dynamically Stable Coast (Natural).
3. Aerial photos from 2015 in the Shoreline Change Study (Baird, 2015a, 2015b) were used to identify stable/accreting beaches, with convex morphology. This shape is indicative of beaches that are not sheltered from incoming waves, due to being within or part of a bay
4. Beaches that fit the criteria were identified as being protected by reefs that front them.

3.2. Ability of restored reefs to increase wave attenuation under storm surge and sea level rise (SLR) scenarios

3.2.1. Restoration location

The ability of coral restoration to attenuate wave energy depends strongly on the reef profile and location of the work. Roelvink (2019, 2021) determined where restoration would be most effective at reducing wave run up by modelling 4 different wave profiles, which were derived from over 30,000 reef shapes. The reef profile of Fitts Village corresponds to Roelvink's Convex Reef Profile which is described as a gentle transition between the reef flat and fore reef. Sandy Lane corresponds to the Typical Fringing Reef Profile, where there is a defined reef flat with a relatively steep forereef slope (Roelvink, 2019).

We pre-selected 3 potential restoration locations and on each of our reef profiles, on reef flats and crests (Fig. 3). Restoration at such shallow areas has been identified as effective at attenuating wave energy, in the literature (Ferrario et al., 2014; van Zanten et al., 2014; Quataert et al., 2015; Elliff and Silva, 2017) and via past modelling at 2 other west coast reefs in Barbados (Baird, 2017). We then visually compared these locations to those of Roelvink, in order to determine their expected effectiveness at reducing wave energy. The green boxes in Fig. 3 show the locations chosen for further investigation, based on effectiveness and cost.

3.2.2. Impact of restoration

In order to confirm the effectiveness of our chosen restoration location, XBeach non-hydrostatic (XBNH), was used to assess the impacts of coral reef restoration on wave attenuation and the effect of the water level at the shoreline. XBNH is an open-source, process-based, morphodynamic model (Roelvink, 2019), which was applied in one-dimensional mode for both cross-shore transects. The model simulates 2 hours of waves, and the results are used to calculate wave run up and wave heights.

Simulations were carried out for storm surge under existing conditions (Runs 1–3) and in a future with predicted SLR (Runs 4–6). The impact of living coral was determined by friction coefficients. A friction factor of 0.1 represents reefs with essentially no live coral and 75–100% algal turf; 0.16 represents reefs with 25–50% live coral; and 0.2 represents reefs with 75–100% live coral (van Zanten et al., 2014). Wave heights, periods and directions remained the same. The three friction values combined with the two water levels, formed the six different model runs (Table 1). The offshore wave condition used for all model runs was set to replicate a common storm for this area (Baird, 2016a,

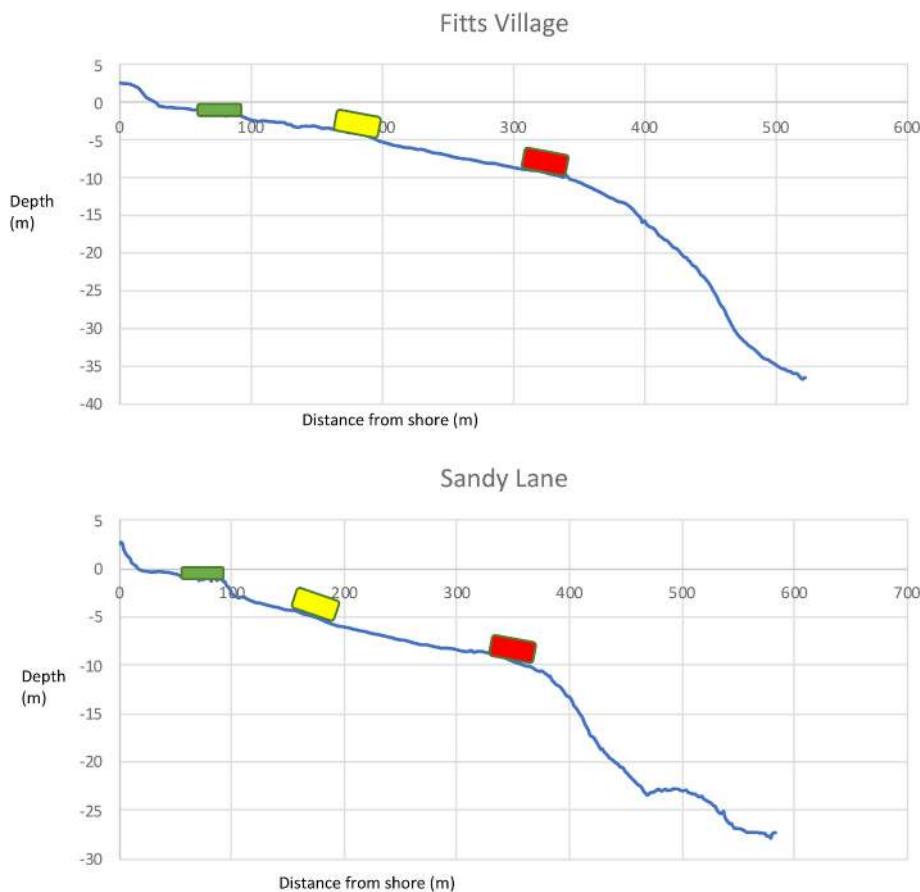


Fig. 3. Cross sectional reef profiles of Fitts Village and Sandy Lane, with a selection of potential restoration locations, represented as boxes. Green boxes represent the proposed options due to their effectiveness and lower costs; yellow boxes represent effective but expensive options and red boxes represent areas where restoration should not be carried out as it could result in greater wave run up at the shoreline. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1

Summary of XBeach input parameters. Runs 1–3 are of existing water levels with increasing friction and runs 4–6 are of increased water levels due to SLR, with increasing friction.

Input Parameters	Present Scenario			SLR Scenario		
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Water level (m + MSL)	0.65	0.65	0.65	0.95	0.95	0.95
Friction (–)	0.1	0.16	0.2	0.1	0.16	0.2
Wave Height (m)	0.7	0.7	0.7	0.7	0.7	0.7
Wave Period (s)	10	10	10	10	10	10
Wave Direction (°N)	345	345	345	345	345	345

2016b). To obtain a direct comparison between the model runs, the exact offshore waves were replicated for all runs.

The model results were then processed to compare the hydrodynamic response of the storm waves over the initial profile to the restored profile (with a reef augmented structure).

The parameters below were assessed:

Wave heights

- Significant wave height at 100 m offshore (H_s 100) - the average height of the highest 1/3 of waves at 100 m offshore.
- Significant wave height at 50 m offshore (H_s 50) - the average height of the highest 1/3 of waves at 50 m offshore.

The reduction in wave heights between 100m and 50m indicates wave transformation moving from offshore to nearshore. The transformation shows the effects of reef structure (including restoration), friction and water level (among others).

3.3. Setup at the shoreline (Setup)

- the increase in mean water level due to breaking waves. This indicates the effect of reef structure on increasing water level set up, which would typically result in greater wave run up and beach erosion. Our aim is to find structures that will reduce set up.

3.4. Two percent exceedance wave runup ($R_2\%$)

- wave run up is the maximum water-level elevation, with respect to mean sea level, measured on the foreshore. If wave run up is greater than beach crest elevation, flooding poses a threat to land. A common measure of wave runup in engineering is the 2% exceedance value ($R_2\%$)

3.5. Swash (IG & HF)

- generally defined as the time-varying location where the ocean meets the beach. It can be broken down into the infragravity (IG) and incident frequency bands (HF), which provide additional information about the processes responsible for the water level at the shoreline. (Stockdon et al., 2006).

The percent difference between restored and unrestored reef was calculated via the following equation:

$$\text{PercentDifference} = \frac{X_{\text{Restoration}} - X_{\text{Initial}}}{X_{\text{Initial}}} \times 100\% \quad (1)$$

4. Cost analysis

We considered the full stream of costs for coral gardening and

artificial reef solutions, as well as the time-value of money for solutions covering an area of 360 sq m.

- (i) for coral gardening, average costs were calculated for growth and outplanting of 360 fragments of *Acropora palmata* (1 fragment per sq m). A survival rate of 66% of the fragments after 2 years of transplant as reported by [Bostrom et al. \(2020\)](#) was used in the calculations. Cost categories include: a. Design & Permits - basic design, ecological surveys and permit applications; b. Material costs (e.g. frames, anchors, drills) c. Construction costs - staff costs (marine biologist, divers), vessel and scuba equipment rental and insurance; d. Annual maintenance and monitoring costs expected during the following 25 years, including staff, transport, replacement materials. An additional 10% of total costs was added as unexpected costs.
- (ii) for artificial reefs & gardening, average costs included: a. Coral gardening as calculated in (i); b. Design & Permits for artificial reefs of same dimensions (12m width x 30 m long) - engineering design, ecological surveys and permit applications. Engineering designs have fixed minimum costs usually sized for larger projects. Following industry standards, we have limited design costs to 10% of the total initial cost of the project to avoid over-weighting this cost category; c. Material costs - quarried limestone and production of the Natrx™ modules (based on direct quotation from the manufacturer); d. Construction costs - including placement, environmental monitoring and engineering observations; e. Annual maintenance and monitoring costs expected during the ensuing 25 years - staff, transport and replacement of select stones after major climate events. Maintenance costs were estimated at 10% of the initial material costs

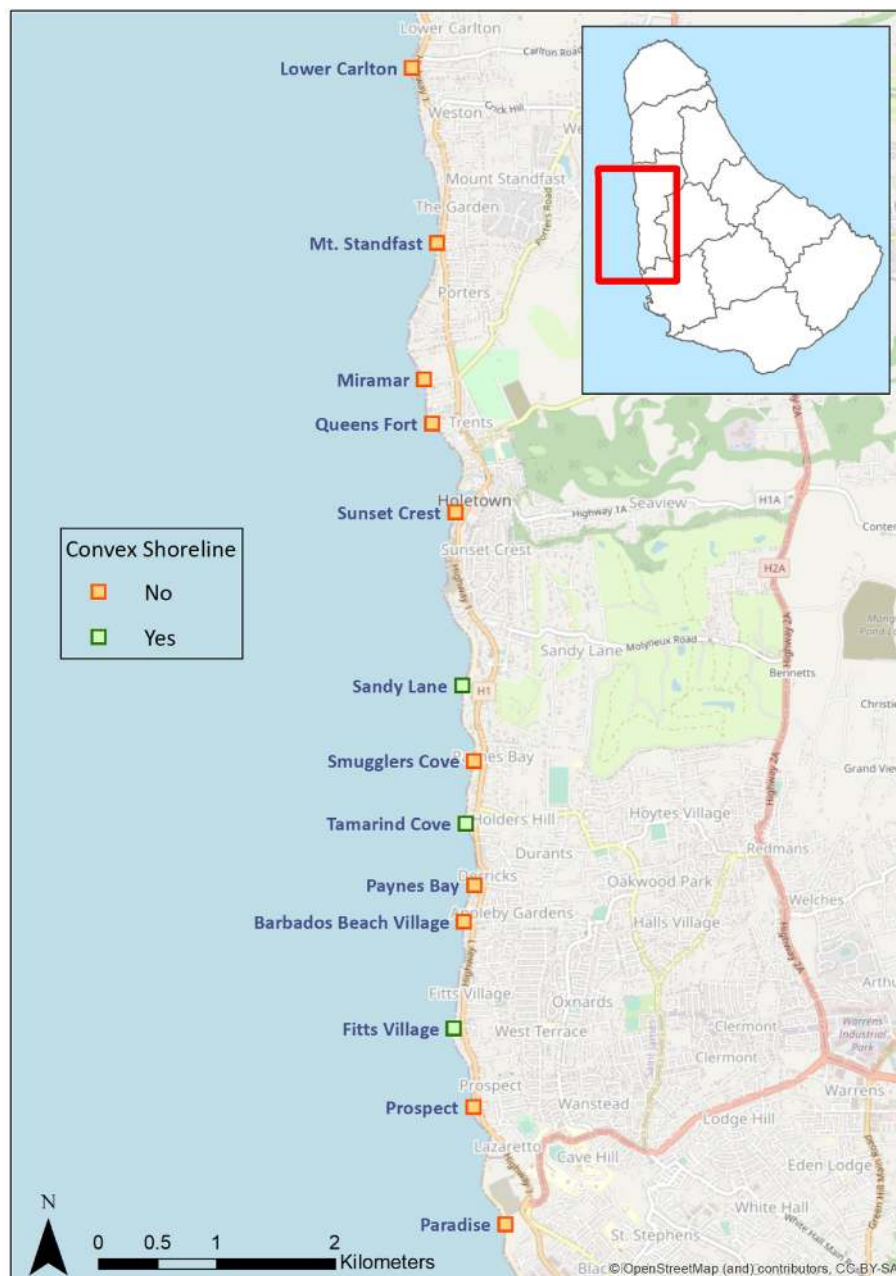


Fig. 4. Fringing reefs fronting beaches going from north to south on the west coast of Barbados, with their status and shoreline shape. Sites with green boxes met the criteria for reefs with protective functions. Sites with orange boxes did not meet the criteria for protective functions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and were annualized evenly over 25 years. Average costs were assessed through expert opinion and review of gray literature.

Costs were calculated on discounted values for a 25y period from the start of the project. This range of 25 years was proposed in similar studies to reflect the ecological responses of ecosystems to the tested scenario (Balmford et al., 2008; Wielgus et al., 2008). A discount rate of 5% was applied in computing present values (Ehrlich, 2008).

4.1. Evaluation for investment potential

In order to discuss the investment potential of the 3 different NbS, we examined: costs, maintenance requirements (over 25 years), timescales (for delivery of coastal protection service), potential negative environmental impacts to the coral reef, and risk of project failure. A gray solution (limestone breakwater) was also presented for comparison.

There are a variety of private sector applicants that would benefit from coastal protection, however, for many SIDS, with the importance of tourism and its strong relationship to coastal protection, one of the most obvious beneficiaries is coastal hoteliers, who desire beach presence and width as a selling point for their businesses. Visitors to Barbados for example, were reported as less inclined to return (for the same price) if the beaches were narrower (Uyarra et al., 2005).

5. Results

5.1. Identification of reefs with protective functions

Thirteen beaches were classified as stable on the west coast of Barbados (Fig. 4). Of these, Sandy Lane, Tamarind Cove and Fitts Village also had convex shorelines and therefore met our criteria for reefs with protective functions. Tamarind Cove and Sandy Lane reefs are of similar size. The decision was taken to focus on Sandy Lane, as this hotel has already explored alternative methods for protecting their shoreline, and therefore in a real life scenario, would be expected to be more amenable to cost sharing.

Both project sites, are characterised by sandy beaches fronted by

fringing reefs, with similar profiles (Fig. 5).

Site beach and reef specifications are summarized in Table 2. The beaches of Fitts Village and Sandy Lane are characteristic of the west coast, varying between 10 and 44m in width. Fringing reefs of 250m (Sandy Lane) and 400m (Fitts Village) width are located between 80 and 100 m from shore, in approximately 2 m of water. Between 2007 and 2017, a statistically significant decline in hard coral abundance was reported at Sandy Lane. At Fitts Village, hard coral abundance fluctuated within the decade, however these differences were not significant (CERMES, 2018). Hard coral cover at Fitts Village (10.1%) in 2017, just meets our reef growth requirement of 10% hard coral cover, with Sandy Lane (6.6%) being slightly below.

5.2. Ability of restored reefs to increase wave attenuation under storm surge and sea level rise (SLR) scenarios

5.2.1. Restoration location

Outputs (Fig. 6) indicate that the locations chosen for restoration at both sites are favourable for improving coastal protection for both current, and expected future increased water levels. Increasing friction, by increasing coral cover for example, (runs 1–3, 4–6), results in decreasing wave runup and wave heights for all the parameters measured. At Sandy Lane for example, H_s wave heights 50m offshore (bottom right graph) decline from 0.57m at friction value 0.1–0.49m at a friction value of 2. The outputs also demonstrate that increasing water levels, (runs 1 vs 4, 2 vs 5 and 3 vs 6) result in wave run up and nearshore wave heights also increasing, thus increasing the probability of coastal erosion. Swash is not included in the outputs, as the other parameters indicate the situation adequately.

5.2.2. Impact of restoration

The percentage difference between restored and unrestored reefs for the 6 runs is shown in Figs. 7 and 8. The bars indicate the percent difference with and without restoration for the parameters shown on the Y axis. The colours indicate positive (green bars) or negative (red bars) impact of restoration.

Almost all of the bars are green, indicating an overall positive benefit

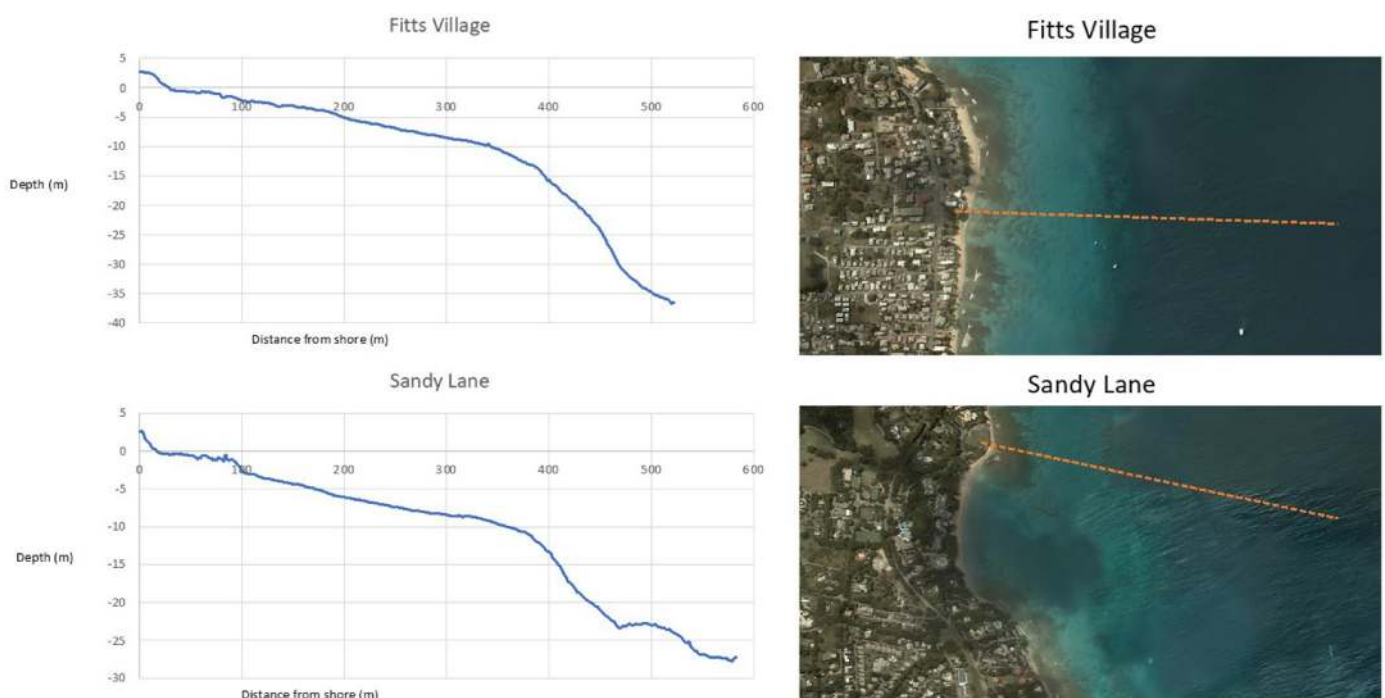


Fig. 5. Aerial photographs of Sandy Lane Bay and Fitts Village fringing reefs and their corresponding cross section profiles. Source CZMU, 2015 - Coastal Zone Management Unit, Coastal Risk Assessment and Management Program, LiDAR Topographic Surveys, 2015

Table 2

Beach characteristics and reef health at Fitts Village and Sandy Lane, Barbados (Sources: CRMP Sediment Transport Study Final Report. June 2016; CRMP – Shoreline Change Study Phase 3 Report. October 2015; CERMES, 2018).

		Fitts Village	Sandy Lane
Reef Health	Year	Mean % hard coral cover	
	2007	8.5	15.2
	2012	6.3	7.5
	2017	10.1	6.6
Beach	Characteristic	Description	
	Length (m)	780	505
	Slope	Flat back beach, steep slope (0.16)	Continuous downward slope from back beach to water (0.13)
	Width (m)	33–44	10 to 20
	Erosion trend	Stable Natural	Stable Natural
	Erosion rate	Net Stable	Net Stable

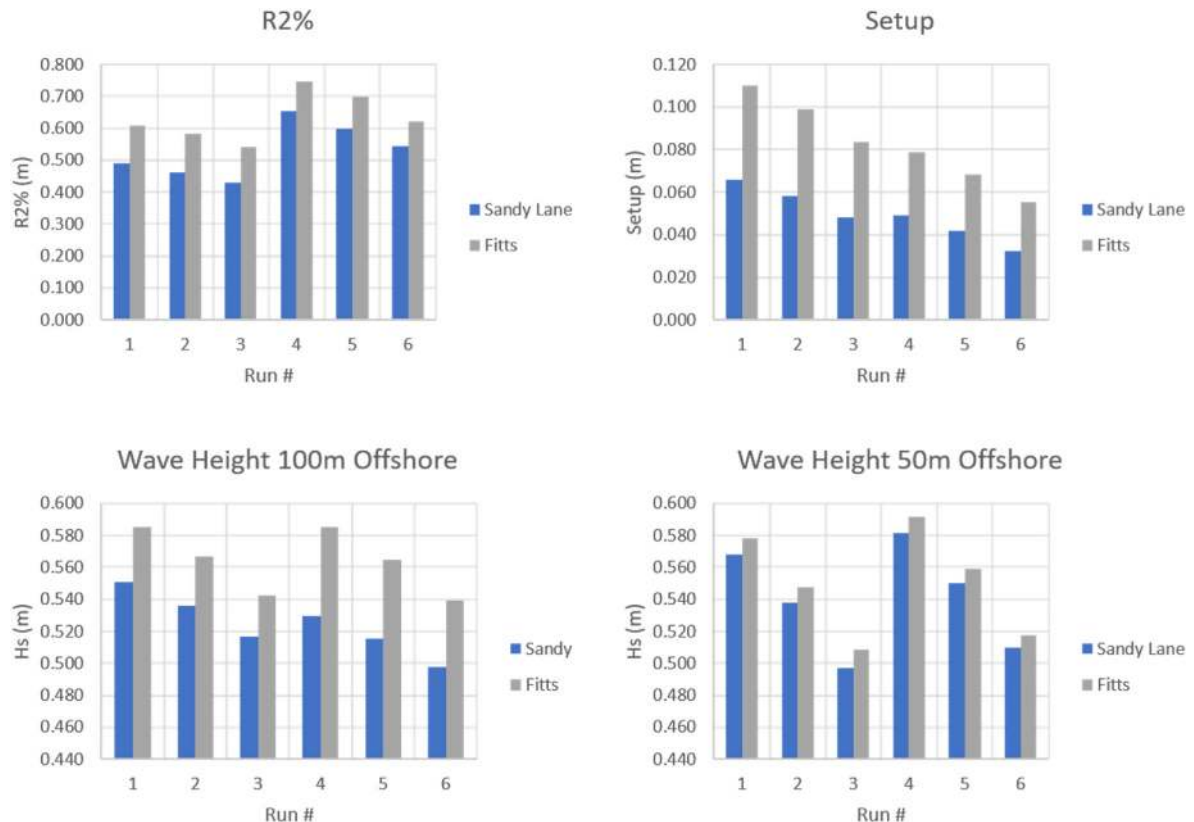


Fig. 6. Outputs of XBeach modelling at Fitts Village and Sandy Lane reefs from Runs 1–6 on: R2% - Two percent exceedance wave runoff– indicates flooding potential; Setup – increase in mean sea levels at the shoreline; Wave height 100m offshore – average height of highest 1/3 of waves at 100 m offshore; Wave height 50m offshore – average height of highest 1/3 of waves at 50 m offshore. Runs 1–3 represent current water levels with increasing friction. Runs 4–6 indicate increased water levels due to future SLR.

of restoration. Red bars are seen for Setup at Sandy Lane and Hs 50 for Fitts Village. This might be due to location of the restoration and reduced water depth, causing wave asymmetry and the wave height increasing before it breaks. The main point for our analysis however, is that the R2% value is always reduced, which means less wave energy reaches the shore.

5.3. Costing of NbS

The standardized costs expected for each solution are summarized in Table 3.

There is a 6-fold difference in cost between the hybrid Natrx™ (highest) and the green coral gardening (lowest), with the limestone structures (hybrid and gray) falling in between these costs. Incorporating the coral gardening component increases total costs of artificial reef solutions by approximately 80% (limestone) and 17% (Natrx™).

When compared to fully gray solutions, the “gray-green” hybrids solutions have an additional cost between +80% and +450%.

5.4. NbS assessment

The NbS and gray infrastructure all have the ability to improve coastal protection with varying technical, ecological and cost-related strengths. NbS, however allow for growth and therefore confer additionality in terms of maintenance and the ability to keep up with SLR over gray solutions (Table 4).

When compared to gray infrastructure, the coral gardening solution has the lowest cost, highest risk and longest time to effectiveness but with positive ecological impacts. The limestone hybrid represents medium cost and risk, providing long term resilience benefits with an increase (+80%) in costs when compared to standalone gray limestone solutions. The Natrx™ hybrid represents the most costly solution, with

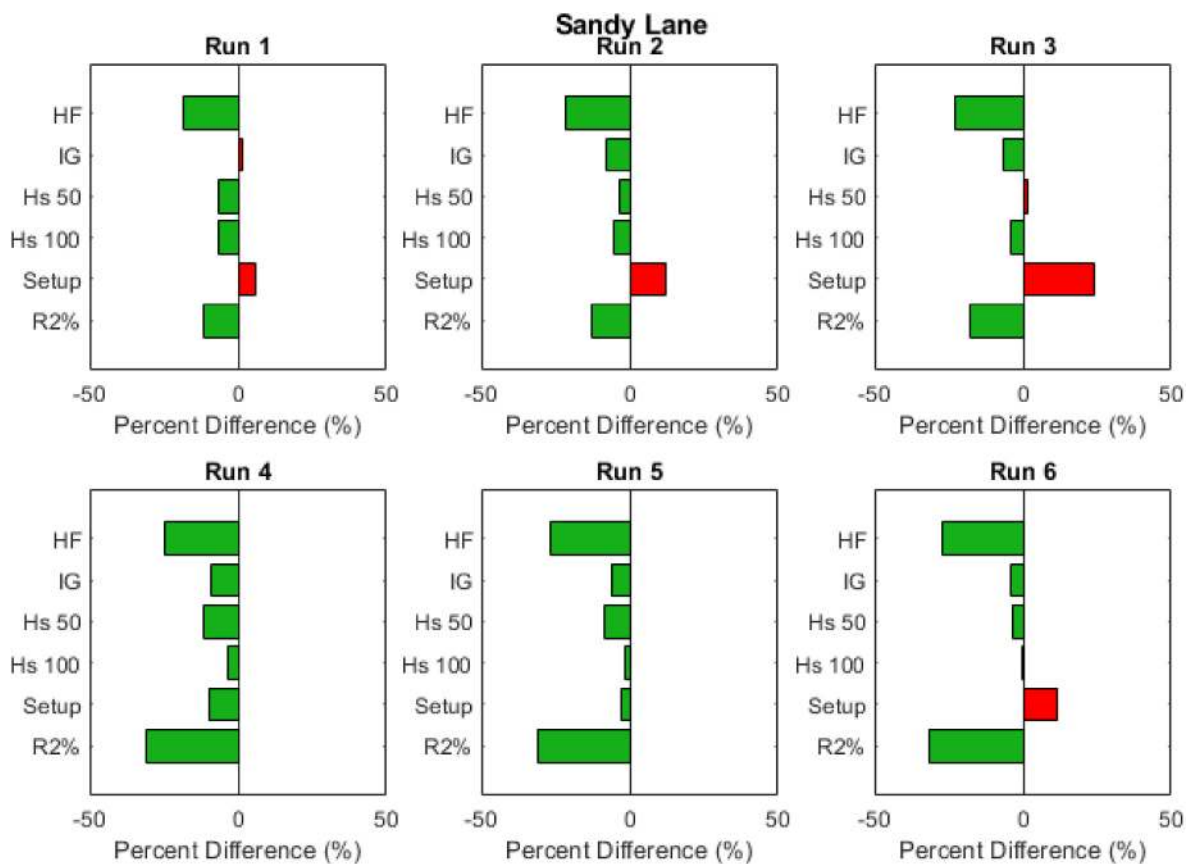


Fig. 7. Graphs demonstrating the percentage difference in the different parameters, between reefs with and without restoration at Sandy Lane. HF – Incident frequency bands; IG – Infragravity bands; Hs 50 – average height of highest 1/3 of waves at 50 m offshore; Hs 100 – average height of highest 1/3 of waves at 100 m offshore; Setup – increase in mean sea levels at the shoreline; R2% – Two percent exceedance wave runup – indicates flooding potential. Green represents that restoration has a positive impact (less wave energy reaching the shore) and red represents a negative impact (greater wave energy reaching the shore). Runs 1–3 represent current water levels with increasing friction. Runs 4–6 indicate increased water levels due to future SLR. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the lowest risk and high ecological benefits. There is a +200% increase in cost when compared to the limestone hybrid and a +450% cost increase when compared to a limestone breakwater.

6. Discussion

Coral reef health is deteriorating and their ability to protect coasts is subsequently declining. We confirmed that some reefs, if restored, can regain their ability to attenuate waves and examined three NbS, as alternatives to gray infrastructure to do so. We determined that the NbS solutions can contribute to coastal protection, provide additional resilience benefits and attract financing that is not accessible for solely gray infrastructure. Depending on the solution chosen, however, and when compared to the gray solution, the NbS can be an initial source of cost reduction, or increase. These findings provide important information for both ecologists, interested in restoration as a means of aiding coastal protection and financiers who are interested in investing in technologies to improve coastal protection.

6.1. Reefs with protective functions

We identified reefs on the west coast of Barbados that provide a coastal protection service. All reefs do not protect beaches and it is important to know which ones have this capacity, especially in cases (such as this) where investment is sought for the specific output of increasing or maintaining coastal protection services and not simply general coral reef conservation. We showed that the fringing reefs at

Fitts Village and Sandy Lane act as wave attenuators and further that restoring them in specific areas, could improve on this service even under storm surge and projected SLR. Currently the Barbados government does not allow construction on the reefs (Baird, 2017), which is sensible if there is live coral to destroy. In cases where reefs are already primarily dead, placement of gray-green infrastructure (hybrids) could increase health of the existing reef, as well as improve its wave attenuating ability. Increasing hard coral cover on the reef, especially our target species *Acropora palmata*, has been shown to greatly improve the recovery potential of reefs (Ortiz et al., 2021) and is therefore beneficial to the reef as a whole, in addition to coastal protection.

6.2. Restoration interventions

While wave dissipation will occur almost immediately with physical contact (on the reef or artificial structure), positive ecological outcomes will take place in the medium to long term timeframes (5–10 years) (Hein et al., 2020a, 2020b) due to the period of time required for coral growth and recovery of ecosystems. *Acropora* spp. for example, one of our key species and one of the fastest corals in the Caribbean, grows at around 10 cm for year, while by comparison, other important reef builders, such *Orbicella* spp. have growth rates of 5–10 mm per year (Dullo, 2005). Coral mortality of outplants is one risk of a fully green solution. Bostrum et al. (2020) for example report that while survival rates of transplanted corals were relatively high at 66%, more than half (60%) of the projects monitored outplants for less than eighteen months. Given the aforementioned length of time it takes corals to grow, and the

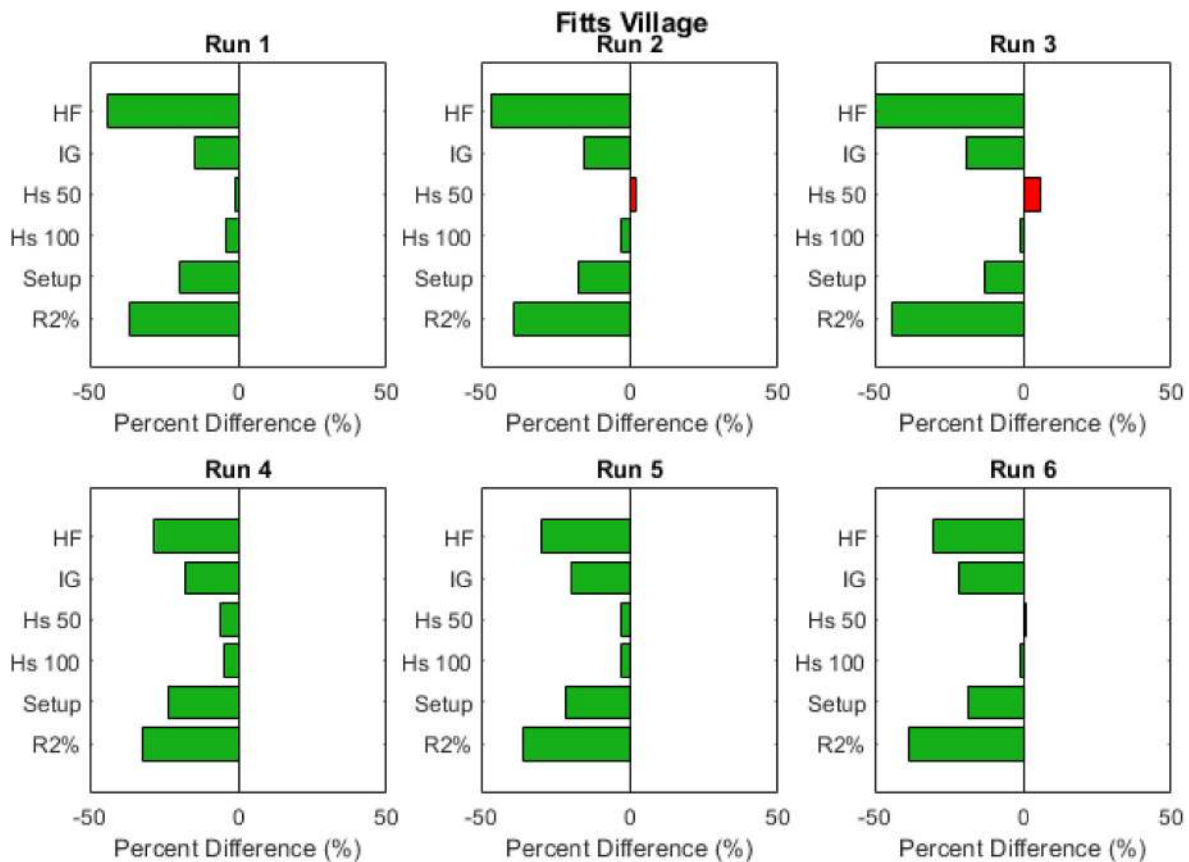


Fig. 8. Graphs demonstrating the percentage difference in the different parameters, between reefs with and without restoration at Fitts Village. HF – Incident frequency bands; IG – Infragravity bands; Hs 50 – average height of highest 1/3 of waves at 50 m offshore; Hs 100 – average height of highest 1/3 of waves at 100 m offshore; Setup – increase in mean sea levels at the shoreline; R2% – Two percent exceedance wave runup– indicates flooding potential. Green represents that restoration has a positive impact (less wave energy reaching the shore) and red represents a negative impact (greater wave energy reaching the shore). Runs 1–3 represent current water levels with increasing friction. Runs 4–6 indicate increased water levels due to future SLR. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3

Costs of green (NbS1), hybrid (NbS2&3) and gray infrastructure.

	US\$ per sq.m						US\$	
	Design & permits	Material	Construction	Total initial project cost	Monitoring cost 25y Present Value	Maintenance cost 25y Present Value	Total project cost 25y Present Value	Total project cost 25y Present Value
NBS 1 Coral Gardening	2	18	26	46	34	57	138	49,500
NBS 2- Limestone + coral gardening	18	133	38	188	54	68	310	111,600
NBS 3 - Natrx + coral gardening	18	748	52	818	54	72	944	339,700
Gray solution - Limestone breakwater	16	115	11	142	19	11	173	62,100

range of stressors already impacting corals, higher levels of mortality are likely over time. Relying solely on coral growth for coastal protection is very risky. However, in cases where the situation is not urgent, in that erosion is not imminent (as at Fitts Village and Sandy Lane) and the hotelier is prepared to assume the risks involved, coral gardening as a stand-alone solution would be suitable.

The hybrid solution is a way of “bridging the gap” between a fully green solution with its long timeframe and risk of failure and a fully gray solution, which is unable to adapt to changing conditions and grow without further intervention. Such eco-engineering strategies have been reported as maximizing storm protection benefits (Gedan et al., 2011); with the greatest chances of success in terms of wave attenuation

(Fabian et al., 2013) as well as providing an opportunity for improvements to reef health (Foley et al., 2014). They also operate at different temporal scales which might also improve outcomes (Rinkevich, 2019). There are many types of artificial reefs that can be utilized for coastal protection (Zepeda-Centeno et al., 2018) and each will require assessment and modelling at each location to ensure its efficacy. Artificial structures used in the hybrids, can also benefit tourism, as divers find their structural complexity attractive (Polak and Shashar, 2013) and are willing to pay for such experiences (Kirkbride-Smith et al., 2016). These solutions, however, in the Barbados case, are substantially higher in cost than gray infrastructure and attractive financing mechanisms will be required for the private sector to consider NbS as alternatives.

Table 4

Evaluation of NbS and Gray Infrastructure in terms of their ability to attenuate waves, ecological impacts, time, risks and costs.

Technical Solution	Green Coral Gardening	Hybrid Artificial Reefs + Coral Gardening		Gray
		Limestone + Coral Gardening	Natrx + Coral Gardening	Limestone breakwater
Functional performance (Ability to attenuate wave energy)	Medium	High	High	High
Reef Growth (Ability to maintain + ve budgets)	High (but conditional on a variety of factors)			Low (relies solely on natural coral recruitment)
Ecological Impact during construction	Low - minimal coastal and marine disruption	High - marine and coastal disruption for placement of material	Medium-low - minimal coastal & marine disruption	High impacts - marine and coastal disruption for placement of material
Time to effectiveness	10 years minimum	Immediate - 5 y minimum for full effectiveness	Immediate - 5 y minimum for full effectiveness	Immediate
Risks of project failure	High risk of complete failure - hurricanes, bleaching, disease events, pollution from land, etc can result in 100% coral mortality, post transplant stress (mortality rate >30%)	Medium risk of complete failure - even with 100% coral mortality, the limestone will still (i) effectively act as a breakwater and reduce wave energy (ii) provide substrate for coral recruitment thus conferring the growth/accretion benefits over time.	Medium risk of complete failure - even with 100% coral mortality, the concrete will still (i) effectively act as a breakwater and reduce wave energy (ii) provide substrate for coral recruitment thus conferring the growth/accretion benefits over time.	Low risk to functional performance (once adequately designed)
Natural Habitat Restoration	Medium - addition of hard coral to the existing reef	High - addition of hard coral and additional substrate to the existing reef	High - addition of hard coral and additional substrate to the existing reef; improved colonization of marine fauna due to void spaces	None
Costs	\$49,500	\$111,600	\$339,700	\$62,100
Costs per sq.m	\$138	\$310	\$944	\$173

6.3. Financing mechanism

There is a role for public, philanthropic and private monies in coral reef conservation finance. The coral reef is a “public good” and ultimately its health is the responsibility of governments, whose funding will always be required but is inadequate (Bos et al., 2015). Grants and philanthropy partially fill the conservation gap and can also be used to leverage public and private investment (Pascal et al., 2021). Delegating some financial responsibility to the private sector is now deemed essential in the quest for achieving sound coral reef conservation (Iyer et al., 2018).

At the level of a single hotel, the costs of coral gardening are below those of the hybrids or gray infrastructure. Given the scant (but encouraging) evidence to support the long-term efficacy of coral gardening techniques and the high risk involved, we suggest catalytic capital for the fully green, coral gardening solution. Grants for example are well suited to this action, as they can be used to implement coral restoration and with effective monitoring, can assist in providing the evidence required for scaling up such a solution. Until there is robust data to support the impact of coral restoration in coastal protection, such catalytic capital is recommended.

Payment for Ecosystem Services (PES) could also be used for coral gardening, once carried out within the confines of a Marine Protected Area (MPA). In this case, hoteliers (Beneficiaries) can make payments to MPA management entities (Providers), for specific conditions such as increasing and/or maintaining the abundance of *Acropora palmata* at 10%, or for a toolbox of conservation action such as fishery effort control and water quality improvement. Broad conservation action reduces the risk of failure to reach conditions (Brathwaite et al., 2021). Further, bundling payments for coastal protection with other ecosystems services such as fisheries and aesthetics, could allow for payments to be made for a range of services, without the complexity of trying to tease out one service from another (Lau, 2013).

Both Limestone and Natrx™ hybrids are more robust than either coral gardening or the breakwater option on its own. The costs are higher, but the risk of project failure is greatly reduced. Blended finance (which combines impact, catalytic and concessional) is recommended.

Impact Investment could allow hotels access to new sources of financing, with more generous requirements than traditional commercial banking. Catalytic funders could provide technical and scientific assistance to the projects to: increase positive impacts, reduce engineering and environmental risk and, provide funding for equipment dedicated to natural resource management activities. Blending impact and catalytic with grant capital is a way of making the investments even more feasible, by reducing the overall amount to be borrowed. Risk is lowered and profitability enhanced thereby being more attractive for private sector participation (Thiele et al., 2020).

There is available funding from the Impact Investment world. At the close of 2018, the industry was worth an estimated US\$502 billion (Core Characteristics of Impact Investing) with investments concentrated on energy (15%), micro-finance (13%) and other financial services (11%). A small but growing proportion of impact investments focus on environmental impacts. However, conservation projects, particularly around marine ecosystems, are not attracting impact capital at the same pace as the rest of the impact investment market, largely due to a shortage of investment-ready projects and the development of future opportunities (Pascal et al., 2021).

Investment in NbS such as coastal restoration projects however respond to several criteria of impact investment: ecological benefits are clearly identified with critical habitat restoration and likely fish biomass recovery; social benefits can be linked to outsourcing of maintenance to local community workers, as well as awareness campaigns with schools and adults in the restoration areas and financially, the operation is bankable with the hotel being the investee and paying-back the financial obligations from its business operations. While the size of individual NbS might be too small for impact investment funds, aggregating a pipeline of projects allows for reduced expense for each hotel and the minimum target to be reached.

Time and uncertainty are other important factors to consider. The time required for interventions to become effective is especially pertinent when involving the private sector (whose incomes depend on outputs) in cost sharing. Added to this, is that significant costs are paid up front, while benefits take a much longer time to manifest (Thiele et al., 2020). At this time, especially with the impact of Covid, the large

increase in cost for the hybrids compared to gray infrastructure could be a great dis-incentive, for hoteliers, even with accessible capital. One way to increase the attractiveness of the hybrid solutions in particular, is via decreasing insurance costs when NbS are used. While each case will differ, insurance premium reductions over a period of 5 years are reported as being able to pay 44% of restoration costs, specifically for hybrids, where risk reduction is assured (Reguero et al., 2020). Bearing in mind however that any improvements to reef health will benefit all, not only hotels, and is ultimately the responsibility of governments, we suggest that the government shares cost with the hoteliers for NbS.

6.4. Study limitations

Our outputs should be considered as illustrative, as we have shown the major steps required and justification for investing in NbS for coastal protection. We have not carried out a full feasibility exercise, which would encompass more intensive modelling and engineering work, nor have we carried out a cost-benefit analysis due to the differing time frames involved in providing the service.

We have proposed very preliminary designs, for the gray-green hybrid solutions, and the “devil is in the details”. Poorly designed and constructed artificial reefs will have similar negative impacts as poorly designed gray infrastructure. There is no attempt here to provide full engineering designs for artificial reefs, but simply identifying appropriate materials and preliminary dimensions such as height and crest width, which will require modelling and testing (with their inherent costs) to determine their efficacy. Our assumption here is that such a structure will be effectively designed with the engineers to provide the required wave attenuation outputs.

The complexity of historical fringing coral reefs cannot be fully replicated by artificial means, due to the diverse interactions between coral morphology and reef hydrodynamics. As a result, the exact mechanisms by which coral colonies attenuate wave energy remain unclear. At present, there are no models that can be referred to in order to determine the size of the area to be replanted, number, positioning, density etc. of each species of coral required, even though the impact of waves on reefs has been extensively measured and numerically modelled (Monismith et al., 2015; Eliff et al., 2019) (Hardy and Young, 1996; Scott et al., 2021). Information from physical models, such as, water flows through adjacent coral canopies, could inform restoration with regards to the quantity and placement of corals. However, while progress is being made, this has proven to be extremely complex (M. Tissier pers comms, May 4th 2021).

We have based our concept of health on live hard coral cover of structural builders. There are however a plethora of interactions, not considered here, that work synergistically to promote reef health. Corals exist in a balance with a variety of organisms, from crustose coralline algae gluing dead coral to form a stable framework and attracting coral larvae, to bioeroders who remove dead coral tissue providing space for new colonization and grazers who remove macroalgae facilitating growth (Dikou, 2010). Our solutions however, provide the building blocks for these processes to occur.

6.5. Future direction

Coral restoration and green engineering (the addition of artificial substrates, designed to mimic and be incorporated within natural systems) are still in their infancy compared to terrestrial ecosystems (Rinkevich, 2021). However exciting innovations such as new seeding approaches for sexual propagation (Chamberland et al., 2017) and accelerated evolution, enhanced tolerance and assisted gene flow (Bay et al., 2019) and eco designs (Mohammed, 2016; Pioch and Léocadie, 2017; Zepeda-Centeno et al., 2018; Hein et al., 2020a, 2020b) are promising signs for increasing success in the future.

The worlds of finance and conservation have not yet successfully merged due to challenges from both sides. These include: a

disconnection between finance and conservation planning, lack of expertise in marine conservation finance, limited baseline data on positive social and environmental impacts, operational risk, hesitancy of NGOs to enter into loan agreements and limited information on expected returns (Pascal et al., 2018). This gap can be bridged by awareness and engagements (on both sides) as well as interdisciplinary collaboration (Bos et al., 2015). The outputs of NbS projects, both successes and failures must be carefully documented and widely shared to increase the knowledge base.

7. Conclusion

In Barbados, the beach asset on the west coast is estimated to be losing BBD\$ 6–8 million annually from erosion linked to SLR (CZMU, 2020). Solutions, such as those suggested in this paper, are actively being sought to improve delivery of the coastal protections service and cost sharing with the private sector. The findings from this study can assist the private sector, in playing a greater role in financing NbS for coastal protection, by (i) providing a framework for determining the protective features of reefs (ii) demonstrating the effectiveness of green and gray-green solutions as alternatives to gray infrastructure and (iii) providing suggestions for mechanisms by which these efforts can be financed. Such information is especially important in SIDS such as Barbados, where flooding and erosion events are already increasing due to coastal storms (Wong et al., 2014). In this age of the Anthropocene, with unprecedented impacts on the coral reefs that buttress their livelihoods, hoteliers in particular, cannot afford to “sit on the sidelines” and must play an active role in conserving/protecting coral reefs. There are many variables that have to be controlled for coral reefs to be able provide this ecosystem service and so it will be important for governments and the private sector to work together on passive and active management interventions in a holistic fashion, in order to give coral reefs their best chance at delivering the coastal protection service. NbS provide significant benefits over time, compared to gray infrastructure, and these must be taken into consideration, even if the upfront costs prove to be higher for some solutions.

Credit author statement

Angelique Brathwaite: Conceptualisation, Writing – original draft & Review: **Ramon Roach:** Software, Visualisation, Writing – review & editing: **Eric Clua:** Project administration, Writing Review: **Nicolas Pascal:** Supervision, Writing Review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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