

# 7 | Effect of sea cucumber density on the health of reef-flat sediments

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## Abstract

Sea cucumbers are thought to play an important role in the recycling and remineralization of organic matter in reef sands through feeding and bioturbation. However, growing demand and high prices from Asian markets are driving the overexploitation of sea cucumbers globally, with little understanding of the consequences of local-scale removal from inshore coral reef ecosystems. Densities of *Holothuria scabra* were manipulated in enclosures *in situ* on a reef flat adjacent to Natuvu village, on the island of Vanua Levu, Fiji, between August 2015 and February 2016 to simulate an unfished and an overfished stock density. Two treatments were used: (i) high sea cucumber stocking density (350 g m<sup>-2</sup>); and (ii) exclusion of sea cucumbers (0 g m<sup>-2</sup>). Two controls accounted for cage effects: (i) cage controls (no cage walls); and (ii) natural density (60 g m<sup>-2</sup>). Sedimentary oxygen consumption (SOC), grain size distribution, sediment porosity, and O<sub>2</sub> penetration depth were recorded. SOC rates were consistently lower in high-density enclosures than when sea cucumbers were excluded, indicative of 'healthy' sediments. O<sub>2</sub> penetration depth decreased significantly when sea cucumber removal coincided with elevated sea surface temperatures which are indicative of sediment health decline. Thus the removal of sea cucumbers reduces the efficiency of reef sediment to function as a filter system to buffer organic matter pulses, and negatively affects the function and productivity of inshore reef ecosystems.

## Introduction

Sediments in tropical coastal habitats are capable of trapping a substantial amount of organic matter (OM) (Wild et al. 2004). Water flows are able to transport OM into and within the sediment, and small organisms living within sediments are able to efficiently degrade OM (Rush et al. 2006). Because the seafloor and the overlying water are closely linked through such transport processes, changing the function of sediments can have direct negative consequences on the quality of the overlying water (Wild et al. 2004). Porous sediments are thus considered as a kind of biocatalytical filter system (Rusch et al. 2006).

Several factors can affect the efficiency of this filter, including temperature, water currents, the amount of organic matter entering the system, and the burrowing or burying activity of organisms digging up and turning over the sediment, referred to as bioturbation (Kristensen 2000). Of these factors, bioturbation has the greatest effect on the efficiency of the biocatalytical filter, as it can increase the surface area of the sediment and mix the sediment (Kristensen 2000). The efficient function of this filter system is critical as it provides the marine environment with capacity to buffer pulses of OM. The ability to buffer negative effects of OM pulses becomes increasingly important as coastal ecosystems face threats from increasing nutrient and OM inputs from agriculture and sewage discharge (Barnes 1973, Mosley and Aalbersberg 2003).

Several species of sea cucumbers inhabit soft bottom habitats (Purcell et al. 2012), interacting directly with and influencing the quality of sediments through feeding and bioturbation (Uthicke 1999, 2001, Purcell et al. 2016). The present study focused on the deposit-feeding sandfish *Holothuria scabra*, historically found in high densities on reef flats throughout the Pacific (Ward 1972, Shelly 1981). *H. scabra* ingests a large amount of sediment and can bury itself in soft sediments (Fig. 1) during part of the day (Mercier et al. 1999; Purcell 2004), therefore playing a key role in bioturbation. This species is also of high value in the sea cucumber trade (Pakoa et al. 2013, Purcell 2014). Our study investigated the effect of *H. scabra* on the function of the biocatalytical filter system by assessing effects on sediment composition, the depth to which oxygen ( $O_2$ ) penetrated into the sediment, and sedimentary oxygen consumption (SOC), which are indicators of the decomposition of organic matter. The combination of SOC and  $O_2$  penetration depth indicate how efficiently the sediment is functioning as a biocatalytical filter system.



Figure 1. Bioturbation from *H. scabra* burying cycle exposes anoxic sediment (black/grey) and breaks up algal mats.

## Methods

Fieldwork was conducted on an extensive reef flat in front of Natuvu village, Wailevu District East, Vanua Levu, Fiji (16°44.940'S, 179°9.280'E), between August 2015 and February 2016. The site was selected as it had been identified by the Wildlife Conservation Society as having a relatively high *H. scabra* density for the region as a result of restocking of community fish grounds in 2009 (Hair 2012). Densities of *H. scabra* at the study site were similar to unfished densities found in Papua New Guinea (Shelley 1981), and therefore were assumed similar to natural population densities.

Sixteen square enclosures (3 m x 3 m) were constructed at the study site and stocked with two densities of *H. scabra*. Two treatments ( $n=4$  per treatment) were used: (i) high sea cucumber density cages (ca. 350 g m<sup>-2</sup>); and (ii) cages without sea cucumbers or 'exclusion cages' (0 g m<sup>-2</sup>). Two controls ( $n=4$  per control) were established to account for cage effects; natural (ca. 60 g m<sup>-2</sup>) and cage controls which had no walls/mesh. Natural density (ca. 60 g m<sup>-2</sup>) was determined in a pilot study at the study site. High density (350 g m<sup>-2</sup>) was based on high stocking biomass for *H. scabra* used in previous studies in natural ranching sites (Battaglione 1999, Lavitra et al. 2010).

To determine grain size distribution, sediment cores were collected to a depth of 3 cm ( $n=3$  per enclosure) and dried in an oven at 70°C for ca. 24 hours. Dry sediment samples were weighed then transferred to a column of sieves ( $\geq 2000$   $\mu\text{m}$ , 1000  $\mu\text{m}$ , 500  $\mu\text{m}$ , 250  $\mu\text{m}$ , 125  $\mu\text{m}$ , <125  $\mu\text{m}$ ). The sieve column was shaken for seven minutes, and sediment remaining in each sieve weighed to the nearest 0.02 g. Grain size analysis, textural classifications and distribution of sediments were based on methods by Folk and Ward (1957).

Sediment porosity was determined by comparing the wet weight to dry weight of sediment cores following methods by Olson (2014). The depth to which oxygen reached (penetrated) into the sediment was measured by collecting sediment cores to a depth of 3 cm using a clear corer. The oxygen penetration depth was determined using methods adapted from Kemp et al. (2015); measured as the distance from the sediment surface to the depth at which sediment was consistently darker<sup>5</sup> (Fig. 2).

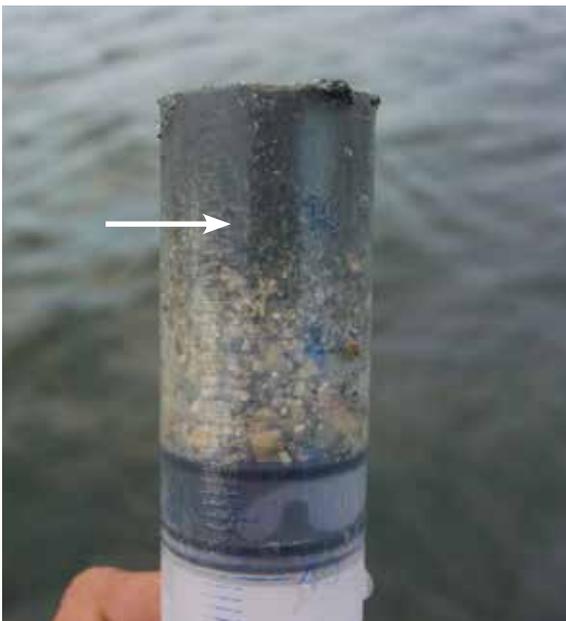


Figure 2. Sediment corer used to quantify oxygen penetration depth. Consistently darker sediment indicates anoxic sediment, as indicated by a white arrow.

<sup>5</sup> Consistently dark sediment indicates low oxygen conditions.

Lastly, *in situ* sedimentary oxygen consumption (SOC) was measured using methods by Ford et al. (unpubl data). Sediment cores ca. 10 cm<sup>3</sup> were collected to a depth of 1 cm from enclosures and transferred immediately to glass incubation chambers (160 ml). Chambers were then filled with undisturbed water from the same location ( $n=4$  treatments per enclosure,  $n=3$  controls per enclosure). Controls only contained undisturbed water from our site; this allowed us to account for microbial activity in the overlying water column. Samples were placed into opaque bags and placed in an icebox filled with water from the site to maintain temperature consistency. Approximately 30 ml of water was removed from the chamber to prevent water overflowing from the chamber during measurement. Oxygen (O<sub>2</sub>) concentration, salinity and temperature was measured using a WTW Multi 3320™ O<sub>2</sub> sensor and salinity probe. Oxygen saturation was consistently at 70–120% at initial measurements. Water removed (ca. 30 ml) was replaced, and additional water (3–5 ml) collected from the site was used to top-up the incubation chamber to ensure the chamber was sealed airtight with no air bubbles. Chambers were incubated in the corresponding opaque bags, in an icebox filled with water from the site for ca. 1 h. Chambers were collected and O<sub>2</sub> concentration, salinity and temperature were re-measured. The exact durations (min) of all incubations were recorded.

Results from cage controls and natural controls, for each parameter, were compared in post-hoc tests and, if there were no significant differences between natural and cage controls, high density and exclusion treatments were compared. Data from enclosures were analysed using repeated-measures ANOVA.

## Results

Cages without sea cucumbers showed no significant difference in grain size composition from September to December. However for the same time period enclosures with high sea cucumber densities exhibited a shift towards finer grains, with an increase in particular in 125 µm grain sediments (*U test*,  $p=0.03$ ) and a significant reduction in the proportion of 1000 µm grain sediment (*U test*,  $p=0.03$ ). Due to storm surge affecting our site five days prior to January measurements, we do not consider January results to be caused by the manipulated densities of *H. scabra* in enclosures (treatment).

Sediment porosity showed a marginally significant change over time from the onset of the experiment (ANOVA,  $p=0.05$ ), however there were no significant differences among treatments (*U test*,  $p>0.05$ ). O<sub>2</sub> penetration depths were similar between high density and sea cucumber exclusion treatments in November (*U test*,  $p=0.73$ ). Although O<sub>2</sub> penetration increased significantly in December within cages with high sea cucumber densities (*U test*,  $p=0.03$ ) (Fig. 3), there was no significant difference between high sea cucumber density cages and cages without sea cucumbers (*U test*,  $p=0.32$ ). February, however, shows a distinctly different pattern. Whilst the high-density treatments had values identical to those in November (*U test*,  $p=1$ ), oxygen penetration depth in the cages without sea cucumbers decreased significantly (*U test*,  $p<0.01$ ) by 63% from 32 mm ( $\pm 3$  SE) to 12 mm ( $\pm 2$  SE). Neither controls showed any significant differences in oxygen penetration depth over time throughout the study (*U test*,  $p>0.05$ ).

At the beginning of the study all cages had similar SOC rates (September *U test*,  $p=0.55$ ). Four weeks later the SOC rates increased significantly in cages with no sea cucumbers (U-test, September–October,  $p<0.01$ ) by almost two-fold from 43.0 mmol O<sub>2</sub> m<sup>-2</sup> day<sup>-1</sup> ( $\pm 4.6$  SE) to 75.96 ( $\pm 4.7$  SE) mmol O<sub>2</sub> m<sup>-2</sup> day<sup>-1</sup>. No changes occurred within the high sea cucumber density cages during the same time period (U-test, September–October,  $p=0.74$ ).

Heavy rains and flooding occurred ten days prior to November sampling (Fig. 4). Following the flooding, SOC rates increased significantly without high-density cages (U-test, October–November,  $p=0.03$ ). In November there were no longer significant differences among treatment cages (U-test; November;  $p=0.25$ ). Following further heavy rains prior to sampling in January, both treatments showed similar patterns as before (i.e. SOC rates decreased within the cages with no sea cucumbers and increased within cages with high densities of sea cucumbers), and were not significantly different from each other in January (U test,  $p=0.99$ ) and February (U test,  $p=0.07$ ).

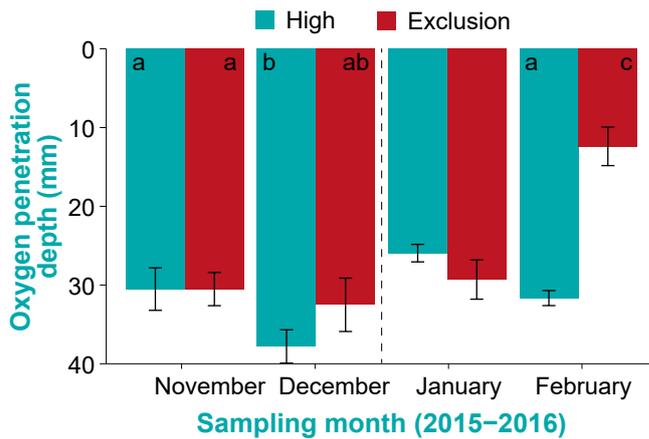


Figure 3. Oxygen penetration depth (mm) of high density and exclusion treatments. Mean values with standard error. Vertical break indicates flooding and storm surge five days prior to January sampling. Different letters (a, b, c) indicate significant differences ( $p < 0.05$ ), same letters indicate no significant differences ( $p > 0.05$ ). January results were not considered in the analysis.

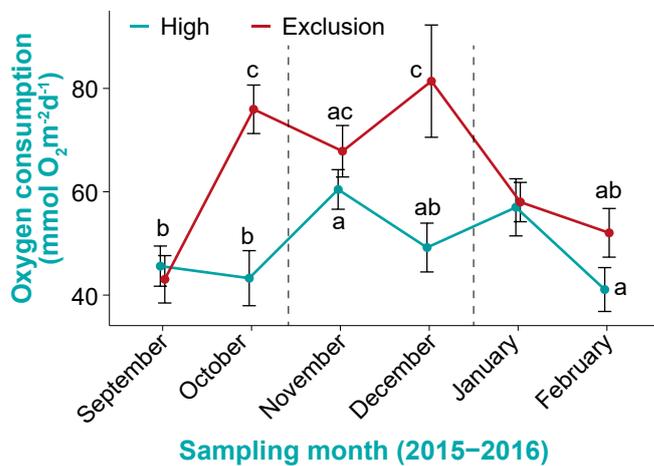


Figure 4. Sedimentary oxygen consumption ( $\text{mmol O}_2 \text{ m}^{-2} \text{ day}^{-1}$ ) of high sea cucumber density (High) and areas void of sea cucumbers (Exclusion). Mean values with standard errors. Vertical break between October and November indicates flooding 10 days prior to November sampling. Vertical break between December and January indicates flooding and storm surge 5 days prior to January sampling. Different letters (a, b, c) denote significant differences ( $p < 0.05$ ), same letters (a, a/ b, b/ c, c) denote non-significant differences ( $p > 0.05$ ). January results were not considered in the analysis.

## Discussion

Changes to grain size composition in the presence of sea cucumbers, and the lack of any significant changes in their absence suggest that when sea cucumbers are present on inshore reef flats they play a key role in the physical reworking and change of sediment structure in marine ecosystems. Several species of sea cucumber are able to change sediment grain size through dissolution via acidity in their gut (Hammond 1981), and potentially abrasion while sediment passes through their gut.

Generally in the presence of high densities of sea cucumbers, SOC rates exhibited a buffered response, recovering to near background levels following flooding at the study site. A similar 'buffered' response was observed in O<sub>2</sub> penetration depth, where the absence of sea cucumbers caused erratic changes in O<sub>2</sub> penetration depth.

The abrupt decrease in O<sub>2</sub> penetration depth from December to February coincided with increased water temperatures (26°C in December to 31°C in February) and calm weather, however O<sub>2</sub> penetration depth remained unaffected in areas with high densities of sea cucumbers. Warmer seawater temperatures likely caused small organisms and microbes within the sediment to consume more oxygen (Nydahl et al. 2013). Relatively calm conditions for the same time period meant limited mixing of the sediment and overlying water column by wave action, normally this mixing helps to deliver oxygen into sediment and the overlying water. The buffered response of O<sub>2</sub> penetration depth recorded in areas with high densities of sea cucumbers suggests that during such weather conditions (warm seawater temperatures, calm seas), bioturbation by sea cucumbers may provide essential mixing, helping to deliver oxygen into the sediment.

Sea cucumbers actively feed on organic matter (OM), reducing its concentration in sediment (Uthicke and Karez 1999, Michio et al. 2003). Therefore, it is likely that there was a reduced concentration of OM in sediment where high densities of sea cucumbers were present compared to areas where sea cucumbers were excluded. The resulting high concentrations of OM in the absence of sea cucumbers likely caused an increase in the activity and abundance of small organisms (including microbes) within the sediment (MacTavish et al. 2012), as they would feed on the abundant OM. Respiration of these small organisms, and their waste products, are likely to have resulted in the increased SOC rates (Kristensen 2000).

The buffered responses of SOC and O<sub>2</sub> penetration depth in sediments where high densities of sea cucumbers were present are likely to have been caused by the considerable bioturbation impact *H. scabra* has on sediments (Purcell, 2004; Lee 2016). Bioturbation increases the surface area of the sediment and helps to drive water flow into and within sediment, delivering O<sub>2</sub> and degradable materials. High densities of sea cucumbers likely promoted aerobic decomposition<sup>6</sup> of OM, which is ca. 10 times faster than anaerobic<sup>7</sup> (Kristensen et al. 1995).

Trends seen in SOC and O<sub>2</sub> penetration depth indicate that some functions of sediments, i.e. as a biocatalytic filter system, are compromised as a result of sea cucumber removal. The resistance and resilience of coastal ecosystems to local (e.g. increased nutrient or OM content) and global (e.g. increased sea surface temperatures) stressors are likely being compromised by the extensive reduction in sea cucumber stocks of inshore areas. Consequently the ecosystem

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<sup>6</sup> Aerobic decomposition – the breakdown of biodegradable material in the presence of oxygen

<sup>7</sup> Anaerobic decomposition – the breakdown of material in the absence of oxygen

functions that Pacific Island communities rely heavily on for their food and livelihoods are being undermined by the removal of sea cucumbers, leaving coastal ecosystems and the communities that rely upon them increasingly vulnerable.

## Recommendations

- Moderate to high densities of sea cucumbers should be maintained on reefs through effective regulatory controls on fishing. This will allow sea cucumbers to play their role in maintaining sediment function.
- Given the current low abundances of sea cucumbers in Fiji, the proposed national sea cucumber management plan should consider a moratorium on collection and sales until stocks are able to sufficiently recover and ecosystem function is restored.

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