WAMSI Dredging Science Node Theme 6 | Synthesis report: Defining thresholds and indicators of filter feeder responses to dredging-related pressures

Muhammad Azmi Abdul Wahab[1,2], Jane Fromont[2,3], Mari-Carmen Pineda[2,4], Brian Strehlow[5], Alan Duckworth[2,4], Ross Jones[1,2], Nicole Webster[2,4]

[1] Australian Institute of Marine Science (AIMS),Indian Ocean Marine Research Centre, Perth, Western Australia 6009, Australia

[2] Western Australian Marine Science Institution, Entrance 2 Brockway Road, Floreat, Western Australia 6014, Australia

[3] Western Australian Museum, Locked Bag 49, Welshpool, Western Australia 6986, Australia

[4] Australian Institute of Marine Science (AIMS),PMB No 3, Townsville, Queensland 4810, Australia

[5] School of Plant Biology & Centre for Microscopy Characterisation and Analysis: University of Western Australia, 35 Stirling Highway, Perth, Western Australia 6009, Australia

WAMSI Dredging Science Node

6 Report

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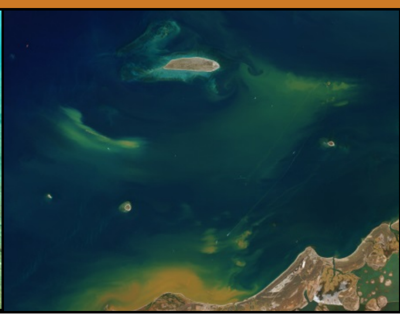


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And critically, the trusted across-sector collaboration developed through the WAMSI model has allowed the sharing of hundreds of millions of dollars worth of environmental monitoring data, much of it collected by environmental consultants on behalf of industry. By providing access to this usually **confidential data,** the **Industry Partners** are substantially enhancing WAMSI researchers' ability to determine the real-world impacts of dredging projects, and how they can best be managed. Rio Tinto's voluntary data contribution is particularly noteworthy, as it is not one of the funding contributors to the Node.

Funding and critical data

Critical data

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Front cover images (L-R)

Image 1: Trailing Suction Hopper Dredge *Gateway* in operation during the Fremantle Port Inner Harbour and Channel Deepening Project. (Source: OEPA)

Image 2: Photograph of mixed filter feeder community at the Onslow study site taken on 07/07/2015, after dredging was completed and after passing of category 3 Cylone Olwyn (Image by MA Abdul Wahab)

Image 3: Riverine discharge plume from the Ashburton River (closer to shore) and dredge plumes at the Onslow study area. Landsat images produced by M. Broomhall and P. Fearns, Remote Sensing and Satellite Research Group, Curtin University. Source of Landsat data: US Geological Survey

Image 4: AIMS scientist, Dr Mari-Carmen Pineda working on an experiment investigating the effects of suspended sediment on

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Contents

1 Sponges

1.1 Introduction

Benthic filter feeders are sedentary animals that obtain some or all of their energy and nutrition requirements by straining particles or small organisms from the surrounding seawater. This is a diverse group of organisms, including bivalves, hard and soft corals, sea squirts and sponges. Filter feeder communities are important marine habitats and often dominate the seafloor particularly in more turbid waters where sunlight penetration is low and in deeper waters towards the lower limit of the photic zone and beyond. Some hard corals occur in these communities where there is sufficient light and appropriate substrates and are the focus of a dedicated research program (see Theme 4 and 7). Sponges are often the most conspicuous components of filter feeding communities, due to their high abundance and diversity, forming extensive 'sponge gardens' (e.g. Schönberg and Fromont 2012). Due to their remarkable ability to filter large volumes of water, sponges are important in linking the pelagic (water column) and the benthos (seafloor) via nutrient cycling and are thus critical to ecosystem functioning (Reiswig 1974; Maldonado et al. 2011; de Goeij et al. 2013). Additionally, sponges provide habitat for a range of mobile taxa (Macdonald et al. 2006; Abdo 2007; Amsler et al. 2009). While most sponges are purely heterotrophic and rely solely on particulate organic matter such as picoplankton and dissolved organic matter for nutrition (Reiswig 1971; de Goeij et al. 2013), some sponges form symbiotic relationships with photosynthetic cyanobacteria and/ or eukaryotes (e.g. zooxanthellae) and may rely on these symbionts for part or most of their nutritional needs (Wilkinson 1983). Because phototrophic sponges require light, they are mostly found at shallow depths (Wilkinson and Evans 1989). Despite their ecological importance, sponge gardens and sponges in general are poorly understood compared to other habitats and very little was known about their susceptibility to dredging-related pressures. For these reasons sponges were selected as the focus for this study into the effects of dredging-related pressures on filter feeding communities.

1.2 The importance of sponges in north west Western Australia

In north west Western Australia (NW WA), sponge gardens are common and can be large in size and biologically complex. While sponge gardens may occur patchily in between coral reef habitats in shallow water, the highest concentrations of these unique filter feeder communities occur in deeper water habitats where corals are less common, it is darker and there is less competition from primary producers for space. For example, deeper habitats (18–102 m depths) off Ningaloo reef are known to harbour dense filter feeder aggregations, with up to 260 species of sponges reported (Heyward et al. 2010; Schönberg and Fromont 2012). Due to their rigid to semi-rigid structure and morphological complexity, sponge gardens are functionally important as habitats for other sedentary and mobile marine taxa including sea squirts, worms, shrimps, bivalves, gastropods and commercially important fish and pearl oysters (Figure 1). In addition, the immense pumping and filtering capacity of sponges underpin their ecological importance in the marine carbon, nitrogen and silicon cycles, retaining nutrients to the seafloor that are otherwise difficult to access from the water column and at the same time improving water quality (Reiswig 1971; Hoffmann et al. 2009; Maldonado et al. 2011; de Goeij et al. 2013).

Many sponges species in NW WA are endemic and it is likely that many more are yet to be discovered and formally described as new species (Hutchings 1990; Butler et al. 2002; Schönberg and Fromont 2012), thus highlighting the global importance of this region for sponge biodiversity. However sponge gardens, and the biodiversity and endemicity they represent, are vulnerable to pressures from large-scale commercial fishing methods (e.g. trawling), and from coastal and offshore development, due primarily to the lack of understanding of their distributions and responses to environmental pressures. It is clear that the management and conservation of these habitats would greatly benefit from research designed to fill these knowledge gaps.

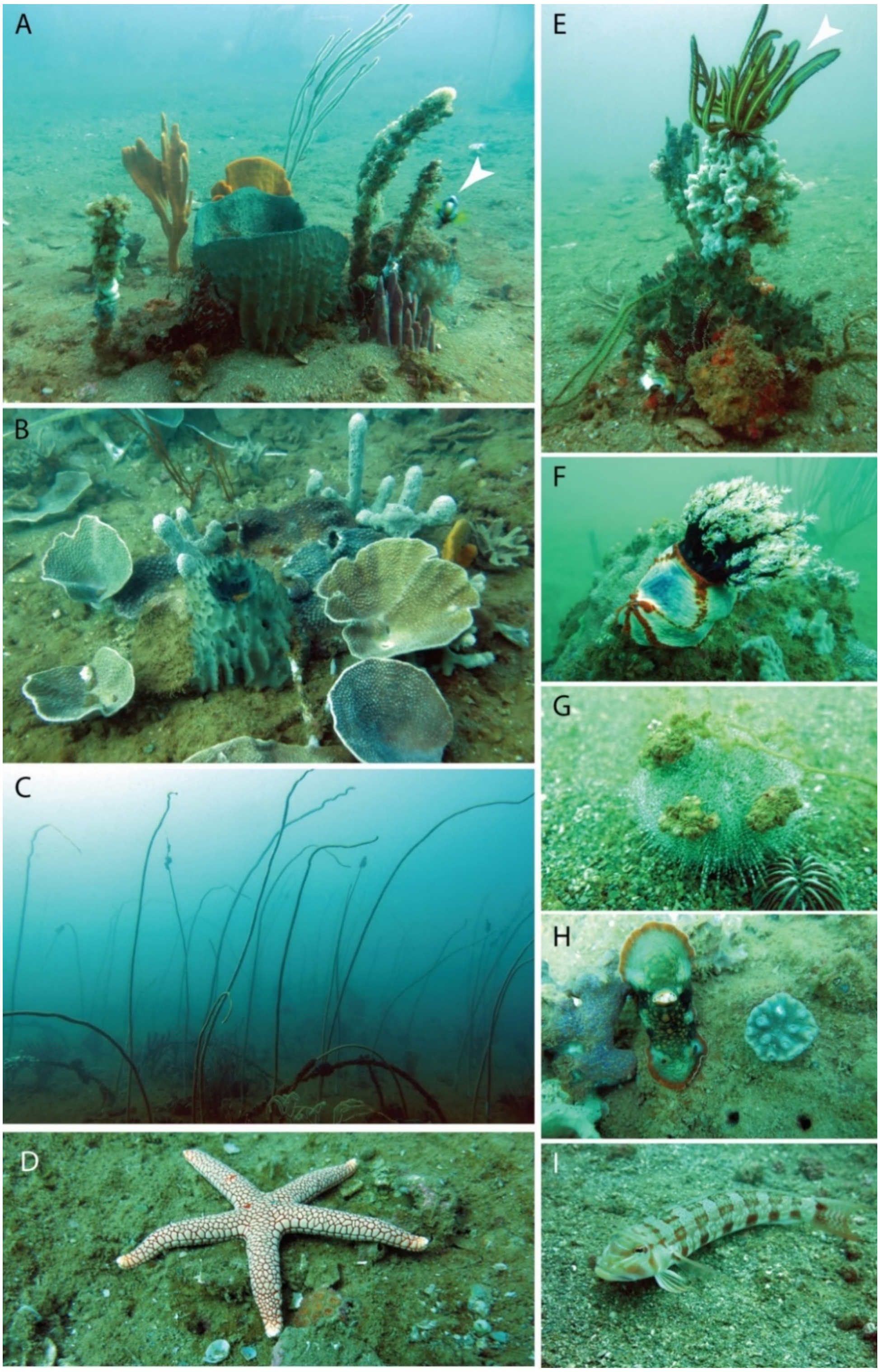


Figure 1. Sponge gardens at the Onslow study site (Pilbara region WA) where capital dredging was completed as part of the Wheatstone project. Images were taken ~4 months after completion of the 2 year capital dredging program and after passing of the category 3 Cyclone Olwyn (March 2015). (A) Sponges formed a significant component of the filter feeder community which also comprised gorgonians, ascidians and bryozoans. A Clark's anemone fish, *Amphiprion clarkii* (see arrow) was found utilizing this patch as habitat. (B) Scleractinian (hard) corals including *Turbinaria mesenterina* and *Favites* spp., and sponges co-exist in the same area. (C) A dense patch of soft corals (Alcyonacea) including the whip gorgonian, *Juncella fragilis.* Mobile taxa also utilize these sponge gardens as habitat including the (D) sea stars (Asteroidea spp.), (E) crinoids (*Crinoidea* spp. see arrow), (F) sea cucumbers (*Holothuroidea* spp., *Pseudocolchirus violaceus*), (G) sea urchins (*Echinoidea* spp., *Salmacis sphaeroides* cf.), (H) nudibranchs and (I) teleost fish spp. (shown here *Parapercis nebulosa*). Photos by MA Abdul Wahab (Onslow, 9–13 m depth, July 2015).

1.3 State of knowledge prior to the WAMSI Dredging Science Node

Prior to the start of the research program, the *a priori* assumption was that sponges were likely to be highly sensitive to fine suspended sediments due to their high rates of pumping and filtering of seawater. However, within the context of dredging, the sensitivity of different sponge species and nutritional groups (heterotrophic vs phototrophic) to differing concentrations and types of suspended sediments and deposited sediments, were largely unstudied. Additionally, no work had consolidated and synthesized the responses of sponge species to dredging related stressors. Although a few studies have shown that some sponges are negatively affected by sediments, the effects of dredging related stressors, such as suspended sediment concentrations (SSCs), light attenuation and sediment smothering, on sponges are poorly understood.

It is likely that dredging effects will vary between sponge species and morphological and nutritional groups. Therefore, Project 6.1 was designed to (1) review the current state of knowledge of the relationships between sponges and sediments, positive or negative, (2) identify gaps in information on dredging related stressors and sponges, and (3) guide the experimental designs of the field surveys (Project 6.3) and laboratory experiments (Project 6.4).

At the start of the research program, there was general consensus that there is a remarkable diversity of filter feeder communities in marine habitats of NW WA. Although sponges were known to be a dominant, species rich and functionally important component of these filter feeding communities (see Brooke et al. 2009; Heyward et al. 2010), only one formal assessment of sponge species compositions and distributions within the NW WA region had been undertaken, and this was for the Dampier Archipelago (Fromont et al. 2006). The Pilbara, together with the Kimberley, are two of the largest regions of Western Australia, however no synthesis of the biodiversity and distribution of sponges throughout the areas was available. This highlighted a critical knowledge gap and as a consequence, resources were specifically dedicated to fully understanding the sponge diversity and species distribution for NW WA to improve the knowledge base for future dredging projects. During the course of this research program, a companion study by Fromont and Sampey (2014) synthesized the biodiversity of sponges from the Kimberley region, consolidating information from databases of the Western Australian Museum, Queensland Museum, Australian Museum and the Museum and Art Gallery of Northern Territory, together with species lists from Hooper (1994), Fromont and Vanderklift (2009) and Keesing et al. (2011), to compliment a similar study in the Pilbara (Project 6.2).

1.4 Research program

The Theme 6 research program was designed to address some of the critical knowledge gaps and to improve our capacity to predict and manage the impact of dredging on sponges. The research program was designed to (1) review and assess the existing knowledge on the relationship of sponges and sediment, (2) review and consolidate the biodiversity and biogeography of sponge species in the Pilbara region where large capital dredging programs are taking place, (3) assess spatial and temporal changes in water quality parameters, and filter feeder communities in the field through a two year capital dredging operation, and (4) assess the effects of dredging related stressors, including SSCs, light attenuation and sediment smothering, in isolation and in combination under conditions simulating realistic dredging scenarios in a series of laboratory experiments.

1.4.1 Project descriptions

Literature review

Project 6.1 reviewed existing knowledge on the relationships of filter feeders and sediments and synthesized information gathered from over 900 peer-reviewed journals and grey literature articles, technical reports and student theses. The focus of the review extended beyond the scope of dredging generated sediment and summarized the negative and positive effects of sediment in general on sponges. The review also summarized what was known of the passive and active adaptations of sponges to sediment related stresses, and importantly identified knowledge gaps within the context of dredging related sediment effects on sponges.

Biodiversity and distributions

Project 6.2 assessed the biodiversity and biogeography of sponge species in the Pilbara region, by amalgamating two large biodiversity datasets from the Western Australian Museum and the Atlas of Living Australia. The project area was defined by a series of coordinates with the coastline forming a natural inshore boundary for the Pilbara (see Figure 2), and complemented the study of Fromont and Sampey (2014) for the Kimberley. The combined database was checked for quality (duplicate and ambiguous records removed) to form the final sponge species dataset used in the study. Species distributions across five Integrated Marine and Coastal Regionalisation for Australian (IMCRA) meso-scale bioregions including Ningaloo, Pilbara (nearshore), Pilbara (offshore), Eighty Mile Beach and part of the North West Shelf; and portions of three IMCRA provincial bioregions including Northwest Transition, Northwest Province and Central Western Transition were assessed, providing a geographic and environmental context for assessing sponge distributions for the area, and also elucidating levels of endemism and global distributions of Pilbara sponges (Commonwealth of Australia 2006).

Importantly, this study also identified co-occurring species from NW WA and the Great Barrier Reef and guided the choice of sponge species used in laboratory experiments at the National Sea Simulator (SeaSim, Australian Institute of Marine Science, Townsville, Queensland) associated with Project 6.4.

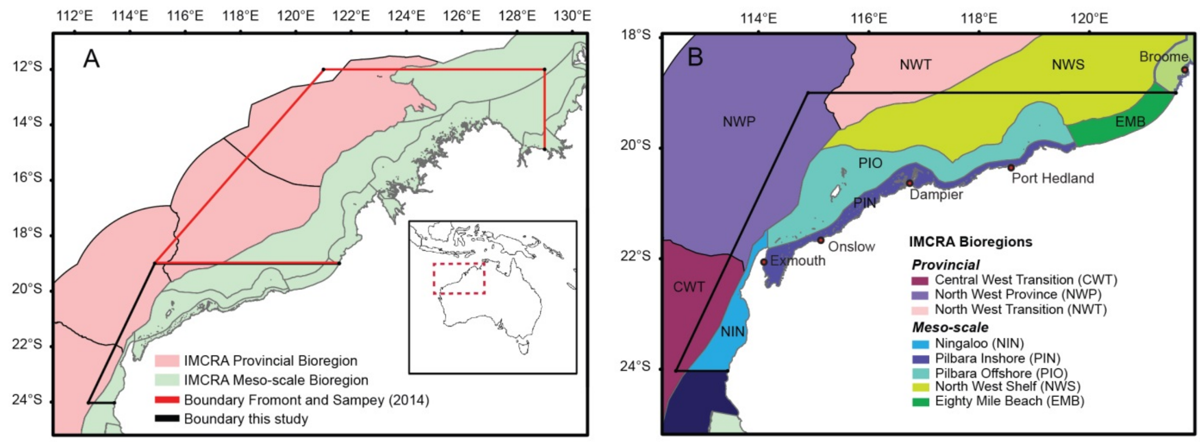


Figure 2. Overview map of the Kimberley and Pilbara region, North West Western Australia. (A) A broad overview of the present study area in relation to previous studies on sponge biodiversity collated by Fromont and Sampey (2014) in the Kimberley region, and (B) the specific area assessed in Project 6.2 which includes three IMCRA Provincial bioregions and five IMCRA Meso-scale bioregions.

Field Studies

The original objective of the field studies was to provide *in situ* community level data for local filter feeders (primarily sponges) before and after a dredging project (Wheatstone Project, see Ministerial Approval Statement MS 873 available on the WA EPA website: http://www.epa.wa.gov.au). The intention was to assess which taxa, growth forms and nutritional modes (heterotrophy or autotrophy) were susceptible to dredging related pressures and whether there were any obvious physiological responses that should be examined further in the subsequent *ex situ* laboratory based studies in Project 6.4. However, the study scope was expanded significantly as water quality and monitoring data were made available from the proponents during the course of the dredging program. These measurements from an actual dredging program provided pressure field information to contextualize, and aid in the interpretation of some of the results of the laboratory-based studies of Project 6.4. Project 6.3 therefore was expanded to include assessments of spatial and temporal changes in water quality parameters, including turbidity (nephelometric turbidity unit [NTU], water clarity), light attenuation and sedimentation (sediment falling out of suspension) using information two years before the start of dredging and for the two years during dredging. The study was also expanded to include the production of a detailed image catalogue of all specimens collected (including sponges, hard corals, soft corals, gorgonians, ascidians, hydrozoans and bryozoans) to provide a practical resource for future marine environmental studies in the area.

This study also investigated the extent of any large-scale changes in benthic filter feeder communities before and after dredging, and assessed shifts in broad taxa composition, sponge functional morphologies, species composition and chlorophyll content. Surveys of filter feeder communities were conducted in nearshore and offshore environments of the Wheatstone Project study area in March 2013, a few weeks before dredging started (pre-dredging survey), and in July 2015 approximately 4 months after dredging finished. A thermal bleaching event and the passing of several cyclones in close proximity to the study area and associated riverine discharge from the Ashburton River, complicated the assessment to some degree. Surveys included: (1) large scale transects using video cameras towed behind a research vessel, which provided broad scale assessments of the benthic habitats; and (2) fine scale transects using SCUBA, which facilitated the collection of sponges for detailed taxonomic investigations and assessments of relative species abundance and chlorophyll content (of phototrophic species). A novel scoring system was used based on sponge functional growth form, which could provide more information on the susceptibility of sponges of different morphology to turbidity and sediment deposition.

Surveys around a shoal at the seaward end of the channel (site name ENDCH) were examined closely, because there were fewer water quality restrictions in this area (in accordance with the approved regulatory framework) and the sponge communities received quite high suspended sediment concentrations and reduced light in absolute terms and relative to baseline conditions.

Laboratory experiments

Project 6.4 involved a series of five controlled laboratory (aquarium) based, *ex situ* experiments to determine cause-effect pathways and dose–response relationships of six sponge species across different morphologies and feeding modes (phototrophic and heterotrophic). These experiments also identified suitable bio-indicators (e.g. sponge bleaching) that are necessary to pro-actively manage dredging projects close to sponge communities. The effects of light attenuation, total SSCs and sedimentation were tested individually and in combination, with treatment levels based on field data from dredging sites in WA. Sediments which are predominantly silt-sized and typical for dredge plumes (~30 µm) were used to ensure environmental relevance. First, a pilot or range-finding experiment tested the effects of a single pulse of sediments (0, 250 and 500 mg L^{-1}; resulting in 0, 8 and 16 mg cm^{-2} of settled sediment, respectively) on ten sponge species encompassing four main morphologies (massive, erect, cup and encrusting) over a 14 d period (Experiment 1). Experiment 2 tested the effects of five different light levels (daily light integrals [DLIs] of 0, 0.8, 3.1, 8.1 mol photons m^{-2} d^{-1} and a natural light control of ~3.2–6.5 mol photons m^{-2} d^{-1}) on three phototrophic and two heterotrophic sponge species for 28 d, followed by a 14 d recovery period under natural light. Experiment 3 tested the effects of five different SSCs (0, 3, 10, 30 and 100 mg L^{-1}) for 28 d, followed by a 14 d recovery period in clear seawater. Experiment 4 tested the effects of sediment smothering (~50 mg cm^{-2} every ~4 d) for 4, 16 and 30 d, followed by a 14 d recovery period. Experiment 5 tested the combined effects of elevated SSCs, light attenuation and sedimentation under realistic dredging scenarios based on field data. Experiments were conducted in custom designed small tank (115 L) and larger tank (1500 L) systems that provided reliable automated sediment delivery, and continuous monitoring of turbidity, light intensity and sedimentation (Figure 3). The infrastructure at SeaSim is unique, hence these experiments could not have been performed elsewhere in Australia (or globally).

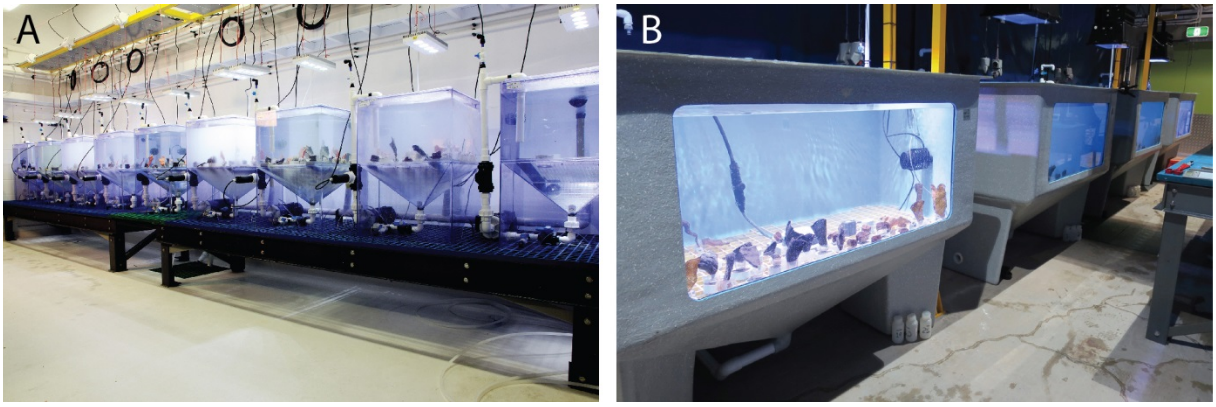


Figure 3. (A) Experiment 3 (SSCs) was performed in custom designed small tank systems (115 L) with automated sediment delivery, and continuous monitoring of light, turbidity and sedimentation, and (B) Experiment 5 (combined effects) was performed in the larger tank systems (1500 L) with similar sediment delivery and environmental monitoring systems.

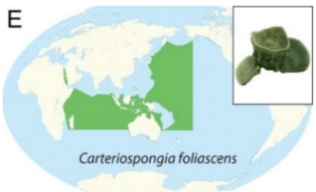
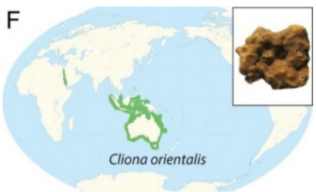
1.4.2 Research priorities

The literature review found that sediments can have numerous negative effects on sponges caused from elevated SSCs (e.g. sediment clogging their aquiferous systems), light attenuation (e.g. reducing photosynthesis in phototrophic sponges) and sediment smothering (e.g. preventing feeding; Project 6.1, Schönberg 2016). However, the levels or thresholds at which these dredging stressors become detrimental are unknown. This knowledge gap was addressed in: (1) Project 6.3 which assessed spatial and temporal changes in light availability, turbidity and sedimentation at the site of a two year dredging program, and the responses of filter feeder communities and sponges in the field; and (2) Project 6.4 which assessed the responses of sponges to dredging related stressors in a laboratory based approach.

1.4.3 Species selection

This biodiversity and biogeography study of NW WA sponge species (Project 6.2, Fromont et al. 2016), enabled the selection of six species of sponges which co-occurred on the tropical west (NW WA) and east of Australia (GBR) for use in laboratory experiments in Project 6.4, with species ranging across multiple functional morphologies and nutritional modes (Table 6.1). These species included the phototrophic species *Carteriospongia foliascens*, *Cliona orientalis* and *Cymbastela coralliophilla*. The first two species are known from NW WA and the GBR, and the latter species is congeneric with a NW WA species, *Cymbastela stipitata*. The heterotrophic species were *Ianthella basta*, *Stylissa cf. flabelliformis* and *Coscinoderma matthewsi* and occur in both NW WA and the GBR.

Table 1. Australia centred maps of global distributions of the six sponge species selected for experiments in Project 6.4, and their common functional morphology, biology and biogeography. (A) *Ianthella basta*, (B) *Stylissa cf. falbelliformis*, (C) *Coscinoderma matthewsi*, (D) *Cymbastela coralliophila*, (E) *Carteriospongia foliascens*, and (F) *Cliona orientalis*. Refer to Schönberg and Fromont (2014) for definitions on sponge functional morphologies.

Species and distribution maps	**Functional morphology**	**Biology and Biogeography**
A 	Erect laminar (E-lam)	Broadcast spawning, heterotrophic feeding (i.e. non-photosynthetic) Widespread Indo-Pacific species and common to the tropical coasts of western, northern and eastern Australia including the Pilbara and GBR
B 	Erect laminar, erect palmate or erect branching (E-lam, E-pal, E-br).	Broadcast spawning, heterotrophic feeding (i.e. non-photosynthetic) Occurs throughout northern and northwestern Australia (including the Pilbara and Kimberley), Indonesia and New Caledonia.
C 	Massive simple (M-s)	Brooder, heterotrophic feeding (i.e. non-photosynthetic) Reported from Micronesia, New Caledonia and parts of tropical Australia including the Pilbara and GBR.
D 	Cup tabulate (C-tab)	Broadcast spawning, phototrophic (i.e. photosynthetic symbionts) Known from the GBR and Torres Strait, not reported outside Queensland. A sister species, *C. stipitata*, is known from the Northern Territory and NW WA, including the Pilbara and Kimberley.
E 	Cup incomplete or cup wide (C-inc, C-wd)	Brooder, phototrophic (i.e. photosynthetic symbionts) Widespread Indo-Pacific species recorded extensively from the GBR and more recently from the Kimberley and offshore atolls. *Carteriospongia* species have been recorded from the Dampier region in the Pilbara and offshore reefs in the Kimberley
F 	Encrusting endolithic (EN-en)	Broadcast spawning, phototrophic (i.e. photosynthetic symbionts) Indo-Pacific species first recorded from Indonesia and since then from the GBR, Northern Territory and NWA including the Pilbara, the Kimberley, and New South Wales and New Caledonia.

2 Overview and synthesis of findings

2.1 Sponge biodiversity and distributions in north west Western Australia

A total of 1164 species and operational taxonomic units (OTUs[1]) were recorded for the Pilbara region from the amalgamation of the two databases in Project 6.2 (Fromont et al. 2016). An additional 69 species and OTUs were further recorded from field collections in Project 6.3 (Abdul Wahab et al. 2017), bringing the total of sponges known from the Pilbara to 1233, and NW WA to 1484 (including additional species from the Kimberley, Fromont and Sampey 2014). The high proportion of OTUs highlights the overwhelming number of species requiring formal taxonomic identification in NW WA. Species richness varied considerably between IMCRA bioregions, with 78% of the species recorded from the Pilbara only occurring in one of the six bioregions investigated, and thus defined as 'apparent endemics' (sensu Hooper et al. 2002; Table 2). At a global scale, almost half (77 species out of 173 described species, 45%) are endemic to Australia and almost a quarter (17 species, 22%) were endemic to NW WA. This high level of endemism is a factor that should be considered when planning large scale coastal infrastructure developments in areas with biodiverse sponge communities. These findings highlight more broadly the importance of having good management protocols in place to avoid and reduce the risks and impacts on biodiversity values when executing development plans, particularly when undertaken in areas where sessile benthic communities such as sponge gardens are poorly described.

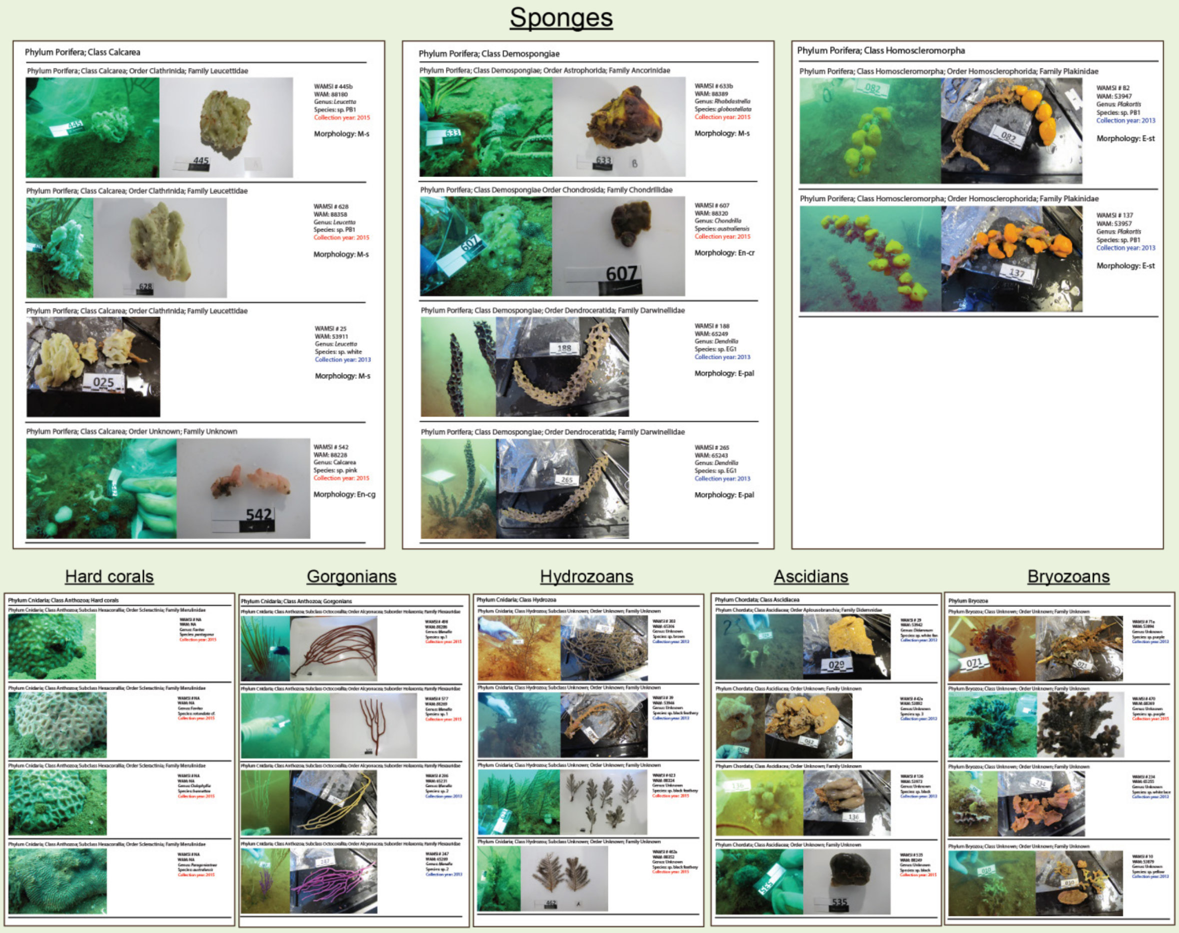
Table 2. Species richness, number of apparent endemics and the proportion of apparent endemics at each Integrated Marine and Coastal Regionalisation for Australian (IMCRA) bioregion. Apparent endemics refer to taxa that are geographically restricted and were not recorded outside a particular bioregion relative to other bioregions investigated (*sensu* Hooper et al. 2002).

IMCRA bioregion	Total species richness (n)	Apparent endemics (n)	Proportion apparent endemics (%)
North West Shelf (NWS)	232	117	50.4
Pilbara Offshore (PIO)	413	209	50.6
Pilbara Nearshore (PIN)	406	285	70.2
Ningaloo (NIN)	331	225	68.0
North West Province (NWP)	110	64	58.1
Central West Transition (CWT)	30	7	23.3

[1] An OTU refers to a group of individuals having distinct morphological characters compared to described Linnean species and other OTUs, but requiring further rigorous assessments to establish their specific taxonomic status. OTUs were considered to be unique species and are relevant taxonomic units for biodiversity assessments following assignments of unique species codes.

Box 1: Field photo catalogue of the benthos for Onslow

Based on surveys in Project 6.3, a detailed 166 page colour image catalogue was developed which consolidated all specimens collected during the field study at Onslow, before and after dredging, which included sponges, hard corals, soft corals, gorgonians, ascidians, hydrozoans and bryozoans. The catalogue includes underwater (*in situ*) photographs and surface (above water) photographs, reference to the Western Australian Museum registration number for each specimen, and is intended as a practical resource for future marine environmental studies in the area. Information on chlorophyll-a concentrations and phototrophic capacities of sponges in this photo catalogue are included as Figure 7 in the Project 6.3 report (Abdul Wahab et al. 2017). See excerpts from the photo catalogue below.



2.2 Natural and dredging related patterns in water quality through a two year capital dredging program (Wheatstone project)

The Wheatstone project comprised the largest capital dredging program to date for Western Australia, and involved the relocations of ~31.4 Mm^3 of sediment from a channel and a shore-connected material offloading facility to a number of offshore dredge material placements sites (spoil grounds). High resolution water quality data (collected every 30 mins) at 16 locations were analysed to examine temporal patterns and the effects of dredging on turbidity (NTU) and light availability (Figure 4). The particle size distribution (PSD) of sediments was also analyzed at 56 stations before, and 1 month and 7 months after dredging, to indicate where dredge sediment was depositing onto the seafloor. The surveys were concentrated on the entrance channel and in 3 areas — an Inner (nearshore) zone, a Middle (transition) zone and an Outer (offshore) zone, as determined by the baseline water quality and PSD analyses. Surveys around a shoal at the seaward end of the channel (ENDCH, Figure 4) were examined closely, because there were fewer water quality restrictions in this area (in accordance with the approved regulatory framework) and the benthic communities received quite high suspended sediment concentrations and reduced light in absolute terms and relative to baseline conditions.

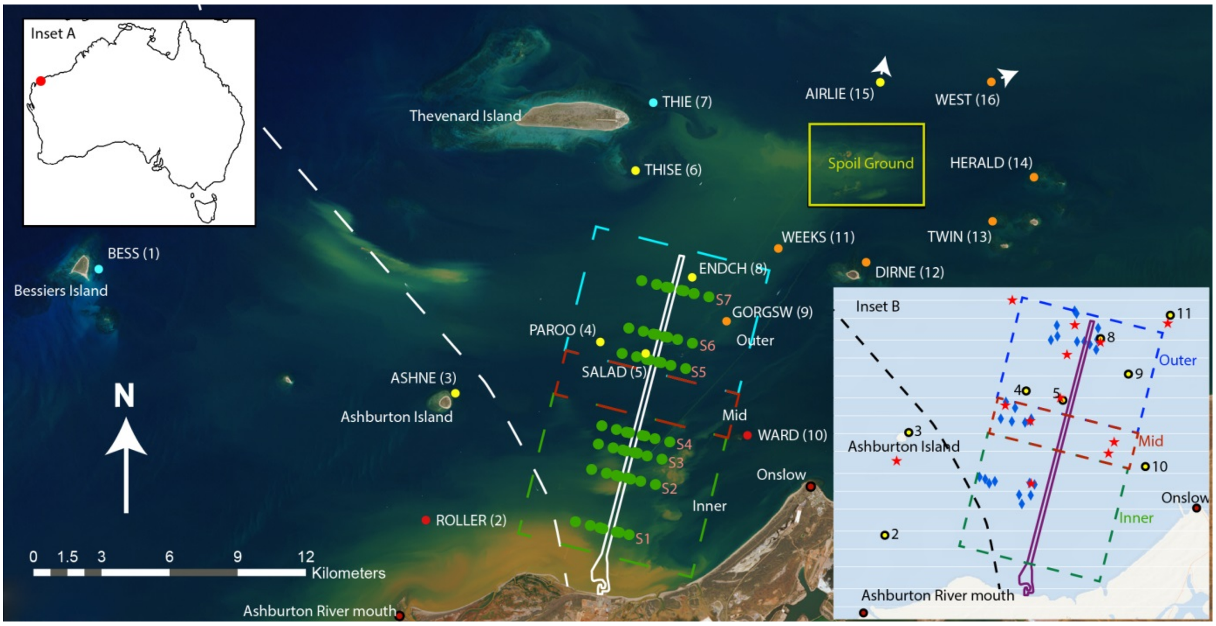


Figure 4. Atmospherically and colour corrected, pan sharpened Landsat image from the United States Geological Survey (USGS) Operational Land Imager (OLI) instrument of the study area on 24th August 2013 during the dredging phase, showing the location of (1) the study site in the Pilbara Region of NWA (see Inset A) 12 km west of the coastal township of Onslow and east of the Ashburton River mouth. A sediment plume from the Ashburton River (see Ashburton River mouth) can be seen migrating eastwards close to the shore, (2) the entrance channel, gas trunk line (dashed line west of the channel) and dredge placement site (spoil ground; yellow box), (3) the 16 water quality monitoring sites. Sites are coloured according to pre-dredging nephelometer turbidity unit (NTU) clusters (light blue = cluster 1, yellow = cluster 2, orange = cluster 3 and red = cluster 4; see Figure 2 of Project 6.3 report), and (4) the seabed particle size distribution (PSD) sampling sites (S1–S7; green dots). Landsat images produced by M. Broomhall and P. Fearns, Remote Sensing and Satellite Research Group, Curtin University. Source of Landsat data: US Geological Survey.

The study area was naturally turbid, with sites located in the nearshore environment (<5 km from the coast) up to 6.5× more turbid than offshore areas (>24 km offshore) during the baseline (pre-dredging) period. Benthic light availability showed a reverse pattern, with the nearshore and deeper sites receiving ~6.5× less light than offshore sites. This natural gradient was attributed to natural wind and wave resuspension events of the shallower nearshore area, and also to the influence of riverine discharges from the nearby Ashburton River (see Figure 4 for satellite imagery of the study area). Dredging increased turbidity by 1.3–2.6×, with the largest change observed in the nearshore area where most dredging occurred, and reduced benthic light availability to 0.3–0.4× that of pre-dredging levels at sites closest to the excavation (Figure 4 and 5). One month after dredging, clay and silt sized particles (<60 um) dominated the seafloor close to the shipping channel and indicated elevated sediment deposition. However seven months after dredging, sediment particle size distributions showed some return to the coarser pre-dredging levels. Cyclone Olwyn, which passed very close to the area as a category 3 cyclone after dredging may have influenced this recovery process, redistributing the finer sediments over a larger area.

Water quality was managed by the proponent during the dredging campaign using a comprehensive environmental management plan which contained a zonation scheme (MS 873). The area around a small shoal (End of Channel Shoal, ENDCH) located 700 m from the most seaward extent of the navigation channel, was of particular interest as there was no water quality management required at the site, and would most likely have been affected by dredging (Figure 4 and 5). ENDCH experienced short term acute turbidity events when dredging occurred nearby, as well as low level chronic elevations associated with westerly drift of sediment from the dredge material placement site. The relative change in water quality at the sites was most pronounced, showing the highest increase of turbidity above baseline levels (2.6× pre-dredging levels) and clear reductions in light availability (0.4× pre-dredging levels). Therefore, the assessment of benthic community changes around the ENDCH water monitoring site is of particular interest in investigating the effects of dredging. For a detailed description and analyses of spatial and temporal patterns in water quality at the Wheatstone Project, refer to the Project 6.3 report (Abdul Wahab et al. 2017).

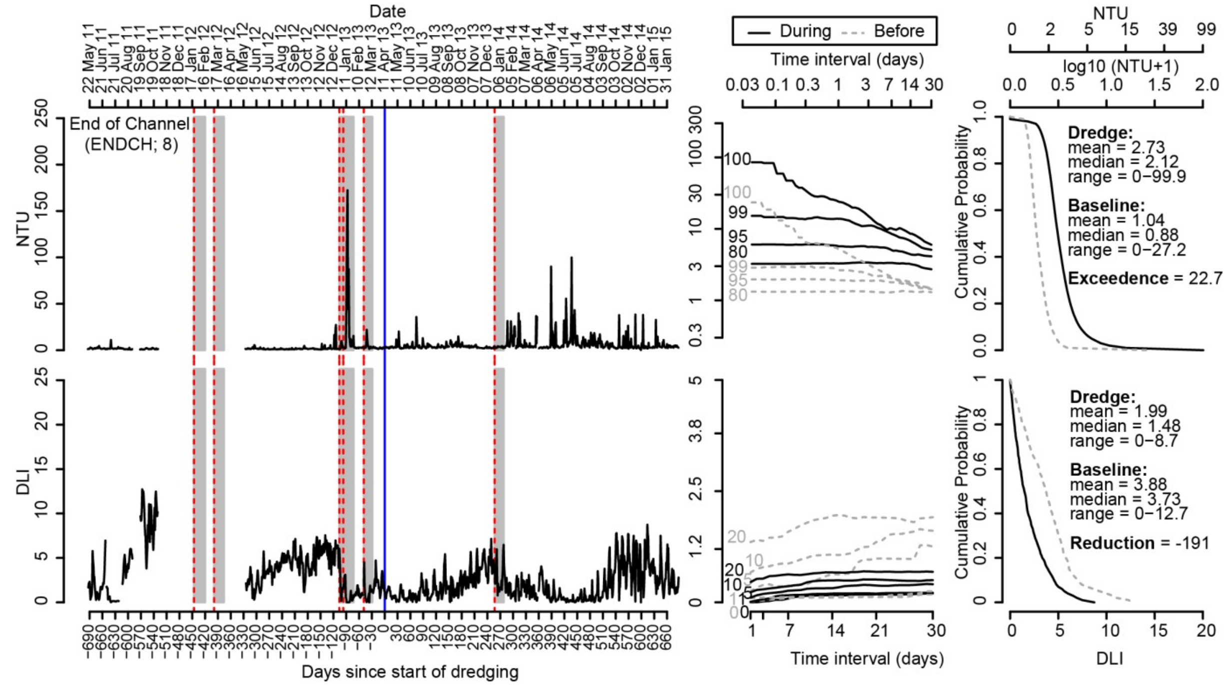


Figure 5. Daily maximum, percentile and cumulative probability plots of NTU (top graph) and DLI (bottom graph) at the End of Channel (ENDCH) water monitoring site, in close proximity to the shipping channel. Blue vertical lines represent time when dredging started. Grey vertical bars with red dashed vertical lines represent the duration and start date of the 5 cyclones that passed near the study area respectively. Turbidity was highly variable with prominent transient and episodic peaks, with depressions in DLI values coinciding with periods of turbidity peaks. NTU values were relatively stable across running mean intervals below the 99th percentile, with a decrease observed at the >7 d running mean interval. A clear increase in NTU is apparent across all percentile values during dredging. The cumulative probability plot of NTU reflects the increase in turbidity with dredging, with the area between before and during dredging curves representing exceedance. Similarly, the cumulative probability plot of DLI showed a decrease in light during the dredging phase with area between before and during dredging curves representing DLI reduction (see Supplementary Figure 1 of Project 6.3 report Abdul Wahab et al. 2017, for plots of all 16 water monitoring sites).

Box 2: Accounting for natural turbidity generating processes

Over the baseline (pre-dredging period) and during the dredging phase of the Wheatstone dredging project described in Project 6.3 we recorded:

- A bleaching event caused by a marine heat wave which had demonstrable effect on the corals in the shallow turbid water communities near Onslow (Lafratta et al. 2016).
- 6 tropical cyclones (TC) passing close to the study site (including TC Iggy = 150+ km away; TC Lua = 17 km; TC Mitchell = 40 km; TC Rusty = 140 km and TC Christine = <10 km) and TC Olwyn, which passed directly over the study site soon after dredging finished.
- Flooding from the Ashburton River on several occasions.

Pre-development surveys

As part of the EIA process, dredging proponents are typically required to describe the receiving environment (EPA 2016). The history of disturbance events such as bleaching events, cyclones and storms, and flooding events should also be considered as part of the baseline habitat description phase. Reference sites, least likely to be affected by dredging, should be identified and monitored prior to and during development phase to differentiate impacts from natural phenomena and dredging. For cyclones, damage zone models exist that can predict whether a sea state is sufficient to severely damage reef communities based on wind speed, duration and fetch. These can be used to identify spatial patterns in historic cyclone exposures and explain the trajectories of habitat conditions (e.g. recovery from cyclones).

Consequently, it is informative to evaluate natural turbidity and sediment characteristics of habitats proposed for future dredging, and recognise that environmental filtering may play a role in selecting for sediment tolerant taxa and/ or morphologies which may reduce the vulnerability of these taxa to dredging related sediment.

To comprehensively sample and survey for changes in benthic communities, water quality data (at least one year of pre-dredging water quality monitoring) should be made available prior to the first baseline assessments. This will allow for selection of reliable reference sites not/ least affected by natural sources of sediment.

2.3 Biological responses to dredging related stressors

The following sections on the effects of dredging related stressors on benthic filter feeder communities integrates information gathered from laboratory based experiments (Project 6.4), which investigated the effects of individual stressors in isolation and in combination, and results from observations in the field during the two-year capital dredging program for the Wheatstone project (MS 873; Project 6.3).

There are many different mechanisms (cause-effect pathways) whereby sediment could affect filter feeders. These include reduced light availability for photosynthesis of the sponges' symbionts (by light scattering in the water column), reduced filtering and feeding by elevated suspended sediment concentrations (SSCs), and increased sediment deposition that could result in tissue smothering. The problem is that these largely physical pressures can act either alone or in combination, which can obscure or confound attempts to relate the various pressures to the biological responses and to define exposure conditions above which effects could occur (i.e. derive guideline values). Laboratory-based studies can offer some solution to the issue of pressures operating in combination, by allowing isolation and separation (disentanglement) of some of the variables and examining mechanisms individually.

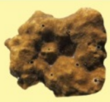
The isolation of stressors eliminated confounding and interactive effects, and produced results to derive trigger values useful for predicting effects of simulated plumes during the environmental impact assessment (EIA) phase, and for supporting water quality monitoring programs during the implementation phase which would alert dredging proponents to levels of light reduction, SSC and sedimentation that, if continued, could detrimentally impact sponge populations. Concurrently, the field study provided an insight into the response of sponges, and other taxa of filter feeder communities to a two-year operational dredging program, and verified to a certain extent, the cause-effect pathways found in the laboratory studies.

2.3.1 Effects of light attenuation on sponge communities

Phototrophic sponge species showed a potential for short-term acclimation to different light levels (photo-acclimation), as suggested by increased chlorophyll fluorescence during the first few weeks under low light conditions in the laboratory (Pineda et al. 2016a). However, light reduction impacted the three phototrophic species differently, with *C. foliascens* being most sensitive and incurring the highest mortality (see Table 3 for a summary of responses for all species tested). *Cliona orientalis* showed some levels of stress (i.e. bleaching) but was able to recover without incurring any mortality; and *Cymbastela coralliophila* was most tolerant to low light. In contrast, the heterotrophic sponge species (*I. basta* and *S. flabelliformis*) were unaffected by light attenuation over the course of the experiment (Table 3).

Table 3. Summary of the effects of light attenuation on phototrophic and heterotrophic sponge species. Red row represents species that are sensitive, yellow represents species that are sensitive but with potential for recovery, and green represents species that are tolerant. No effect was seen in heterotrophic sponges.

Effects of light attenuation

			Sub-lethal stress	Recovery	Mortality	Mechanism
Phototrophic	Cup inc/ wd	 *C. foliascens*	Survive in >0.8 DLI for 28 d Bleaching in <0.8 DLI in 7 d Mortality in <0.8 DLI in 28 d	Yes for DLI > 0.8 No for DLI < 0.8	Yes <0.8 DLI, 28 d	Total loss of photo-symbionts. Highly specialised microbi-ome. Energy deple-tion
Phototrophic	Encrusting en	 *C. orientalis*	Survive in 0 DLI for 28 d Bleaching in <0.8 DLI in <7 d	Yes	Not observed	Ability to switch between nutritional modes (compensates with heterotrophic feeding)
Phototrophic	Cup tab	 *C. coralliophila*	Survive in 0 DLI for 28 d Minor bleaching in <0.8 DLI in 28 d	Yes	Not observed	Ability to feed heterotrophically. No changes observed in microbiome
Heterotrophic	Erect lam	 *S. flabelliformis*	No effect	No effect	No effect	Feeds heterotrophi-cally
Heterotrophic	Erect lam	 *I. basta*	No effect	No effect	No effect	Feeds heterotrophi-cally

Increased turbidity (reduced water clarity) corresponds to reductions in light penetration through the water column, thus reducing the amount of photosynthetically active radiation to the benthos. The Wheatstone Project study area was relatively turbid pre-dredging with daily light integrals (DLI) ranging between 1.9 and 5.0 (based on the 20th percentile of the 30 day running means for ASHNE, PAROO, ENDCH, SALD and GORGSW). Four of the species or sister species tested in the laboratory experiment, namely the phototrophic species *Cliona* sp. PB1 and *Cymbastela stipitata*, and the heterotrophic species *S. flabelliformis* and *I. basta* were found during the pre- and post-dredging surveys, corroborating resilience of these species under low light condition as seen in the laboratory experiments. The highly phototrophic cup sponge *C. foliascens* which showed bleaching and mortality when exposed to low experimental DLI levels (Table 3) was absent at the field study site even prior to dredging.

Carteriospongia spp. have been reported from other clear water localities in the Pilbara Nearshore bioregion (e.g. Dampier Archipelago) and neighbouring Pilbara Offshore bioregion (Abdul Wahab et al. 2014; Fromont et al. 2016). The absence of *Carteriospongia* spp. at Onslow suggests that historical exposure (>2 y) to natural DLI levels between 1.9 and 5.0, interspersed with extended periods of high turbidity (minimum DLI of the 30 d running means ranging between 0.2–3.1), may have incurred mortalities to adults and new recruits of *C. foliascens* arriving to the area. This suggests the relatively turbid environment of Onslow is a poor habitat for highly phototrophic sponges. This was further reflected in the relatively low levels of chlorophyll-a concentrations of the majority (>90%) of sponge species collected from the Onslow area (Abdul Wahab et al. 2017).

Box 3: Implications of the findings on sponge responses to light attenuation for the management of dredging

- Heterotrophic sponge species were not affected by light reduction
- Phototrophic sponge species showed species-specific responses to light reduction.
    - *Carteriospongia foliascens* bleached after 7 d in darkness (0 DLI treatment), concomitant with significantly reduced fluorescence yields, reduced chlorophyll concentrations, a significant shift in the composition of the microbial community and was unable to recover under natural light, with half of the bleached individuals dying during the recovery period (SENSITIVE)
    - *Cliona orientalis* bleached after 3 d in darkness, concomitant with reduced fluorescence yields and chlorophyll concentrations, but recovered completely after 14 d under natural light conditions (SENSITIVE – with potential for RECOVERY)
    - *Cymbastela coralliophila* appeared less affected by low light showing only a slight decrease in photosynthetic pigments and growth rates, and all individuals recovered fully under natural light conditions (Highly RESILIENT)

Pre-development surveys

Proponents are encouraged to survey areas for cup and phototrophic sponge species pre-dredging, which will facilitate strategic deployment of sensitive water quality monitoring receptors for future monitoring and management of phototrophic sponge communities. Project 6.3 compiled a 166 page colour photographic catalogue of sponges, and other benthic taxa, collected from the Onslow area which can be used for standardisation of data with respect to sponge functional morphology and benthic taxa species identification.

Monitoring

Cup and phototrophic species such as *Carteriospongia* spp. (sensitive species) with a detrimental bleaching response to light attenuation, represent suitable visual indicators for the monitoring and management of dredging related stressors. When used in conjunction with water monitoring programs, early detection of discolouration in phototrophic sponges between reference and impact zones (to account for natural variation) can inform dredging proponents of any detrimental stress to phototrophic sponge populations allowing for management measures to be implemented to reduce stress.

Management

Phototrophic and heterotrophic sponge species can survive under moderately low light intensities (DLI ≤3.1 mol photons m^{-2} d^{-1}) for 28 d. However, some phototrophic species bleach within 72 h while the health of other species is seriously impaired after 7–14 d in complete darkness. Hence, dredging events that cause complete and continuous darkness (DLI 0 mol photons m^{-2} d^{-1}) should be limited to <7 d to prevent sponge mortality.

2.3.2 Effects of total suspended sediment concentrations on sponge communities

Five sponge species – *C. foliascens*, *C. orientalis*, *C. coralliophila*, *S. flabelliformis* and *C. matthewsi* – were exposed to varying levels of SSC (0, 3, 10, 30 and 100 mg L^{-1}) for 28 d followed by a 14 d recovery period in clean water.

Most sponges survived the 28 d exposure period, although many sponges exposed to >23 mg L^{-1} shrunk in size, had fewer lipid (energy) reserves and bleached (Table 4). Mortality was only observed in *C. foliascens* and *C. matthewsi* exposed to >23 and 100 mg L^{-1}, respectively. An increase in phototrophic feeding in high SSC was indicated by a reduction in choanocyte chambers, increased *Symbiodinium* sp. cells in *C. orientalis*, increased Chl d concentrations (viz. Cyanobacteria) in both *C. foliascens* and *C. coralliophila*, and increased Cyanobacteria OTUs among the phototrophic species. Most sponges recovered 14 d after experimental exposures in control conditions. However, *C. foliascens* exposed to >23 mg L^{-1} exhibited necrosis and subsequently died.

In the field, dredging had clear and pronounced effects on water column turbidity as reported in several other dredging projects in Western Australia (Fisher et al. 2015; Jones et al. 2015). The ratio of dredging/ baseline turbidity ranged between 0.9–2.5 (based on the 80th percentile of 1 d running means), maxima of which is lower than in three other large scale capital dredging projects in Western Australia, where values ranged between 0.5–6.8 (Barrow Island project), 1.3–4.8 (Burrup Peninsula project), and 1.5–18.6 (Cape Lambert project, see Fisher et al. 2015). The existing patterns in sponge functional morphology remained relatively stable through periods of elevated sediment levels, which indicate an established community adapted to living in environments exposed to high sediment load. The persistence of *Cliona* sp. PB1, *C. stipitata*, and *S. flabelliformis* through the two year dredging program corroborated results from the laboratory study.

Table 4. Summary of the effects of suspended sediment concentrations (SSCs) on phototrophic and heterotrophic sponge species. Red row represents species that are sensitive, yellow represents species that are sensitive but with potential for recovery, and green represents species that are resilient.

			Effects of suspended sediment concentrations (SSCs)			
			Sub-lethal stress	Recovery	Mortality	Mechanism
Phototrophic	Cup inc/wd	 *C. foliascens*	Survive at SSCs <23 mg L^{-1} for 28 d High mortality and necrosis at SSCs >23 mg L^{-1} from 7 d	Yes for SSCs <23 mg L^{-1} No for SSCs >23 mg L^{-1}	Yes for SSCs >10 mg L^{-1} for 28 d Necrosis at SSCs >23 mg L^{-1} from 7 d	Decreased respiration rates and lipids. Discruption of the holobiont under high SSCs. Enerrgy depletion
	Encrusting en	 *C. orientalis*	Survive in SSC >70 mg L^{-1} for 28 d with bleaching observed No effects at SSC <23 mg L^{-1}	Yes	Not observed	Ability to increase phototrophic feeding under high SSCs as long as light is available
	Cup tab	 *C. coralliophila*	Survive at SSCs >70 mg L^{-1} for 28 d	Yes	Not observed	Ability to increase phototrophic feeding under high SSCs as long as light is available
Heterotrophic	Erect lam	 *S. flabelliformis*	Survive at SSCs >70 mg L^{-1} for 28 d, but negative growth under any SSC	Yes	Not observed	Reduced feeding ability with depletion of energy reserves under high SSC
	Massive s	 *C. matthewsi*	Survive at SSCs <23 mg L^{-1} for 28 d, but negative growth under any SSC Some mortality and necrosis at SSCs >70 mg L^{-1} for 28 d	Yes	20% mortality at 70 mg L^{-1} after 28 d	Reduced feeding ability with depletion of energy reserves under high SSC

Box 4: Implications of the findings on sponge responses to suspended sediment concentration (SSCs) for the prediction and management of dredging impacts on sponges

- Exposure to high SSC (>23 mg L^{-1}) for extended periods (28 d) had a negative effect on sponge feeding behaviour with associated depletion of energy reserves.
- Exposure to ≤10 mg L^{-1} (in isolation) for <28 d was tolerated by most species and could be established as a reasonable sub-lethal threshold for SSCs in adult sponges.

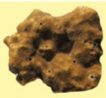
2.3.3 *Effects of sediment smothering on sponge communities*

Two experiments were performed to test the effects of sediment smothering on sponges. In the first experiment (Experiment 1; Pineda et al. 2016), the effects of high sedimentation included mortality of cup shaped *Callyspongia confoederata* and small areas of tissue necrosis in other species, with massive, encrusting and wide cup morphologies particularly affected. However, the sediment concentrations tested did not cause changes in the concentration of sponge pigments or the structure of the symbiotic microbial community in any species. Results indicated that a single pulse of sediments less than 16 mg cm^{-2} is not detrimental to most sponge species.

In the second experiment (Experiment 4), all sponges survived the 30 d smothering period and subsequent recovery phase and, in most species, sediment smothering did not cause any visible signs of stress (viz. tissue necrosis; Table 5). A number of different mechanisms for coping with sedimentation stress were observed across the various species including sediment sloughing by mucus production and removal of sediment from the sponge surface by infauna. It was expected that active cleaning mechanisms (e.g. mucus production) may have an energetic cost for the sponges and that repeated and prolonged smothering would cause a further depletion of energy reserves. Accordingly, negative growth rates were observed in most sponges exposed to 16 and 30 d of smothering. However, a 30 d sediment smothering period did not cause any mortality, visible signs of host stress, lipid depletion or overall changes in sponge respiration rates and did not affect the photosymbiont activity or microbiome composition of any of the five sponge species. While partial bleaching was observed in some specimens of the phototrophic encrusting species *C. orientalis* when exposed to 16 and 30 d of smothering, full recovery was observed at the end of the recovery phase.

Table 5. Summary of the effects of sediment smothering on phototrophic and heterotrophic sponge species. Red row represents species that are sensitive, yellow represents species that are sensitive but with potential for recovery, and green represents species that are resilient.

Effects of sediment smothering

			Sub-lethal stress	Recovery	Mortality	Mechanism
Phototrophic	Cup inc/ wd	 *C. foliascens*	Survive being smothered for 28 d No necrosis observed	Yes	Not observed	Mucus production and sediment sloughning
	Encrusting en	 *C. orientalis*	Survive being smothered for 28 d No necrosis observed Partial bleaching	Yes	Not observed	High sediment clearing removal rates. Ability to close oscula and develop new ones
	Cup tab	 *C. coralliophila*	Survive being smothered for 28 d No necrosis observed	Yes	Not observed	Unknown. Potential for self-cleaning strategies.
Heterotrophic	Erect lam	 *S. flabelliformis*	Survive being smothered for 28 d No necrosis observed	Yes	Not observed	High sediment removal rates, likely due to erect morphol-ogy and microhispid surface
	Massive s	 *C. matthewsi*	Survive being smothered for 28 d No necrosis observed	Yes	Not observed	Ability to develop new oscula. Removal of sediment from the aquiferous canals by infauna e.g. Ophiuroids

Box 5: Implications of the findings of sponge responses to sediment smothering for the prediction and management of dredging impacts on sponges
• A single pulse of sediments less than 16 mg cm^{-2} was tolerable for most of the sponge species studied, although some negative effects (necrosis) were observed, primarily in massive, encrusting and horizontal cup morphologies.   • Although negative growth rates were observed in most sponges exposed to 16 and 30 d of smothering, a 30 d sediment smothering period did not cause mortality, visible signs of host stress, lipid depletion or overall changes in sponge respiration rates, and it did not affect the photosymbiont activity or microbiome composition of any of the five sponge species

2.3.4 Effects of combined dredging stressors on filter feeder communities

A final experiment combined the effects of the three dredging related stressors viz. light attenuation, suspended sediment concentrations and sediment smothering. In the high impact treatment (SSC of ~70 mg L^{-1} and DLI of 0.11 mol photons m^{-2} d^{-1}), high levels of bleaching/partial mortality and total mortality of 90% and 20% were observed in *C. foliascens* and *C. orientalis* respectively, after 28 d exposure (Table 6). In *C. foliascens*, stress responses were observed in all treatments ≥10 mg L^{-1}, with an LC_{50} of 47.02 mg L^{-1} (LC_{50} corresponds to the concentration at which 50% mortality was encountered; range: 39.8–56.0 mg L^{-1}) with 0.266 mol photons m^{-2} d^{-1} (range: 0.214–0.334), and an LC_{10} of 22.50 mg L^{-1} (LC_{10} corresponds to the concentration at which 10% mortality was encountered range; 13.9–30.6 mg L^{-1}) with DLI of 0.861 mol photons m^{-2} d^{-1} (range: 0.615–1.256 mol photons m^{-2} day^{-1}) with ranges representing 95% confidence intervals. Although *C. orientalis* was adversely affected in the high impact treatment, this species fully recovered during the 14 d recovery period. *Ianthella basta* showed signs of stress including tissue regression and mucus production when exposed to ≥10 mg L^{-1}, but this species did not experience any mortality and showed high potential for recovery during the post-exposure recovery period. Hence, the combination of stressors simulating field conditions at a dredging site had a higher impact on sponges than the individual effects of high turbidity, smothering or light attenuation. However, the impacts were species-specific, being most detrimental to the phototrophic species *C. foliascens*. In contrast, the phototrophic *C. orientalis* exhibited 100% survival for up to 21 d under the high impact dredging scenario, while the heterotrophic species *I. basta* tolerated even longer periods (viz. up to 28 d) and was able to recover once returned to control conditions (viz. no suspended sediment or smothering and a DLI of ~6 mol photons m^{-2} d^{-1}).

Table 6. Summary of the effects of combined dredging stressors on phototrophic and heterotrophic sponge species. Red row represents species that are sensitive, yellow represents species that are sensitive but with potential for recovery, and green represents species that is resilient.

Effects of combined stressors under realistic dredging scenarios

			Sub-lethal stress	Recovery	Mortality	Mechanism
Phototrophic	Cup inc/ wd	 *C. foliascens*	Survive under low impact dredging scenarios <10 FNU	No, at > 30 FNU	Mortality under moderate-high scenarios, >30 FNU	Mucus production and sediment sloughning
	Encrusting en	 *C. orientalis*	Survive under moderate impact dredging scenarios <70 FNU	Yes	20% mortality under high impact dredging scenarios for 2 wks,	Oscula closure. Partial compensation of photosymbiont. Passive self-cleaning strategy.
Heterotrophic	Erect lam	 *I. basta*	Survive under high impact dredging scenarios	Yes	No	Tissue regression to avoid clogging. Mucus production. Lipid reduction and energy depletion.

Box 6: Implications of the findings on sponge responses to combined dredging related stressors for the prediction and management of dredging impacts on sponges

- Most sponges survived under low-moderate turbidity scenarios (viz. ≤30 mg L^{-1}, ≥0.5 mol photons m^{-2} d^{-1}) for up to 28 d, with 20% and 90% mortality observed in *C. orientalis* and *C. foliascens* under the highest turbidity scenario (viz. 70 mg L^{-1}, 0.1 mol photons m^{-2} d^{-1}).
- The combination of high SSCs and low light availability accelerated and increased mortality in the two tested phototrophic species.
- Most sponges possessed mechanisms or adaptations to effectively deal with dredging related pressures in the short term. However, these tolerance mechanisms had a cost, evidenced by reduced lipids and deterioration of sponge health in all species towards the end of the experiment, suggesting that longer term exposure to similar conditions is likely to result in higher mortality.
- The LC_{50} (SSCs: 47.02 mg L^{-1}; DLI: 0.266 mol photons m^{-2} d^{-1}, for 28 d) and LC_{10} (SSCs: 22.50 mg L^{-1}; DLI: 0.861 mol photons m^{-2} d^{-1}, for 28 d) values derived for *C. foliascens* can be used by managers and dredging proponents when implementing zones of impact based on dredge plume models.

While the thresholds and pressure:response relationships can be used in guidelines for impact prediction and management, it is important to note that considerable inter-species variability exists in how sponges respond to dredging pressures. Confidence could be improved by testing the sensitivity of ecologically important or endemic species at planned dredging sites. In addition, early life history stages are expected to be more sensitive to dredging related pressures than adult sponges, so the response of larval and juvenile sponges should be considered before final conclusions are drawn about the effects of dredging on sponge community dynamics.

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