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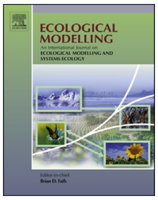

Modelling for management: Coral photo-physiology and growth potential under varying turbidity regimes

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ABSTRACT

Suspended and deposited sediments can negatively impact coral health by reducing light penetration and smothering coral tissue. As coral sediment thresholds vary among species and between locations, setting sediment thresholds for the management of activities that increase sediment loads continues to be a challenging goal. Static threshold values used to date do not take into account temporal and spatial variations in a coral's ability to acclimate to high sediment loads leading to either management approaches that are overly conservative or do not protect corals. This study presents a numerical model that quantifies the relationship between coral photosynthesis and growth potential under varying turbidity-driven light regimes. The model accounts for coral acclimation potential as well as a dynamic energy transfer between host and symbiont using field data collected from nearshore reefs in Singapore combined with both established and novel mathematical relationships. The model yielded photosynthetic and respiratory outputs that were comparable to in situ data collected, illustrating the predictive capability of modelling coral growth potential to declines in light driven by suspended sediments. The inclusion of more than one coral species into the model allows for variations in responses to sediments among different coral morphologies and taxa, and will strengthen the predictive capacity for management of sediment related events. As demonstrated here, the model can be used to identify least risk scenarios for dredging operations as a means of both conserving coral reefs as well as ensuring cost-effective management practices.

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1. Introduction

Many nearshore coral reefs face significant threats from coastal development, dredging activities and nutrient and sediment runoff, all of which affect water quality in coastal regions; Erftemeijer et al., 2012; Fabricius, 2005; Rogers, 1990). These local pressures increase the vulnerability of nearshore coral reefs to global climate change, including the effects of rising seawater temperature and ocean acidification (Anthony et al., 2011; Veron et al., 2009). Given the economic, biological and social value of coral reefs (Cesar et al., 2003; Moberg and Folke, 1999), together with increasing reports of declines in coral reef health and stability worldwide (Bryant et al., 1999; Burke et al., 2011; Mumby et al., 2007), coastal zone managers seek new and adaptive ways in which to better address the balance between the conservation of these biodiverse ecosystems and economic growth.

High sediment loads lead to a range of negative outcomes for corals both when in suspension and when deposited on the benthos. These effects have been reported widely and include: reduced autotrophy due to high turbidity and low light levels (Anthony and Connolly, 2004; Anthony and Fabricius, 2000), increased self-cleaning and tissue necrosis following sedimentation (Lasker, 1980; Stafford-Smith, 1993; Weber et al., 2012), which may also lead to increase in bacterial infections (Haapkyla et al., 2011) as well as reduced heterotrophy (Rogers, 1990), and reduced growth (Browne, 2012; Crabbe and Smith, 2005) and reproduction due to lack of light and energy availability (Jones et al., 2015c). Sediments are also frequently associated with nutrients and trace metals which can have negative impacts on cellular and metabolic processes (Bielmyer et al., 2010; Browne et al., 2015b; Weber et al., 2006). The combination of these stressors reduces ecological fitness in the short-term and, if sustained, can lead to significant

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changes in community composition (Fabricius et al., 2005; Wenger et al., 2016). Even though current knowledge on sediment effects on corals has greatly improved over the last 20 years, there has been limited development of tools for managing the health of coral reefs exposed to activities such as dredging.

Typically, management of dredging activities relies on suspended sediment thresholds. If suspended sediment loads exceed these thresholds, the risk of damage to corals is assumed to be too high and dredging activities are suspended (Falkenberg and Styan, 2014; PIANC, 2010). The threshold values used, however, may not be appropriate given that they are usually based on exposure scenarios or experimental conditions that do not translate beyond set parameters (Falkenberg and Styan, 2014; Jones et al., 2015a). Further, threshold values are rarely derived from the reef at risk and do not take into account the frequency of events or cumulative stress and hence the long-term stress that corals might experience. This results in either over-conservative dredging management or a decline in reef condition due to coral mortality. Furthermore, as corals can acclimate to sediments (Browne et al., 2014; Hennige et al., 2010), the use of static threshold values to manage dredging effects on coral reefs is far from ideal. Hence, there is a need for a numeric model based on site-specific biological and physical data that can monitor and predict coral health in response to sediment loads over time. Such a model can advise managers as to the duration, severity and frequency of sediment resuspension events that can be tolerated by a coral community.

Singapore has experienced rapid coastal development together with associated declines in coral reef cover during the past 60 years. Today only 40% of Singapore's original reef area remains following land reclamation, port construction, and the amalgamation of several reef-fringed islands on which petrochemical facilities and industrial estates currently stand (Chou, 2006). Despite the decline in coral cover, coral biodiversity has remained comparatively stable with approximately 250 hard coral species (Tun, 2012). The main pollution issue that Singapore reefs face is sediments (Todd et al., 2010), originating from river outflows, large scale land reclamation programmes, and resuspension events following the regular dredging of shipping channels (van Maren et al., 2014). Hence, Singapore represents an excellent case study for a pollution problem that is impacting corals reefs globally.

Here, we present the first numeric model of coral growth potential under varying light regimes observed during sediment resuspension events that incorporate coral acclimation potential and accounts for variable energy transfer. The model focuses on the coral and algal response to light only and does not include the potential negative effects of suspended and deposited sediments. A reduction in light has recently been found to pose a proportionally greater risk to coral health than the effects of suspended sediments alone (Bessell-Browne et al., 2017), and hence is the current focus of the model. Field data for physical (light attenuation, turbidity) and biological (coral photosynthesis-irradiance curves, photosynthetic yields) parameters were used to develop, calibrate, and validate the model. It was validated using four light–turbidity scenarios to assess the impacts of reduced light levels on coral growth potential. Furthermore, twelve dredging scenarios (three different severities and four different durations) were run to illustrate the use of the model for management purposes. The model provides the groundwork for developing a site specific model that would aid and improve the management of coral reefs exposed to high sediment loads.

2. Model

The numerical model describes the relationship between coral photosynthesis and growth potential under varying light regimes (Fig. 1). The model was developed using field data collected in inshore shallow turbid waters in Singapore. Here, we describe the development of the conceptual model, the coral photosynthesis-irradiance (PI) data collection, and model structure, parametrisation and calibration. Details on light and turbidity, and yield data collection can be found in Browne et al. (2015b).

2.1. Conceptual model development

To reduce coral mortality, the model needs to track changes in coral health associated with increased stress. Prior to coral tissue mortality, corals display stress symptoms such as increased photosynthetic yield, increased respiration rates and reduced growth and reproduction. Increased photosynthetic yield indicates that corals are acclimating to lower light levels to counter balance reduced energy production from photosynthesis (Anthony and Hoegh-Guldberg, 2003; Browne et al., 2014; Junjie et al., 2014), whereas increased rates of respiration may indicate increased sediment cleaning following polyp extension (Riegl and Branch, 1995). Lower rates of energy production and increased respiration result in reduced net energy available for coral functions such as immunity, growth and reproduction. Conversely, the more net energy available, the more likely corals can protect themselves, feed, grow and reproduce (Leuzinger et al., 2012). Here, we collectively refer to net energy availability as the coral growth potential with a decline in coral growth potential as a measurable and inclusive indicator of coral stress and, therefore, health status.

The effects of sediments on corals are dependent on sediment characteristics as well as the duration, frequency and severity of sediment resuspension events (Erftemeijer et al., 2012; Jones et al., 2015a), which can be further complicated by additional stressors (e.g. high sea surface temperatures) that may reduce a coral's ability to cope with sediment stress (Ganase et al., 2016). A model that incorporates all these elements is beyond the scope of this paper, and would require further observational data and better theoretical understanding than is currently available. The first step towards the development of such a model is to quantify and characterise the coral response to light levels that can vary considerably during sediment resuspension events. Variable light levels are directly linked to energy production that affects the coral growth potential. Corals can, however, acclimate to lower light levels through changes in their photo-physiology that include increased number and size of zooxanthellae cells (biomass) and increased chlorophyll content per cell (Mass et al., 2007; Rogers, 1979; Titlyanov et al., 2001; Vogel et al., 2015). As the density of zooxanthellae increases there is the potential for self-shading but given that the rate and extent of zooxanthellae density change in response to fluctuating light levels is known to be variable both among coral species as well as within a coral colony (Moothien Pillay et al., 2005), the extent of impact from self-shading on photosynthesis is, at present, difficult to quantify. Therefore, we incorporate the potential to acclimate to lower light conditions into the model through increases in zooxanthellae biomass relative to coral biomass only.

The amount of energy transferred from the zooxanthellae to the coral becomes critical at lower light levels when energy production by the algae is limited. In oligotrophic tropical waters and optimal light conditions, most of the energy produced by the zooxanthellae (>90%) is transferred to the coral (Falkowski et al., 1984; Yellowlees et al., 2008). Of the energy transferred, between 40% to75% is utilised for respiration (dependent on coral species and environmental conditions) and the remainder is allocated either for growth, reproduction or mucus production (Davies, 1984; Muscatine et al., 1984; Spencer Davies, 1991). This symbiotic process is, however, sensitive and has been shown to breakdown rapidly during 1–2 °C temperature rises (Brown, 1997). The influence of reduced light levels on the amount of energy transferred

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