

MODELING THE FUTURE OF CORAL REEFS: AN ECO-MORPHODYNAMIC APPROACH

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INTRODUCTION

Coral reefs are complex biological structures that provide critical ecosystem services, such as provision of habitat for marine organisms, fisheries supply, recreational space for tourism industry, and coastal protection. Coral reefs attenuate up to 97% of the incoming wave energy, protecting coastlines from tropical storms and benefiting 197 million people around the world (Ferrario et al., 2014). Moreover, healthy reef systems are fundamental for the long-term carbonate sediment balance of islands and continental coastlines in their vicinity (Browne et al., 2021).

Due to climate change, coral reefs have been undergoing, and will continue to experience, alterations in their capacity to deliver essential ecosystem services. To comprehend these existing alterations and forecast reef responses to future climate change scenarios, it is imperative to employ dynamic modeling approaches that encompass both abiotic and biotic factors. This study aims to build an eco-morphodynamic point model (also known as a Zero-Dimensional - 0D - Model) that incorporates the key variables responsible for driving changes within reef systems, ultimately affecting their capacity to mitigate wave impacts and facilitate sediment production. For the development of this model, we chose the Great Barrier Reef (GBR) as a testing ground, due to its extensive reef network, offering a wide range of scenarios, and its ample and long-term data availability.

STUDY CASE: THE GREAT BARRIER REEF

The GBR (Figure 1) is the largest living structure in the world, with over 3000 individual reefs. The GBR has an economic, social and icon asset value of \$56 billion and provides over 64,000 jobs for the region (Deloitte, 2016). In addition, it attenuates the incoming wave energy and supplies sediment for hundreds of reef islands and about 2700 km of reef-fronted shoreline in Queensland mainland (Gallop et al., 2014).

Hard coral cover has oscillated over the last three decades throughout the GBR, with a 50% decline between 1985 and 2012 (De'ath et al., 2012). This variability is not uniform across the reef, as it responds to various stressors having localized effects on the different regions - the northern, central, and southern GBR. Overall, Tropical Cyclones (TCs), coral predation by crown-of-thorns starfish (COTS), and bleaching accounted for 48%, 42%, and 10%, respectively, of the coral mortality during this period (De'ath et al., 2012).

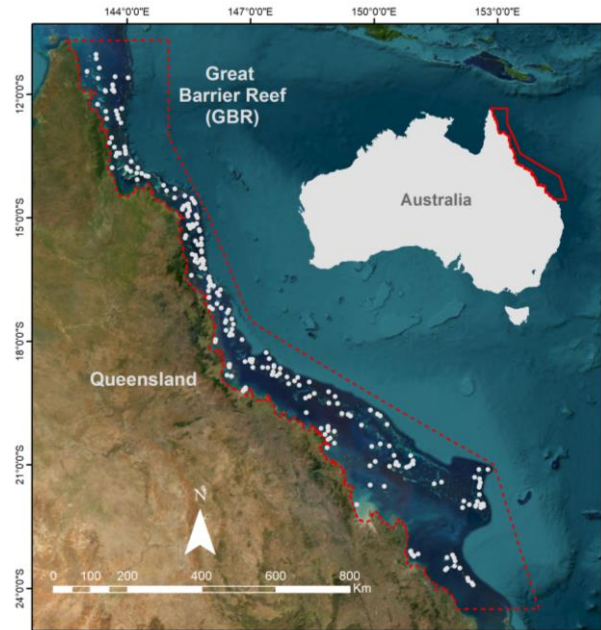


Figure 1 - The Great Barrier Reef with the location of 244 reefs with coral cover data acquired by the Australian Institute of Marine Science (AIMS) over last 30 years.

Interestingly, since 2012 the GBR has widely recovered despite the occurrence of four mass coral bleaching events. This recovery is attributed to the increase in fast-growing *Acropora* corals (AIMS, 2022). Hence, while the reef demonstrates a notable capacity for quick recovery after disturbances, the dominance of *Acropora* corals increases the GBR susceptibility to the disturbances - such as TC waves and COTS outbreaks - that commonly have significant impact on this coral family (AIMS, 2022).

ECO-MORPHODYNAMIC MODEL DEVELOPMENT

0D models represent the simplest yet effective approach to assess the balance between input and output variables in a given system, with no consideration of time and spatial-scale variations. Such models have been successfully employed to create eco-morphodynamic predictions of intertidal environments stability in response to sea level rise (Kakeh et al., 2016). 0D models enable the representation of various relationships through sets of equations while being computationally efficient.

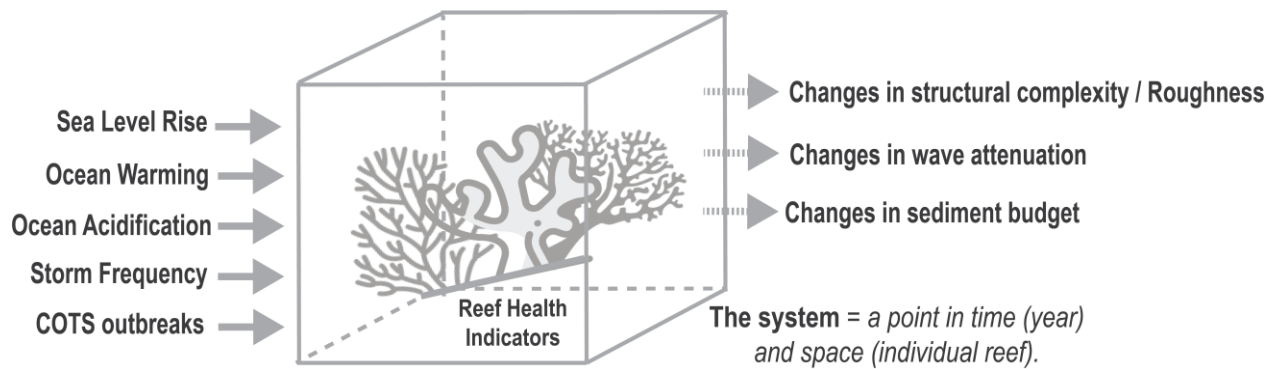


Figure 2 - Conceptualization of a Zero-D Model for predicting the eco-morphodynamic responses of coral reefs. The model is focused on examining and predicting a system that is fixed in time and space (e.g., an individual reef). This reef system is subject to the variability of the main stressors (on the left) which impact its structure (e.g., percentage of hard coral cover), resulting in changes in the reef's structural complexity, as well as its ability to attenuate waves and contribute to the sediment budget (on the right).

To create a 0D model centered on the eco-morphodynamics of coral reefs, we employ two core modules: a biological module, which assesses the impact of stressors on coral reef health and structure, and a physical module that utilizes the resulting coral structure and associated roughness for calculations related to changes in wave energy dissipation, mechanical erosion, rubble production, and ultimately, sediment budget (Figure 2). The model operates at a reef-scale (point in space), and it derives input-output data for annual averages (point in time). While the eco-morphodynamic process across a reef involves oscillations over both space and time, it is necessary to introduce certain limitations and assumptions as an initial step in developing a tool capable of accounting for a multitude of complex relationships.

Despite the plethora of pertinent variables affecting reef ecology and dynamics (Browne et al., 2021), this model incorporates only the main parameters with widely available data. For example, percentage of hard coral cover (total and per family) is employed as a reef health indicator, considering that a reef's structural complexity is contingent on the coral cover and the diversity of their morphologies. Additional elements considered encompass the reef stressors - such as sea surface temperature (marine heatwaves and degree heating weeks), ocean acidification, sea level rise, extreme storm events, and COTS outbreaks - as well as morphodynamic components, including wave parameters, wave energy, flow velocity, rubble production due to wave action and sediment transport.

The first component developed accounts for sea level rise (SLR) as a driver of both biological and physical transformations. Coral reefs have historically adapted to long-term sea level fluctuations. In cases of gradual SLR, a vertical accommodation space tends to be created which may favor the reef expansion, provided the reef is in good condition to match the SLR rates (Woodroffe and Webster, 2014). In this sense, the SLR component in this model integrates factors such as SLR anomalies, potential mechanical erosion of various coral morphologies, the interplay between radiance, turbidity, carbonate production and reef growth, and, ultimately, the resulting coral structure that is responsible for wave energy dissipation.

FINAL REMARKS

The ongoing development of this eco-morphodynamic model represents a step forward towards generating accurate predictions for coral reef wave attenuation and sediment production in the context of future climate change scenarios. While presently using the GBR as a testing ground, the model will eventually be accessible for application to coral reefs worldwide. This is an open-source model that allows for continuous refinement and expansion to accommodate diverse reef conditions and other stressors not included at present.

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