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Research article

Coral reefs for coastal protection: A new methodological approach and engineering case study in Grenada

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ABSTRACT

Coastal communities in tropical environments are at increasing risk from both environmental degradation and climate change and require urgent local adaptation action. Evidences show coral reefs play a critical role in wave attenuation but relatively little direct connection has been drawn between these effects and impacts on shorelines. Reefs are rarely assessed for their coastal protection service and thus not managed for their infrastructure benefits, while widespread damage and degradation continues. This paper presents a systematic approach to assess the protective role of coral reefs and to examine solutions based on the reef's influence on wave propagation patterns. Portions of the shoreline of Grenville Bay, Grenada, have seen acute shoreline erosion and coastal flooding. This paper (i) analyzes the historical changes in the shoreline and the local marine, (ii) assess the role of coral reefs in shoreline positioning through a shoreline equilibrium model first applied to coral reef environments, and (iii) design and begin implementation of a reef-based solution to reduce erosion and flooding. Coastline changes in the bay over the past 6 decades are analyzed from bathymetry and benthic surveys, historical imagery, historical wave and sea level data and modeling of wave dynamics. The analysis shows that, at present, the healthy and well-developed coral reefs system in the southern bay keeps the shoreline in equilibrium and stable, whereas reef degradation in the northern bay is linked with severe coastal erosion. A comparison of wave energy modeling for past bathymetry indicates that degradation of the coral reefs better explains erosion than changes in climate and historical sea level rise. Using this knowledge on how reefs affect the hydrodynamics, a reef restoration solution is designed and studied to ameliorate the coastal erosion and flooding. A characteristic design provides a modular design that can meet specific engineering, ecological and implementation criteria. Four pilot units were implemented in 2015 and are currently being field-tested. This paper presents one of the few existing examples available to date of a reef restoration project designed and engineered to deliver risk reduction benefits. The case study shows how engineering and ecology can work together in community-based adaptation. Our findings are particularly important for Small Island States on the front lines of climate change, who have the most to gain from protecting and managing coral reefs as coastal infrastructure.

1. Introduction

Shorelines change in a wide range of temporal and spatial scales from both natural and human-induced factors (Stive et al., 2002). Coastal erosion and flooding are major global problems but becoming more acute as climate change converges with coastal development and natural geomorphic changes (Hallegatte et al., 2013; Kron, 2013; Reguero et al., 2015a). For example, over 85% of

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the barrier beaches along the east coast of the United States have experienced erosion during the past century (Zhang et al., 2004), contributing to deteriorate a natural physical defense from flooding. In Hawaii, changes in sea level have been identified as the proximal cause of shoreline erosion (Romine et al., 2013). The risk of flooding and erosion is increasing from sea level rise, subsidence and coastal storms (Aagaard and Sørensen, 2012; Cazenave and Cozannet, 2014; Hinkel et al., 2013; Nicholls and Cazenave, 2010; Rosati et al., 2013; Wong et al., 2014).

Tropical developing nations in general and Small Island States in particular are the most vulnerable to the impacts of climate change due to population concentration in coastal areas, exposure to hazards, limited land space, geographic isolation, scarce freshwater supplies and significant dependence on tourism and fisheries (Kumar and Taylor, 2015; Nurse et al., 2014; Reguero et al., 2015a). They will be the most impacted by enhanced coastal flooding and erosion. For these small island nations, climate adaptation is essential now, regardless of the trajectory of future greenhouse gas emissions (Wong et al., 2014).

Increasing evidence indicates that coastal habitats protect coastal communities and could serve as effective adaptation and risk reduction strategies while also providing other valuable services (Cheong et al., 2013; Spalding et al., 2014; Temmerman et al., 2013). Coral reefs in particular constitute a first line of defense from erosion and flooding through wave attenuation and the production and retention of sand (Elliff and Silva, 2017; Ferrario et al., 2014; Pascal et al., 2016). Fringing natural reef crests function much like low crested breakwaters (Beck and Lange, 2016), dissipating wave energy and protecting the shoreline (Gallop et al., 2014; Rogers et al., 2013; Sheppard et al., 2005). Coral reefs also generate fine coral sand supplying shores with sand generated by physical forces as well as the biota (e.g. Bellwood, 1995).

Specific research exist on how reef parameters and geometry influence the geophysics of wave dynamics and wave energy attenuation (Buckley and Lowe, 2013; Costa et al., 2016; Lowe et al., 2010; Monismith, 2007; Monismith et al., 2013; Quataert et al., 2015; Torres-Freyermuth et al., 2012). Live coral provide the reef with shallower geometrical complexity and more surface roughness that dissipate wave energy through friction and wave breaking (Quataert et al., 2015). Correspondingly, coral mortality increase the wave energy reaching shores as the reef presents less friction to waves and the removal of the coral skeletons increases the depth of water over the reef flat (Sheppard et al., 2005).

However, direct knowledge on how coral reefs prevent coastal impacts such as erosion and flooding is scarcer. This paper investigates a possible direct link between reef condition and coastal protection. Only a few direct studies draw causality between coral reefs and shoreline stability (Frihy et al., 2004; Ruiz de Alegria-Arzaburu et al., 2013). Studies in the Maldives, Red Sea, Cancun (Mexico) and Bali (Indonesia) show that factors like coastal development, reef degradation and artificial defenses are related but causality is difficult to establish (Ferrario et al., 2014). This is partly because changes in coral reefs modify wave energy propagation, and in turn currents and sediment transport, in complex spatial ways beyond wave attenuation (e.g. Monismith, 2007). Furthermore, in many communities across small island nations other factors such as sand and coral mined for their use in construction further destabilizes the shoreline and damages the reefs through sedimentation, driving a perverse cycle. Linking coral reefs condition to coastal impacts has therefore been challenging given the multiple factors at play, the complexity of the coastal processes involved, and the lack of historical observations and data.

This study also presents an innovative project to use reefs in climate adaptation for both risk reduction and conservation. There is an urgent need of conservation and robust local action to tackle stressors, threats of climate change and to increase the resiliency of coral reefs (Bellwood et al., 2004; McGowan et al., 2016; Rinkevich, 2015, 2008). Degraded reefs can be structurally and functionally restored using both biological and physical techniques, including the use of artificial reefs. Artificial reefs are a combination of a submerged structure and natural reefs (Jaap, 2000); as submerged breakwaters, they mimic the protection and ecological benefits of a natural reef (Goreau and Trench, 2012; Pilarczyk, 2003) and exist in several forms and materials (Carlisle and Ebert, 1964). Artificial reefs have been used to favor conditions for diving, swimming and surfing, as wells as protecting beach areas for tourism and other recreational purposes (Black, 2001; Ranasinghe and Turner, 2006; Scarfe et al., 2009). Artificial reefs also serve as shelter and habitat for algae and fish, thus increasing the ecosystem resilience and marine biodiversity (Pickering et al., 1999). However, they have rarely been designed for coastal protection specifically at a scale comparable to traditional coastal structures and in a challenging energetic environment similar to natural conditions. Many questions remain on how to design and implement these projects (Narayan et al., 2016; Saleh and Weinstein, 2016). Despite existing favorable momentum for nature-based risk reduction, examples of reefs designed and engineered as natural infrastructure are practically inexistent.

This paper contributes to addressing these gaps by directly linking coral reefs with shoreline protection and outlining how reefs can be used as a tool for climate adaptation. First historical changes in coastal processes and the potential role that coral reef system have played on coastal impacts are examined in a Bay in the Caribbean, suggesting a direct link between coral reefs and shoreline stability in the Bay. Secondly, the design and field-test of an artificial reef aimed at providing joint benefits in risk reduction and conservation is outlined.

2. Field site description

Grenville is a fishing community located at the water's edge in the country of Grenada (Fig. 1). Adapting to existing coastal impacts is an immediate priority for the country emphasized in the National Adaptation Plan (Charles, 2000). The shoreline has been eroding in many parts of the country and coastal ecosystems degraded (Charles, 2000). The Intergovernmental Panel on Climate Change highlights the devastation wreaked on Grenada by 2004's Hurricane Ivan as “a powerful illustration of the reality of small-island vulnerability” (Box 16.3 in Mimura et al., 2007). Ivan, a category 3 hurricane, struck Grenada killing 28 people and causing damage of US$ 800 million, twice the nation's gross domestic product. As in other Small Island States, climate change adds further threats and stress to these coastal communities rendering the need to adapt a priority.

Grenville bay faces the North Atlantic wave climate and can be considered a high-energy environment (a wave climate description can be found in the Results and Supplementary Information). However, the shoreline is protected by a system of coral reefs (Fig. 1-c). The bathymetry presents deeper banks and shallower zones near shore, which alternate sand and seagrass beds (Fig. 2). Hard coral framework and reef rubble alternate with algae cover over the most exposed areas of the Bay, while algae presence is predominant closer to shore and in the shallowest areas (Fig. 2-b). Benthic algae and corals are among the main groups competing for space on coral reefs (Fong and Paul, 2010). Favorable conditions for algal growth are created by the reduced abundance of herbivorous fish due to overfishing and eutrophication resulting from the unsustainable use of coastal areas (Hughes, 1994). However, the benthic survey shows large areas still dominated by live coral in the Bay (Fig. 2), despite signs of historical loss in sections, in particular