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Impacts of turbidity on corals: The relative importance of light limitation and suspended sediments

Pia Bessell-Browne [a,b,c,d,e,*], Andrew P. Negri [a,e], Rebecca Fisher [b,e], Peta L. Clode [c,d], Alan Duckworth [a,e], Ross Jones [b,c,e]

[a] Australian Institute of Marine Science, Townsville, QLD, Australia
[b] Australian Institute of Marine Science, Perth, WA, Australia
[c] The Oceans Institute, The University of Western Australia, Perth, Western Australia, Australia
[d] The Centre for Microscopy, Characterisation and Analysis, The University of Western Australia, Perth, Western Australia, Australia
[e] Western Australian Marine Science Institution (WAMSI), Perth, Western Australia, Australia

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ABSTRACT

As part of an investigation of the effects of water quality from dredging/natural resuspension on reefs, the effects of suspended sediment concentrations (SSCs) (0, 30, 100 mg L^{-1}) and light (~0, 1.1, 8.6 mol photons m^{-2} d^{-1}) were examined alone and in combination, on the corals *Acropora millepora*, *Montipora capricornis* and *Porites* spp. over an extended (28 d) period. No effects were observed at any sediment concentrations when applied alone. All corals in the lowest light treatments lost chlorophyll *a* and discoloured (bleached) after a week. Coral mortality only occurred in the two lowest light treatments and was higher when simultaneously exposed to elevated SSCs. Compared to water quality data collected during large dredging programs and natural resuspension events (and in the absence of sediment deposition as a cause-effect pathway) these data suggest the light reduction associated with turbidity poses a proportionally greater risk than effects of elevated SSCs alone.

1. Introduction

Dredging is an essential activity for port operations and its requirement is projected to increase in the future associated with the current trend towards larger ships with deeper draft requirements (Ports Australia, 2014). Dredging releases sediment into the water column, creating turbid plumes which can migrate away from the initial activity and onto nearby sensitive habitats (Foster et al., 2010). The suspended sediments can reduce light, clog filtering and feeding apparatus, and settle onto benthic organisms, and therefore pose an environmental hazard (Bak, 1978; Brown et al., 1990; Dodge and Vaisnys, 1977; Erftemeijer et al., 2012; Foster et al., 2010; Jones et al., 2016; Rogers, 1990). To effectively manage this hazard, it is critical to identify and understand the specific cause-effect pathways for dredging-relating pressures on key biota, especially for ecologically important, habitat forming groups such as corals. Partitioning the various impacts of dredging, such as light attenuation, shifts in light wavelength, increased suspended sediment concentrations (SSCs), and sediment deposition is important to enable more targeted and effective generation of concentration-response relationships (reviewed by Jones et al. (2016)). Water quality thresholds developed following this process will have increased environmental relevance, and once established will improve the ability of dredging proponents to predict the impact of dredging (at the environmental impact assessment stage) and to minimise the impact of dredging using adaptive management (Holling, 1978).

Most shallow water tropical corals are sessile colonies of filter-feeding polyps that live in a mutualistic symbiosis with dinoflagellates of the genus *Symbiodinium* (Stat et al., 2008; Trench, 1979). They can obtain energy heterotrophically, and capture up to meso/macro sized zooplankton by nematocyst discharges and tentacle grabbing (reviewed by Houlbrèque and Ferrier-Pagès (2009)). Corals can also ingest and assimilate particles in suspension (Anthony, 1999a; Anthony, 1999b; Anthony and Fabricius, 2000; Goreau et al., 1971), or that have settled on their surfaces (Mills et al., 2004; Mills and Sebens, 2004). Corals can also obtain energy autotrophically, and the endosymbiotic algae provide the coral host with photosynthate that can represent up to 90% of its daily energy requirements (Falkowski et al., 1984; Muscatine, 1990; Muscatine et al., 1981). Some corals have flexibility in their feeding strategies and can maintain a positive energy balance by shifting from photoautrophy to heterotrophy with increasing depth (Palardy et al., 2006), following bleaching (Bessell-Browne et al., 2014; Grottoli et al., 2006), and in turbid environments (Anthony and

* Corresponding author at: Australian Institute of Marine Science, Townsville, QLD, and Perth, WA, Australia.
E-mail address: pia.bessell-browne@research.uwa.edu.au (P. Bessell-Browne).

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Fabricius, 2000). Despite this plasticity, the dual nutritional mode leaves corals vulnerable to pressures, such as dredging, that can affect both the heterotrophic and autotrophic modes of nutrition.

One of the key proximal stressors associated with dredging is an increase in SSCs (reviewed by Rogers (1990) and Jones et al. (2016)). Suspended sediments typically have small particle sizes (silt and clay sized) and remain in suspension for extended periods with limited water turbulence (Masselink et al., 2014). Several studies have shown that corals may benefit from ingestion of organic matter associated with sediments at low concentrations (Anthony, 2006; Anthony et al., 2007; Mills and Sebens, 1997; Mills et al., 2004); however, higher SSCs can cause coral polyps to contract and feeding to cease (Anthony, 2000; Mills and Sebens, 1997).

Another key proximal stressor associated with dredging is decreased light availability from increased turbidity (reviewed by Jones et al. (2016)). The amount of light attenuation that occurs in a plume depends on depth, as well as the sediment concentration and its scattering and absorption properties including colour, composition, and particle size (Storlazzi et al., 2015). Recent modelling studies of benthic light availability experienced during dredging plumes, showed that incident down-welling irradiance of ~725 μmol photons m^{-2} s^{-1} at 5 m depth in 1 mg L^{-1} SSC is reduced to <5 μmol photons m^{-2} s^{-1} in a 30 mg L^{-1} SSC plume (Jones et al., 2016). Most hermatypic scleractinian corals have high photosynthetically active radiation (PAR, 400–700 nm) requirements due to their association with symbiotic dinoflagellates (Achituv and Dubinsky, 1990; Falkowski et al., 1984; Gattuso et al., 2006; Muir et al., 2015). Prolonged light attenuation will lead to decreased photosynthesis, a negative energy balance and reduced growth (Falkowski et al., 1990; Richmond, 1993). In extreme cases it can even result in dissociation of the coral-algal symbiosis (bleaching) (Brown, 1997; DeSalvo et al., 2012; Glynn, 1996; Kevin and Hudson, 1979; Yonge and Nicholls, 1931).

The close association between suspended particles and light attenuation creates difficulties for assigning a coral's response to one or both of these pressures following turbidity events such as plumes from dredging, river discharge, or natural resuspension. Water quality monitoring programs associated with dredging projects have typically focused on measuring turbidity using nephelometric turbidity units (NTUs) as a proxy measure of pressure fields (Foster et al., 2010; Hanley, 2011; Sofonia and Unsworth, 2010). This approach has recently been questioned by Sofonia and Unsworth (2010), who suggested a refocus on PAR rather than NTU, as it is more relevant biologically and inclusive of other site conditions. In this study, we examined the potential impacts of sediments on corals by experimentally exposing three common morphologies to elevated SSCs and light reduction alone, and in combination (3 light × 3 SSC regimes). Sediments were kept in suspension in these studies, reducing or eliminating a suite of other cause-effect pathways associated with sediment smothering such as anoxia. The purpose of the study was to provide insights into the cause-effect pathways of turbidity for each of these species, determine viable indicators of stress, and guide the development of future experiments to determine appropriate concentration-response relationships for management purposes.

2. Materials and methods

The study was conducted with *Acropora millepora* (Ehrenberg 1834), *Porites* spp. and *Montipora capricornis* (Veron 1985), representing branching, massive, and foliaceous morphologies respectively. All these species are common throughout the Indo-Pacific, including the east and west coasts of tropical Australia. For *A. millepora* and *M. capricornis*, 8 colonies were collected by hand, while 8 colonies of *Porites* spp. were cored with a pneumatic drill. All coral species were collected between 3 and 10 m from the lagoon of Davies Reef, a mid-shelf reef centrally located in the Great Barrier Reef (GBRMPA permits G12/35236.1 and G13/35758.1). Due to difficulty identifying *Porites* spp. colonies to species in the field as they have small and variable corallites (Veron, 2000) a mixture of species (*P. lutea* and *P. lobata*) were used for the experiment. Colonies that were free of biofouling and diseases were fragmented (~15 cm^2) into replicates. Fragments were then glued onto aragonite coral plugs and held in 200 L flow-through holding tanks in the National Sea Simulator (SeaSim) at the Australian Institute of Marine Science (AIMS), in Townsville, Australia for 6 weeks to recover from the collection and preparation procedures. During the holding period, corals were exposed to a 12-h light:dark (L:D) cycle made up of a 2 h period of gradually increasing light in the morning (06:00–8:00 h), 8 h of constant illumination at 200 μmol photons m^{-2} s^{-1}, and then a 2 h period of gradually decreasing light in the afternoon (16:00–18:00 h). Over the course of the day the corals experienced a daily light integral (DLI) of 7.2 mol photons m^{-2}.

Experiments were conducted in clear PVC tanks (115 L capacity) with an inverted pyramid at the base to reduce sediment deposition on any horizontal surfaces. Water was circulated by a magnetic drive, centrifugal pump that collected water from the top of the tank and forced flow up from the centre point of the inverted pyramid at the base, also reducing sediment deposition (see Fig. 1. A for a schematic representation of the experimental system). A second pump VorTech ™ MP10 (EcoTech Marine, PA, US) was placed in the tank at the same height as the corals to aid in circulation. Experiments were conducted with 100 L of ultra-filtered (to 0.4 μm) seawater pumped into each tank at a rate of 400 mL min^{-1} to ensure 6 complete turnovers of water each day. Water temperature and salinity was maintained at 27 ± 0.5 °C and 33‰ respectively. Turbidity within each experimental tank was monitored using nephelometers (Turbimax CUS31, Endress and Hauser) and nephelometric turbidity units (NTUs) were converted to mg L^{-1} by applying sediment specific algorithms (see below). To replace sediment lost from the tanks during water exchanges, new sediment was periodically introduced from a concentrated stock suspension housed in a separate 500 L tank. The dosing of the tanks was controlled using a programmable logic controller (custom control logic on Siemens S7-1500 PLC) that opened and closed pivoting solenoid valves connected to the stock suspension tank via a high velocity loop powered by an air diaphragm pump. Light was provided by two AI Hydra FiftyTwo™ HD LED lights (Aquaria Illumination, IA, US) suspended above each tank, which generated even illumination with an equal mix of white, blue, and red light. To ensure there was no sediment deposition on coral tissue, *A. millepora* fragments consisted of a single, upright, straight branch, while *Porites* spp. and *M. capricornis* fragments were positioned vertically. Light intensity was measured at the depth of the corals using an underwater spherical quantum sensor (Li-COR LI-193).

All sediment used in the study was biogenic calcium carbonate sediment collected from Davies Reef (Great Barrier Reef Marine Park Authority permit: G13/35758.1). Sediment was first screened to 2 mm and then ground with a rod mill grinder until the mean grain size was ~30 μm (range: 0.5–140 μm), measured using laser diffraction techniques (Mastersizer 2000, Malvern instruments Ltd., UK). Total organic content of the sediment was 0.25%.

Experiments were conducted using 9 treatments, made up of 3 SSCs levels (0, 30, 100 mg L^{-1}) and 3 light levels (darkness, 1.1, 8.6 mol photons m^{-2} d^{-1}). For the darkness treatments, the tanks were wrapped in black plastic (to reduce light contamination), but the corals nevertheless experienced very low level light exposure (albeit for a few minutes), during weekly photographing (see below); thus, the treatment is referred to as a DLI of ~0 mol photons m^{-2}. For the remaining two light treatments the corals were exposed to a 12-h L:D cycle composed of a 6 h period of gradually increasing light in the morning (06:00–12:00 h), reaching 50 or 400 μmol photons m^{-2} s^{-1} at local noon, and then a 6 h period of gradually decreasing light in the afternoon (12:00–18:00 h). Over the course of the day the corals experienced a daily light integral (DLIs) of 1.1 or 8.6 mol photons m^{-2} respectively. A total of 8 coral fragments from each of the 3 species