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SEAMANCORE: A spatially explicit simulation model for assisting the local MANagement of COral REefs

Sara Miñarro[a,b,c,*], Johannes Leins[a,d,e], Esteban Acevedo-Trejos[a], Elizabeth A. Fulton[f,g], Hauke Reuter[a,b]

[a] Leibniz Center for Tropical Marine Research (ZMT), Fahrenheitstraße 6, 28359 Bremen, Germany
[b] University of Bremen, Faculty for Biology and Chemistry, Bibliothekstraße 1, 28359 Bremen, Germany
[c] Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona, Bellaterra 08193, Spain
[d] Carl von Ossietzky University Oldenburg, Ammerländer Heerstraße 114-118, 26129 Oldenburg, Germany
[e] Helmholtz Centre for Environmental Research – UFZ Gmbh, Permoserstr. 15, 04318 Leipzig, Germany
[f] CSIRO Oceans and Atmosphere, GPO Box 1538, Hobart, Tasmania 7001, Australia
[g] Centre for Marine Socioecology, University of Tasmania, Hobart, TAS 7001, Australia

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ABSTRACT

Simulation models have a broad potential as decision-support tools for resource management by mechanistically representing and projecting complex ecological processes. In the case of socioeconomically and biologically important coral reef ecosystems, models have been used to address important questions regarding the effects of human impacts on their ecological dynamics and to inform management approaches. However, few of the models integrate benthic and fish dynamics with the influence of external anthropogenic stressors, and virtually none is available as a user-friendly platform for non-scientist managers to easily access. We propose a new ecological model to assess the effects of simultaneous stressors on coral reef ecosystems which includes a dynamic representation of benthic and fish spatial processes, linked by their ecological feedbacks. SEAMANCORE is a two-dimensional model representing the dynamics of local coral reefs which can be used to explore the influence of bleaching, eutrophication, and fishing, including destructive fishing such as bomb and cyanide fishing. The model is coupled with a menu-based interface that allows users with no programming experience to simulate numerous scenarios in specific contexts that can be customized with depth profile maps and initial coral reef conditions of fish and benthos functional group abundance. This study includes SEAMANCORE's description and shows the model's sensitivity to its parameters by means of sensitivity analyses. Its utility is exemplified by exploring various scenarios of no stressors, fishing and bleaching regimes in a theoretical coral reef. We expect that linking fish demographics with changing habitat quality will prove insightful for fisheries management.

1. Introduction

Coral reefs are important ecosystems both for their biological diversity and multifaceted ecosystem services. Their structural complexity provides a unique living environment for numerous organisms, which sustain the livelihoods of millions of people (Moberg and Folke, 1999). Despite their social and ecological relevance, the world's coral reefs have suffered a long-term declining trend, with an estimated 75% being degraded to some extent (Pandolfi et al., 2003; Burke et al., 2011). Overfishing, coastal development, watershed pollution, marine diseases, global warming, and ocean acidification are all considered to be threats to coral reefs in their own right (Jackson et al., 2001; Mora, 2008; Fabricius, 2005; Harvell et al., 1999; Hoegh-Guldberg, 1999; Edmunds et al., 2016), and can have interactive effects amongst them. The impact of one stressor can be exacerbated by its co-occurrence alongside others, or by a reduction in the coral reef ecosystem's resilience due to previous exposure to a different stressor (Ban et al., 2014, Nyström et al., 2000; Pandolfi et al., 2011). For instance, poor water quality has been linked to lower bleaching resistance in coastal symbiotic corals compared to corals in more oligotrophic reefs (Wooldridge, 2009; Wooldridge and Done, 2009). These observed impacts have led to the anticipation that coral reef ecosystems as we know them will be rare by 2050 (Hoegh-Guldberg and Bruno, 2010), and that the emergence of novel assemblages of species composition and interactions (Graham et al., 2014) will have consequences for subsistence-based coastal societies and regional economies through impacts on

* Corresponding author.
E-mail address: sara.minarro@uab.cat (S. Miñarro).

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fisheries, coastal protection, and tourism (Hoegh-Guldberg et al., 2007). To mitigate negative impacts on coral reefs, effective science-based management is needed to achieve trade-offs where desired ecological states can be maintained while being less taxing on reef-dependent human communities.

Computational models are important decision-support tools and can also help improve our understanding of the complex ecological links and feedbacks found in coral reefs by providing a mechanistic representation of their ecological processes. Model simulations have been used to quantify the interactive effects of multiple stressors or coral reef dynamics (e.g. Mumby et al., 2007; Gurney et al., 2013), assess the effects of fishing intensity and selectivity on coral reef food webs (McClanahan, 1995; Opitz, 1996; Arias-González et al., 2004; Mumby, 2006; Kramer, 2008), and evaluate the effects of different management approaches on coral reef ecosystem state (Holmes and Johnstone, 2010, Melbourne-Thomas et al., 2011; Gurney et al., 2013; Sebastián and McClanahan, 2013; Weijerman et al., 2015). Models have been used to evaluate trade-offs between exploitation strategies and preserving desirable ecological states (Blackwood et al., 2012; Bozec et al., 2016), and to highlight important data gaps for understanding predator-prey relations in coral reefs (Guénette and Hill, 2009). However, while changes in benthic habitat have been shown to have profound effects on reef-associated fish assemblages (Friedlander et al., 2003; Graham et al., 2006; Pratchett et al., 2008), explicit habitat dynamics are rarely represented in detail in such ecosystem-based management models. Randomness in the occurrence of interactions and the role of habitat distribution on the outcomes of those interactions make it relevant to consider spatially explicit simulations for their study (Wallentin, 2017). Detailed spatial models of coral reef benthic dynamics have provided insights on the effectiveness of coral transplantation strategies (Sleeman et al., 2005), dynamics of coral diseases (Brandt and McManus, 2009), and on the influence of stressors on benthic community dynamics (Langmead and Sheppard, 2004; Mumby et al., 2007; Tam and Ang, 2012, Kubicek et al., 2012; Sandin and McNamara, 2012) and resilience (Bozec and Mumby, 2015), but they tend to exclude the dynamics of upper trophic levels. A few models linking fish and benthic dynamics include works on the impact of loss of prey refugia on coral reef fish size spectra (Rogers et al., 2014), and of coral cover on fisheries productivity (Ainsworth and Mumby, 2015), albeit not being spatially explicit.

Furthermore, most of the aforementioned models have focused on Caribbean coral reefs while coral reef dynamic models for the Indo-Pacific area remain scant in comparison. Indo-pacific coral reef dynamics fundamentally differ from the Caribbean leading to a seemingly overall greater resilience (Roff and Mumby, 2012), recruitment rates (Smith, 1992; Edmunds et al., 2014) and capacity to recover from disturbances (Adjeroud et al., 2009, Graham et al., 2011). On the other hand, the Indo-Pacific region contains some of the world's most impacted reef systems in tandem with some of the most vulnerable human populations to reef loss (Burke et al., 2011), and the suitability for coral reef habitat is predicted to be reduced in the central Indo-Pacific under future global warming and ocean acidification (Guinotte et al., 2003; Couce et al., 2013). Parameterizing models for Pacific coral reefs is challenged by a lack of adequately collected data until the 1980 s, and a likely varying historical baseline data due to subregional variation in disturbance regimes and morphology of dominant coral species (Bruno and Selig, 2007). Some notable contributions include Ecosim models addressing ecosystem-based fisheries management research priorities for Raja Ampat in Indonesia (Ainsworth et al., 2008), and a spatially explicit mean-field model to assess how local management of fishing and water quality could affect coral reef trajectories under different bleaching scenarios (Gurney et al., 2013).

Models need to be user-friendly tools for managers. Despite the demonstrated power of modelling approaches for evaluating sets of management scenarios (Weijerman et al., 2015) and the substantial progress and growing number of coral reef models, their complexity and demand for technical expertise mean they remain largely out-of-reach for the stakeholder community (Nielsen et al., 2017). This is unfortunate as community-based conservation has been shown to be a successful and desirable management strategy (White et al., 1994, Cinner et al., 2016) particularly in regions characterized by decentralized overexploitation of marine resources – the case in most tropical archipelagic nations. Involving marine resource users in the decision-making process is a critical factor for successful conservation programs (Johannes, 2002), as is developing case specific management strategies (Arkema et al., 2006; Mumby and Steneck,2008; Long et al., 2016). Successful management plans need to incorporate community goals (McClanahan et al., 2006), and they have been shown to benefit from education programs and the involvement of traditional fishermen (White and Vogt, 2000). By providing user-friendly platforms with easy-to-obtain data requirements, models can help stakeholders explore the likely outcomes of management strategies across a range of socio-ecological variables.

Building upon earlier models developed to aid local coral reef management (e.g. Chang et al., 2008; Buddemeier et al., 2008; Holmes and Johnstone, 2010; Weijerman et al., 2015), we propose a Spatially Explicit simulation model for Assisting the local MANagement of COral REefs (SEAMANCORE) as a new user-friendly ecological model to assess the effects of simultaneous global and local stressors on coral reef communities. First, we developed a model based on coral reef ecological theory, prioritizing the processes connecting benthic substrate with the fish community and anthropogenic pressures, and parameterized it to exemplify the dynamics of Indo-Pacific coral reefs. We then developed a menu-based user-friendly interface to allow users with no programming experience to simulate scenarios of different stressor combinations. It includes a detailed and customizable setup which lets users apply the model to a range of tropical regions. The data required to parameterize a case study are kept to a minimum and can be collected in a rapid assessment of the coral reef study site. SEAMANCORE can be used to explore the potential temporal trajectories of coral reefs under different scenarios of depth profile, nutrient levels, bleaching frequency and fishery management strategies. In the following sections, we describe SEAMANCORE's principles and equations, and perform sensitivity analyses to highlight the model's sensitivity to its ecological parameters. We then exemplify its utility by exploring scenarios of no stressors and sets of four fishing and three bleaching regimes in a theoretical coral reef.

2. Methods

SEAMANCORE is a two-dimensional spatially explicit model representing the dynamics of a coral reef under the influence of local and global stressors. It focuses on the dynamics of three selected fish and four benthic functional groups, the ecological relationships amongst them, and the influence of three stressors, i.e. climate change, fishing and eutrophication. Each time step represents one day, which is the highest temporal resolution of the modelled processes. The model domain is defined using a continuous cellular automaton (CA) grid, which represents the benthos of one coral reef patch of up to 1000 x 1000 m (1 km^2) with a resolution of 10 x 10 cm. A second, lower resolution grid layer is superimposed characterizing the dynamics of three idealized fish functional groups, i.e. Browsers and Grazers (BG), Scrapers (S), and Carnivores (Car). Herbivorous functional groups were loosely based on Green and Bellwood (2009). The browser and grazer group represents herbivores feeding on macroalgae i.e. browsers including unicornfishes, rudderfishes and batfishes, and algal turf i.e. grazers such as surgeonfishes, rabbitfishes, and small angelfishes. Scrapers feed on epilithic algal turf and remove sediment and other material by closely cropping or scraping the reef surface, limiting the establishment of algae and providing areas of clean substratum for coral recruitment (Green and Bellwood, 2009). The scraper group represents parrotfish species. Carnivores (or piscivores) feed on the other two fish groups and