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Effects of suspended sediments and nutrient enrichment on juvenile corals

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ABSTRACT

Three to six-month-old juveniles of *Acropora tenuis*, *A. millepora* and *Pocillopora acuta* were experimentally co-exposed to nutrient enrichment and suspended sediments (without light attenuation or sediment deposition) for 40 days. Suspended sediments reduced survivorship of *A. millepora* strongly, proportional to the sediment concentration, but not in *A. tenuis* or *P. acuta* juveniles. However, juvenile growth of the latter two species was reduced to less than half or to zero, respectively. Additionally, suspended sediments increased effective quantum yields of symbionts associated with *A. millepora* and *A. tenuis*, but not those associated with *P. acuta*. Nutrient enrichment did not significantly affect juvenile survivorship, growth or photophysiology for any of the three species, either as a sole stressor or in combination with suspended sediments. Our results indicate that exposure to suspended sediments can be energetically costly for juveniles of some coral species, implying detrimental longer-term but species-specific repercussions for populations and coral cover.

1. Introduction

An estimated 25% of coral reefs globally are threatened by increasing loads of sediments, nutrients and pollutants from terrestrial runoff associated with coastal development, dredging, deforestation and agriculture (Burke et al., 2011). Declining coastal water quality can lead to increases in macroalgal cover (Fabricius, 2005), reductions in coral biodiversity (De'ath and Fabricius, 2010), proliferation of macro-bioeroders that weaken the structural integrity of coral reefs (Le Grand and Fabricius, 2011), increases in the frequency and severity of coral diseases (Bruno et al., 2003), and changes in the composition of biofilms that provide conditioned surfaces for larval settlement and metamorphosis of many sessile organisms (Wieczorek and Todd, 1998, Webster et al., 2004, Sawall et al., 2012).

Field and laboratory studies have shown that sediments and nutrients can both negatively affect corals. High concentrations of suspended sediments reduce gamete fertilization success of gametes and larval settlement (Gilmour, 1999, Jones et al., 2015b, Ricardo et al., 2015, Humanes et al., 2017), cause shifts in the dominance of energy acquisition from phototrophy to heterotrophy (Anthony and Fabricius, 2000), alter colony morphology, and cause declines in growth and survivorship (Anthony and Fabricius, 2000, Jones et al., 2016). Suspended sediments can affect adult corals in three major ways (reviewed by Jones et al. (2016)). Firstly, contact between suspended particles and the coral can cause irritation, disrupt feeding mechanisms, and increase the energy expenditure into tentacle movement and mucus production for self-cleaning. The suspended particles can also attenuate light and change light quality, which affects energy acquisition by the associated *Symbiodinium* symbionts. Finally, settling sediments can smother corals, which again increases cleaning efforts which may be overwhelming, resulting in bleaching and tissue death by anoxia. Elevated concentrations of nutrients also negatively affect all coral life history stages, reducing gamete production (Ward and Harrison, 2000, Loya et al., 2004), fertilization success (Humanes et al., 2016) and calcification rates, as well as increasing the ratio of symbiont to host cells, which can increase the vulnerability of this symbiotic partnership to disruptions (bleaching) associated with high sea temperatures (Marubini and Davies, 1996, Cunning and Baker, 2012, Vega Thurber et al., 2014). Conversely, when co-occurring with conditions that promote shifts from autotrophy to heterotrophy, elevated nutrients can stimulate calcification and growth rates, and increase host tissue protein content and biomass in some coral species (Bongiorni et al., 2003a, Sawall et al., 2011, Ezzat et al., 2015).

In combination, nutrient-enriched sediments in inshore areas influenced by river runoff (Brodie et al., 2012) can exacerbate the already detrimental effects of suspended and deposited sediments on corals,

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further reducing larval settlement success, and adult survivorship and growth rates (Fabricius, 2005, Weber et al., 2006, Humanes et al., 2017). Dissolved inorganic nutrients, especially nitrogen and phosphorus also promote the formation of phytoplankton blooms (Furnas, 2003, Kroon et al., 2012), which transform the dissolved inorganic nutrients and convert them into particulate organic nutrients (Grossart and Ploug, 2001, Brodie et al., 2010). Particulate organic nutrients reduce water clarity and stimulate microbial communities that exude mucopolysaccharides (Angly et al., 2016), form aggregates with sediments that compromise coral juvenile and adult survivorship when deposited on their tissues (Fabricius et al., 2003, Weber et al., 2012), and promote the development of coral diseases (D'Angelo and Wiedenmann, 2014).

The Great Barrier Reef (GBR), the World's largest coral reef system, is located adjacent to tropical catchments along the North Queensland coast of Australia that have been modified by extensive agriculture. At present, rivers discharge an estimated 17 million tonnes of suspended sediments, along with 80,000 t of nitrogen and 16,000 t of phosphorous annually, a 3–8-fold increase compared to pre-European settlement (McCulloch et al., 2003, Kroon et al., 2012). Over 30 major rivers discharge sediments and nutrients into the GBR lagoon during the wet season (December–March), simultaneously introducing dissolved and particulate organic and inorganic nutrients together with fine terrigenous sediments (Fabricius et al., 2014). Fine sediments then undergo repeated cycles of deposition and resuspension at < 20 m bathymetry (Fabricius et al., 2013), until they are eventually deposited either on the deeper seafloor below the reach of storm waves, or in north-facing coastal embayments (Larcombe et al., 1995, Wolanski et al., 2005). Consequently, high concentrations of suspended sediments are commonly found throughout the year in the shallow GBR lagoon, and their effects on the structure and function of these inshore marine ecosystems is of great concern (Schaffelke et al., 2005, Brodie and Waterhouse, 2012).

Although there has been some research on the impacts of organically enriched suspended or deposited sediments on fertilization, larval survivorship and settlement (Humphrey et al., 2008, Humanes et al., 2017), and on juvenile and adult stages of scleractinian corals (Fabricius and Wolanski, 2000, Weber et al., 2006, Weber et al., 2012, Perez et al., 2014, Liu et al., 2015, Moeller et al., 2016), the effects of physical contact of suspended sediments together with nutrient enrichment on key physiological processes of juvenile corals in the months following settlement remain unknown. This represents a significant knowledge gap, particularly as: i) sediment and nutrient discharges into coastal areas are a growing problem worldwide (Syvitski et al., 2005); ii) juvenile growth and survivorship rates play a key role in the maintenance and replenishment of coral populations (Ritson-Williams et al., 2010); iii) early life history stages of corals are typically considered more sensitive to environmental change and pollution than adult stages (Fabricius, 2005); and iv) scleractinian corals are the main ecosystem engineers of coral reefs (Bellwood and Hughes, 2001).

To improve current understanding of the effects of nutrient-enriched suspended sediments on juvenile corals, we performed a series of controlled laboratory exposure experiments over 40 days. We compare the effects of the physical contact of suspended sediments (in the absence of deposition and light attenuation), with and without nutrient enrichment, on juveniles of three coral species that are common on inshore reefs of the GBR and throughout the tropical Indo-Pacific (*Acropora tenuis*, *A. millepora* and *Pocillopora acuta*). Our data on juvenile survivorship and growth, photochemical efficiency, respiration and photosynthesis provide insights into the vulnerability of coral juveniles to nutrient-enriched suspended sediments commonly associated with runoff events in inshore areas.

2. Materials and methods

2.1. Spawning, gamete collection and larval settlement

Gravid colonies (> 20 cm diameter) of the broadcast spawning corals *Acropora tenuis* (Dana 1846) and *A. millepora* (Ehrenberg, 1834) were collected on the 6th of November 2014 at ~6 m depth, under permit G12/35236.1 issued by the Great Barrier Reef Marine Park Authority; gravid colonies of the brooding coral *Pocillopora acuta* (Lamarck, 1816) were collected in February 2015, from Davies Reef (19° 06′S, 146° 51′E). All three species have branching growth forms and are zooxanthellate corals, meeting much of their energy demands through photosynthesis by endosymbiotic *Symbiodinium* communities. Colonies were transferred to an outdoor flow-through system, with temperature set to the reef conditions on the day of collection (27 °C) in the National Sea Simulator facility (SeaSim) at the Australian Institute of Marine Science (AIMS). Following spawning of 11 colonies of *A. tenuis* and 13 colonies of *A. millepora* (on days 5 and 8 after the November full moon, respectively), egg-sperm bundles were gently scooped from the surface of aquaria. Eggs were separated from sperm using a 100 µm mesh filter and washed five times in FSW (0.2 µm filtered sea water), and then cross-fertilized as described by Negri and Heyward (2000). Larvae were reared in 500 l flow-through tanks using 1 µm-filtered seawater at 27 °C. To collect larvae from the brooding coral *P. acuta*, 15 colonies were isolated in 25 l flow-through tanks with 100 µm mesh collectors positioned at outflows, which collected larvae released between the 22nd and 25th of February 2015. Artificial aragonite substrata (~2 cm in diameter, Oceans Wonders LLC) and overgrown with crustose coralline algae (CCA), were offered to larvae of the three species as settlement substrata. The resulting recruits were reared in flow-through tanks at 27 °C until the beginning of the experiment on 13th May 2015. Their ages at the beginning of the experiment were: 188 days for *A. tenuis*, 185 days for *A. millepora*, and 78 days for *P. acuta*.

2.2. Experimental design and treatment types

Juveniles were exposed for 40 days to eight treatments, consisting of four levels of suspended sediments (0, 10, 30 or 100 mg l^{-1}) and two levels of nutrient enrichment (+ 0 or + 0.6 mg OC l^{-1} FSW) in a fully crossed experimental design. Treatments mimicked the impact of terrestrial runoff events, wind-driven resuspension events, or dredging activities that simultaneously introduce nutrients and fine-sized particle sediments into inshore reef waters. Sediments and nutrients were collected from the seafloor at 2 m depth at Orpheus Island (18° 36′S, 146° 29′E) and transported to AIMS two weeks before starting exposures. Sediments were wet-sieved to obtain fine particles (average ± sd. particle size: 7.3 ± 1.5 µm, 95% < 20 µm), and kept in 60 l flow-through tanks at 27 °C until experiments commenced. Plankton containing organic and inorganic nutrients were collected with a plankton net (mesh size 100 µm), sieved to remove large fragments (> 26 µm), homogenized with a blender, and frozen in aliquots until use. Natural plankton was used as the nutrient source to maintain a realistic stoichiometric composition of organic and inorganic nutrients and trace elements present in inshore reefs, a method previously used for studying the effects of nutrient enrichment on hard corals (Fabricius et al., 2003, Weber et al., 2012, Humanes et al., 2016, Humanes et al., 2017).

Suspended sediment concentrations (0, 10, 30 and 100 mg l^{-1}) were verified using a nephelometer calibrated with the same sediments (TPS 90FL-T). Experimental suspended sediment concentrations were chosen to represent the range of *in situ* conditions that have been recorded on inshore GBR reefs and in association with dredging projects. Concentrations recorded *in situ* have been up to 5 mg l^{-1} under calm conditions on inshore reefs (Macdonald et al., 2013), between 5 and 30 mg l^{-1} after storms and in river plumes, and up to 100 mg l^{-1} close

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