Effects of dredging-related pressures on critical ecological processes for corals | Synthesis Report

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WAMSI Dredging Science Node

7 Report

Project 7.6

March 2019

WAMSI Dredging Science Node

The WAMSI Dredging Science Node is a strategic research initiative that evolved in response to uncertainties in the environmental impact assessment and management of large-scale dredging operations and coastal infrastructure developments. Its goal is to enhance capacity within government and the private sector to predict and manage the environmental impacts of dredging in Western Australia, delivered through a combination of reviews, field studies, laboratory experimentation, relationship testing and development of standardised protocols and guidance for impact prediction, monitoring and management.

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Funding Sources

The $20 million Dredging Science Node is delivering one of the largest single issue environmental research programs in Australia. This applied research is funded by **Woodside Energy, Chevron Australia, BHP Billiton and the WAMSI Partners** and designed to provide a significant and meaningful improvement in the certainty around the effects, and management, of dredging operations in Western Australia. Although focussed on port and coastal development in Western Australia, the outputs will also be broadly applicable across Australia and globally.

This remarkable **collaboration between industry, government and research** extends beyond the classical funder-provider model. End-users of science in regulator and conservation agencies, and consultant and industry groups are actively involved in the governance of the node, to ensure ongoing focus on applicable science and converting the outputs into fit-for-purpose and usable products. The governance structure includes clear delineation between end-user focussed scoping and the arms-length research activity to ensure it is independent, unbiased and defensible.

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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Year of publication: 2019

Citation: Negri AP, Ricardo GF, Jones R (2019) Effects of dredging-related pressures on critical ecological processes for corals – synthesis report. Report of Theme 7– Project 7.6 prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 23 pp.

Author Contributions: All authors wrote the report

Corresponding author and Institution: Andrew Negri (AIMS)

Collection permits/ethics approval: No collection occurred in the production of this report.

Publications coming from this study:

Gilmour, J., Speed, C.W. and Babcock, R. (2016) Coral reproduction in Western Australia. Gilmour, James 4, e2010. DOI: 10.7717/peerj.2010

Jones, R., Ricardo, G. and Negri, A.P. (2015) Effects of sediments on the reproductive cycle of corals. Marine Pollution Bulletin 100, 13-33. DOI: 10.1016/j.marpolbul.2015.08.021

Ricardo, G.F., Jones, R.J., Clode, P.L., Humanes, A. and Negri, A.P. (2015) Suspended sediments limit coral sperm availability. Scientific Reports 5, 18084. DOI: 10.1038/srep18084

Ricardo, G.F., Jones, R.J., Negri, A.P. and Stocker, R. (2016) That sinking feeling: Suspended sediments can prevent the ascent of coral egg bundles. Scientific Reports 6, 21567. DOI: 10.1038/srep21567

Ricardo, G.F., Jones, R.J., Clode, P.L. and Negri, A.P. (2016) Mucous secretion and cilia beating defend developing coral larvae from suspended sediments. PLoS ONE 11(9), e0162743. DOI: 10.1371/journal.pone.0162743

Ricardo, G.F., Jones, R.J., Nordborg, M. and Negri, A.P. (2017) Settlement patterns of the coral *Acropora millepora* on sediment-laden surfaces. Science of the Total Environment 609, 277–288. http://dx.doi.org/10.1016/j.scitotenv.2017.07.153.

Ricardo, G.F., Jones, R.J., Clode, P.L., Humanes, A., Gioffre, N. and Negri, A.P. (in press) What's causing the flocs? Sediment characteristics influence on the fertilisation success of the corals *Acropora tenuis* and *Acropora millepora*.

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 (Source: AIMS)

Image 3: Dredge Plume at Barrow Island. Image produced with data from the Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS) taken on 29 August 2010.

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

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1 Introduction

It has been recognized since the early 1990s that dredging activities off the north west coast of WA (NW WA) that generate large amounts of suspended sediments may impact on the potentially sensitive and ecologically important events such as mass coral spawning. The reproduction and recruitment processes of corals underpin the maintenance of coral reef communities and their resilience to disturbance, and corals utilise a range of reproductive strategies that differ between species (Harrison and Wallace, 1990). While many species release asexually or sexually derived larvae (brooders), the majority of species reproduce through external fertilisation of gametes during highly synchronised mass spawning events (Harrison and Wallace, 1990) (Figure 1). The fertilised gametes of broadcast spawners develop into embryos and early larvae at the surface of the water before moving down into the water column as ciliated planula in search of a location for permanent attachment and metamorphosis. These early juvenile coral polyps are approximately one mm in diameter and develop into colonies by budding, reaching sexual maturity generally after three years or more (Baria et al., 2012). Usually the multi-specific mass spawning occurs only once a year for any given population, so physical (thermal stress) or water quality (sediments and pollution) impacts on these potentially vulnerable early life processes can have major and long-term effects on reef heath (Richmond, 1997).

2 The importance of corals in north west Western Australia

Scleractinian or ‘hard’ corals are the key reef building organisms on coral reefs, forming complex topographic structures that provide habitat for highly productive and diverse tropical communities (Sorokin, 2013). The critical value of tropical coral reefs to the environment, fisheries and tourism along with their sensitivity to a range of stressors is well recognised by management agencies internationally (Nyström et al., 2000).

Coral reef habitats of WA are characterized by widely contrasting environments, ranging from isolated open ocean atolls surrounded by deep oligotrophic waters in the Kimberley Oceanic Region, to reefs heavily influenced by coastal processes such as tidally driven sediment resuspension in the inshore Kimberley and Pilbara Regions (Veron and Marsh, 1988). Corals of the Ningaloo Reef comprise the world’s longest fringing reef and those of the Abrolhos Islands and the Southwest Region represent unique subtropical and temperate reefal habitats. There are a variety of coral community compositions across these regions and this influences the patterns and timing of reproduction, both within and between species, and multi-specific coral spawning can occur in autumn or spring and sometimes during both seasons at a single location (Gilmour et al., 2016). Many of the coral reefs of WA, including the Ningaloo Reef and Rowley Shoals are protected by World Heritage listings or by State or Commonwealth Marine Park legislation due to their inherent conservation value. In addition, these reefs support valuable commercial and recreational fisheries and tourism industries (WA Fish, 2017). Unlike the Great Barrier Reef, oil and gas exploration and extraction occurs in close proximity to several coral reef ecosystems of the Pilbara and Kimberley regions of WA. This proximity necessitates close attention by resource management agencies and regulators that assess potential impacts of developments (artificial structures and dredging) and accidents (spills and blowouts) (Swan et al., 1994) to local coral populations.

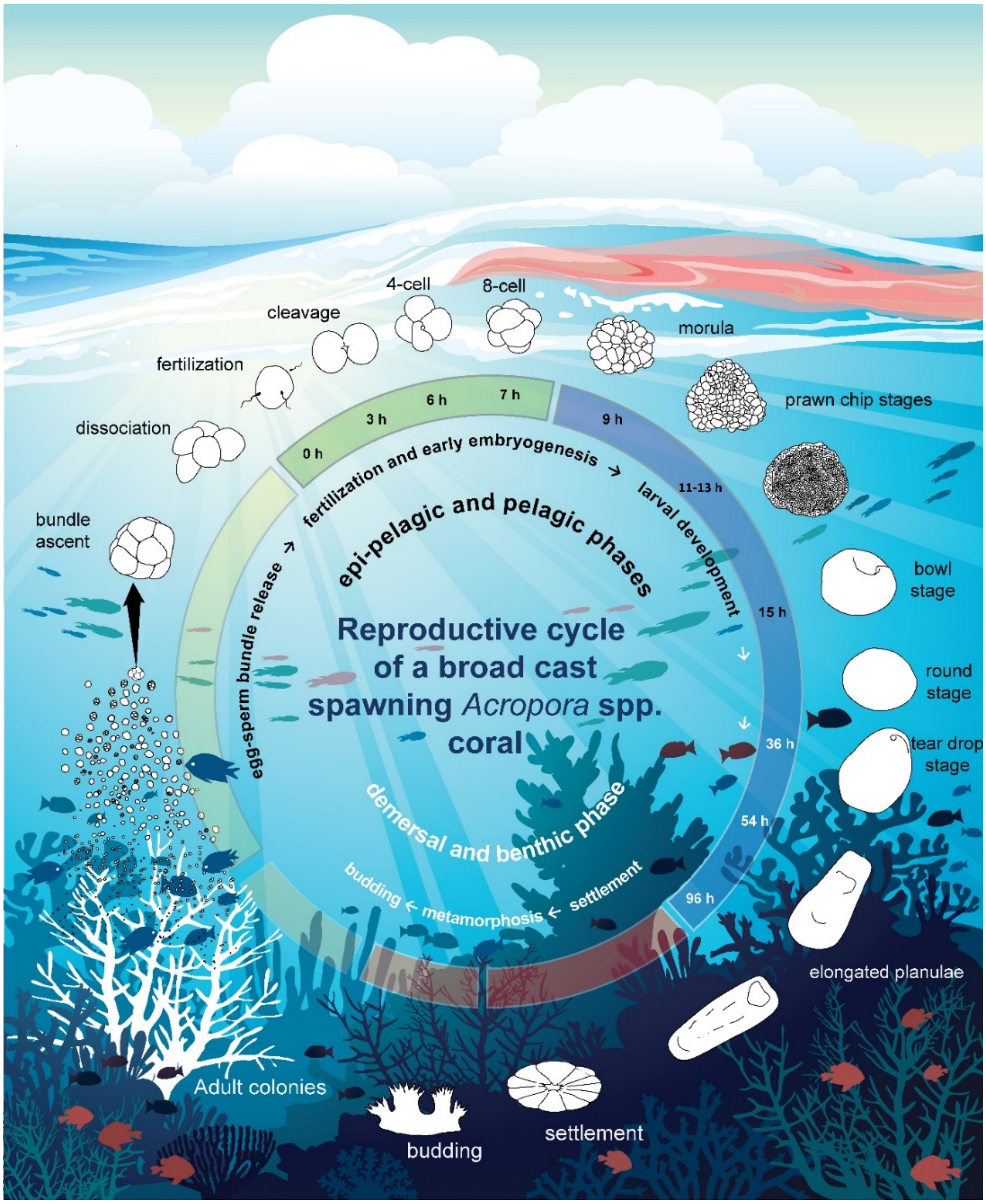

Figure 1. A stylized depiction of the reproductive cycle of a broadcast spawning *Acropora spp.* (see text)

3 State of knowledge prior to the WAMSI Dredging Science Node

Prior to the start of the research program our understanding of the timing and extent of coral spawning events on WA reefs was piecemeal with no compendium of data for reference, analysis, or review. Most studies on coral reproduction had been conducted over a limited number of months, and many of these were unpublished, resulting in large gaps in knowledge. The importance of filling these data gaps is apparent, given the limited data available indicates that WA corals exhibit unique patterns of reproduction which vary considerably among habitats and regions. It was recognized that the dominant mode of reproduction was broadcast spawning and that the timing of synchronous spawning varied among species, regions (longitudinally) and possibly between nearshore and offshore coral communities. Biannual spawning (spawning in both autumn and spring) was recognized at some locations but the proportions of species partaking in each of these events was unclear. In addition, limited taxonomic resolution and the application of non-standard sampling methods limited the utility of much of the available data. There has been a recent increase in the number of studies on coral reproduction in WA due to the rapid industrial expansion through tropical coastal and offshore regions of NW WA; however, much of the associated data are contained within confidential reports to industry and government. To optimize the application and timing of the coral spawning ‘critical window of environmental sensitivity’ (CWES; see EPA 2016) across the different bioregions it was necessary to collate and critically examine the published and ‘grey literature’ data to prioritize information gaps and improve approaches for field sampling for quantifying significant periods of reproductive output of coral communities in WA.

Until the start of the current research project there was also great uncertainty around the hazard posed by dredging-related sediments to the each of the complex life history stages and transitions of broadcast spawning corals, particularly for the reproductive and larval settlement stages. As a result resource managers have often implemented regulations or conditions that limit or temporarily stop turbidity generating activities over this CWES for corals. The coral spawning CWES has evolved over time as new information on the timing of spawning and effects of sediments on coral reproduction became available. Most recently proponents in WA have been required to temporarily cease dredging for 10 d: i.e. 3 d before and for 7 d after the predicted first night of mass spawning but with a caveat whereby proponents could continue to engage in turbidity generating activities if they could provide ‘...*peer-reviewed scientific evidence that if those turbidity generating activities were to continue during coral mass spawning events, any effect, if it were to occur, would not significantly impact the functional ecology of local and regional reefs*...’. While a number of studies have provided information on the timing of spawning in NW WA and the effects of sediments on the success of the early life phases of corals, understanding is still limited and regulators typically adopt a precautionary approach of requiring shutdowns over the spawning CWES (with the caveat described above). This can be costly to proponents while very expensive dredging equipment lays idle for days or weeks, and the environmental benefits are uncertain.

Not only were the magnitudes of impacts poorly described but, critically, the modes of action of suspended sediments, light attenuation and sediment deposition were unclear (but likely to differ between life stages) (Erftemeijer et al., 2012). Furthermore, the studies that had been performed to test the effects of sediments on early life stages and transitions usually: (i) ignored the potential interactions between mechanisms; (ii) only reported nominal (not measured) values of total suspended solids or sediment deposition and (iii) invariably reported only point estimates of the effect rather than fitting the data to continuous pressure-effect curves to derive valid thresholds for stress.

Improvements in operational efficiency and environmental effectiveness of the coral spawning CWES rely on a more comprehensive understanding of coral spawning patterns in WA and on better quantifying the hazards posed by dredging-generated sediments on all early life phases of coral. The Western Australian Marine Science Institution Dredging Science Node (WAMSI DSN) Theme 7 aimed to address these knowledge gaps. Despite the serious limitations of the available hazard data on the effects of sediments to early life phases of coral, these thresholds for fertilisation and coral larval health have been combined with sediment plume models to assess spatial risks posed by dredging operations. The coral spawning CWES was primarily concerned with protecting the pelagic, planktonic stages when the gametes and embryos/larvae are in the water column. However, the success of the coral spawning CWES as a management instrument could be better evaluated in terms of overall recruitment success across each life stage, including the settlement of larvae and survival of early recruits that are critical for sustaining coral population.

4 Research program and objectives

The main objective of the Theme 7 program was to improve understanding of the relative sensitivity of the reproductive and larval settlement stages of corals to the pressures of elevated suspended sediment concentrations (SSC), light attenuation and sedimentation leading to enhanced confidence in the prediction and management of dredging related impacts on corals.

Theme 7 was divided into two phases, the first involving a review of the available literature and the second based around laboratory experiments that were informed by the reviews. Phase 1 was made up of two projects involving a literature review of the effects of sediments on the reproductive cycle of corals (Theme 7.1) and of reproductive process of corals in WA (Theme 7.2). Phase 2 (Research themes 7.3 – 7.5) involved experiments on the effects of dredging pressures on the early life-history stages of corals from fertilization through to settlement (i.e. the coral spawning CWES**)**. Experiments involved laboratory-based manipulation of SSC, sedimentation and light levels (informed by the Theme 7.1 Reviews) and were conducted in the National Sea Simulator (SeaSim at AIMS). The choice of test species was informed by Theme 4 and Theme 7.2 reviews that examined the species distributions and biogeographic range of corals in WA. Experiments were conducted with species that are found in both the Pilbara region of NW WA and the GBR.

4.1 Literature review: Effects of sediments on the reproductive cycle of corals

Project 7.1 critically reviewed and evaluated the relevance of the existing scientific literature on the effects of sediments on the early life-history stages of corals based on a contemporary understanding of the water quality conditions that can occur during dredging events. All plausible pressure-response pathways between sediments and each life history stage were described and the existing scientific literature assessed to inform: (i) current management of large scale dredging projects in NW WA and (ii) priorities and design of laboratory experiments (Projects 7.3-7.5).

4.2 Literature review: Coral reproduction in Western Australia

Project 7.2 reviewed existing studies to compile the most comprehensive dataset possible on spawning patterns of WA coral reefs. The degree of synchrony and the timing of coral spawning was assessed for the diverse coral populations of WA, including turbid-water (typically inshore) and clear-water (typically offshore) coral communities. Spawning patterns in WA were also contrasted with spawning pattern in the GBR. The purposes of the review were to provide a contemporary resource of spawning synchrony data for WA coral populations, and to outline protocols and procedures for assessing coral community reproductive output over the course of a year – i.e. how to either collect and examine corals in the field or sample corals for inspection under a microscope, to assess when coral spawning will occur.

4.3 Studies on the effects of sediments on coral fertilisation

Broadcast spawning corals synchronously release egg and sperm bundles that rise to the water surface where cross-fertilization occurs between gametes from different colonies. This project validated the most plausible pressure-response pathways whereby suspended sediments can affect fertilisation success. Firstly, we tested the potential for sediments to adhere to the mucous membrane of the egg-sperm bundles, reducing their ascent or preventing them from reaching the water surface. We then investigated how elevated suspended sediments may directly impact the fertilisation stage of coral gametes at the water's surface. Once these mechanisms were validated, the SSC thresholds at which a variety of suspended sediment types affect bundle ascent and fertilisation were identified using models and controlled laboratory experiments.

4.4 Studies on the effects of sediments on coral larval development

Elevated SSCs were considered the most relevant dredging-related hazard for the pelagic stages involving embryogenesis at the surface, and larval development at the surface and in the water column. Project 7.4 comprised a series of controlled laboratory experiments where we examined the impacts of SSCs that can be realistically expected during dredging operations on the development of embryos and on larval survival as well as the latent impacts on larval function (ability to undergo successful settlement).

4.5 Studies on the effects of sediments on coral larval settlement

The final set of experiments (Project 7.5) examined how deposited sediments and light intensity can affect coral larval settlement including attachment and metamorphosis. Firstly these experiments examined the settlement preference of larvae on surfaces with different aspects (angles) that had been coated in different levels of deposited sediment. Once the settlement patterns in three dimensions had been characterized, further experiments were undertaken to identify the thresholds at which deposited sediments of different types affected settlement success.

5 Overview and synthesis of findings

This section sets out the key findings of the research program in the context of providing knowledge to better evaluate the level of risk posed to coral reproductive processes from suspended and deposited sediments associated with dredging activities in WA.

5.1 Effects of sediments on the reproductive cycle of corals

5.1.1 Key findings and conclusions

This study reviewed the effects of dredging activities on the reproduction of predominantly broadcast spawning corals. The development of a conceptual model for dredging effects on coral reproduction (Figure 2) allowed the identification of key stressors, steps in a causal pathway and modes of action and effects, highlighting how they are interlinked and can interact. The effects of dredging on coral reproduction were considered to fall into two broad categories: (i) chemical - including changes in water quality and introduction of pollutants; and (ii) physical stressors - primarily elevated suspended sediment concentrations (SSCs), light reduction and elevated levels of sediment deposition. The chemical effects can be important; however, as many capital dredging projects in NW WA are green-field sites (without historical contamination), they were considered of secondary importance compared to the physical mechanisms. A minority of physical effects of suspended sediments can be considered positive, such as a reduction in UV light penetration from high water turbidity which could reduce DNA damage to gametes and embryos near the surface. Importantly, the overwhelming majority (>30) of the known or plausible effects on the adults, gametes, embryos, larvae and new recruits were considered negative.

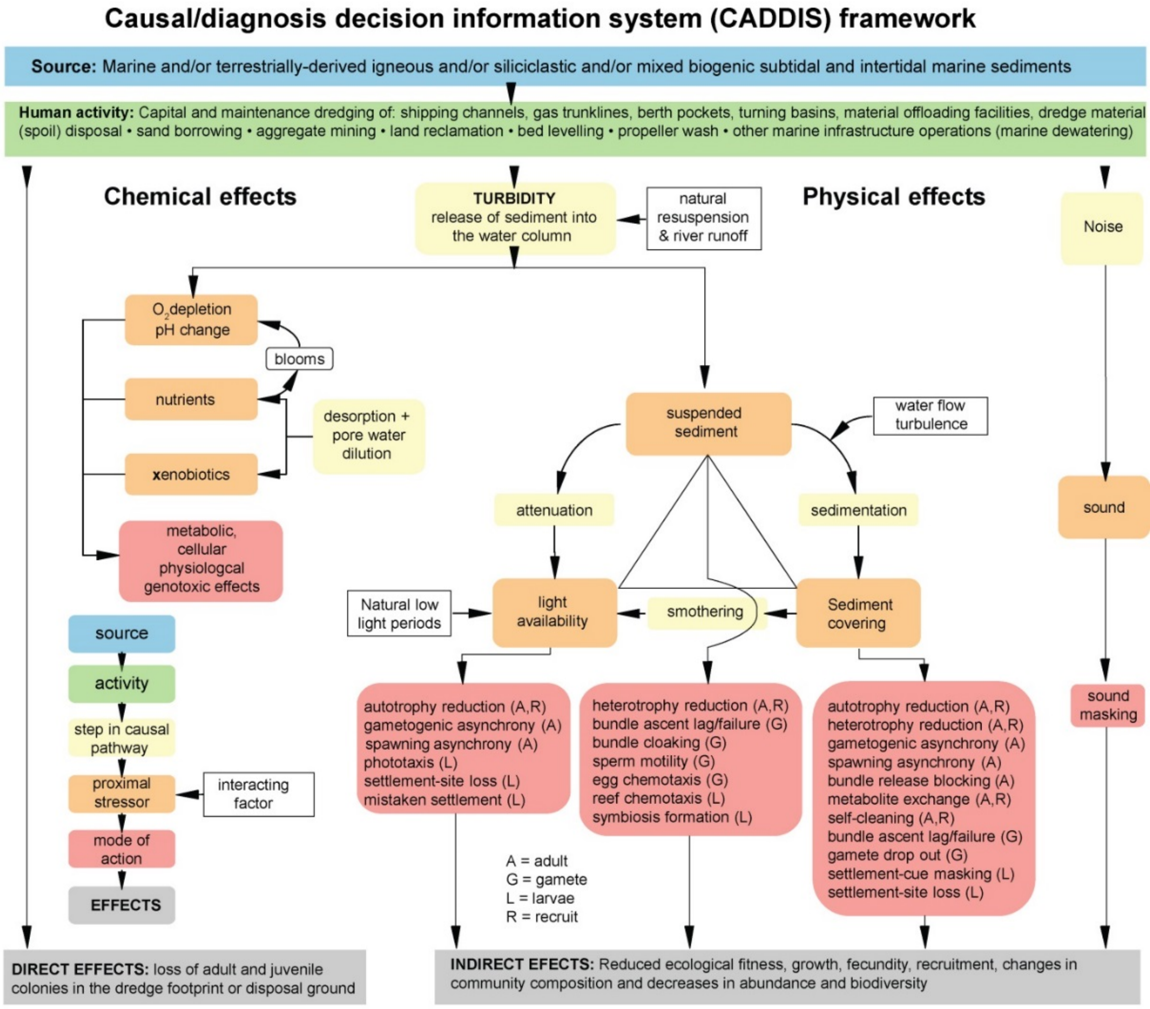

Figure 2. Conceptual model for the effects of dredging on coral reproduction based on the US EPA causal/diagnosis decision information system (CADDIS).

The review did not identify any studies that have directly manipulated SSC and sedimentation levels to examine the effects of sediments on pre-spawning processes such as gametogenesis, on spawning synchrony or on delaying or preventing egg-sperm bundles ascent to the water surface. Twelve studies (5 field and 7 laboratory) described effects of elevated sediments on fertilisation, embryogenesis, larval development, survival and settlement and juvenile survival. However, it was found that effect thresholds identified in these studies were generally inadequate for application in risk models for dredging, because they did not consider cause-effect pathways or account for likely interactions or interdependence between stress pathways. In addition stress thresholds had not been derived from concentration-response relationships and sediment concentrations were not sufficiently measured. Broadly, the review concluded that embryogenesis and larval development stages appear to be less sensitive to elevated suspended sediment concentrations than the fertilization process and larval settlement appears to be a very sensitive stage. The effects of dredging activities on early post-settlement survival in the weeks to months after settling are also likely but this needs to be verified in future studies. Overall, the review emphasized that more data are needed to improve the ability to predict and manage the consequence of dredging during coral spawning periods. Effect studies need to: (a) adequately quantify exposure conditions, (b) ascertain the mechanism(s) of effects, and (c) recognize the close interlinking of proximate factors which could confound interpretation of studies.

5.1.2 Implications for management

The (CADDIS) framework applied in the review to develop a conceptual diagram of potential effects/pathways proved useful for identifying areas of uncertainty, knowledge gaps and for guiding future laboratory or field studies. This process also highlighted some of the difficulties associated with establishing concentration–response relationships for sediments and in particular, the interaction between dredging-related stressors which could potentially confound causal links. Cause-effect pathways therefore need to be carefully considered when designing new studies and interpreting the results of past laboratory or field manipulations for risk assessment purposes.

The coral spawning CWES has been designed as a management tool to protect the potentially vulnerable planktonic life stages of coral from dredging derived turbidity (typically 3 d before until 7 d after the predicted night of coral spawning). However, based on the analysis of settlement patterns from ~20 studies in this review, the CWES is likely too short to fully accommodate the potentially sensitive settlement stage, especially if corals spawn over several nights.

5.1.3 Priority information gaps for further study

The review highlighted the need to derive more reliable threshold levels for suspended sediments and sediment deposition. This can be achieved by applying contemporary approaches for deriving water and sediment quality guidelines, including the generation of concentration-response curves to calculate EC_{10} and EC_{50} values. Reliability could also be improved by considering the effects on the early life history stages of additional coral species and from adequately describing the sediment size classes and compositions that seem to strongly impact on early life stages of corals.

The results of this review indicated that the coral spawning CWES currently applied to dredging projects in NW WA is likely to be too short to cover the sensitive larval settlement stage for many species. However, in order to determine how long it should be, more information is needed to assess how long small juvenile corals remain vulnerable to sediment deposition. To be able to methodically assess the possible consequences of different dredging scenarios (dredging locations, equipment type, disposal options) on the full life cycle of corals, detailed empirical information on the effects of sediments on each life-history stage is required for a range of species over appropriate time frames.

5.2 Coral reproduction in Western Australia

5.2.1 Key findings and conclusions

In this review of broadcast spawning in WA we combined information for tens of thousands of corals and hundreds of species, from over a dozen reefs spanning 20 degrees of latitude, based on grey-literature and published reports to comprehensively update our knowledge of coral reproduction in WA. Most studies investigated spawning in Acropora corals over a few months and at a few locations, usually within the Kimberley oceanic region, the inshore Pilbara or at Ningaloo, leaving large spatial and temporal gaps in knowledge. Nevertheless, patterns of spawning seasonality and synchrony are evident from across the vast expanse of WA's coral reefs. There is a gradient in the spawning activity of most corals among seasons, with mass spawning during autumn occurring on all reefs (apart from the temperate southwest). Participation in a multi-specific mass spawning during spring decreased from roughly 25% of corals on the Kimberley oceanic reefs to little or no multi-specific spawning in spring at Ningaloo, where spawning may be more protracted. Within these two seasons, mass spawning occurred most commonly in March and/or April, and in October and/or November, or can be split over the two consecutive months in each season depending on the timing of the full moon. Split-spawning typically occurs every few years, but can also occur in consecutive years, and will dramatically affect inferences about the participation by colonies and species in spawning events if only one of the two months is sampled. On most WA reefs, there is still a poor understanding of monthly variation in spawning and comparatively few data available for non-Acropora corals, which may have different patterns of reproduction.

Gaps in knowledge were also due to the difficulty in identifying species and methodological issues. This review provides a brief summary of the methods and sampling protocol for quantifying patterns of reproduction in corals and an approach to quantifying the relative significance of periods of reproductive output that may occur throughout the year. Hypothetical examples are provided, and the approach provides a basis for further development of a method to quantify the importance of reproductive periods for maintaining coral communities, which is useful for managing dredging and construction operations around coral spawning seasons (see (Gilmour et al., 2016)).

5.2.2 Implications for management

The timing of coral mass spawning is reasonably predictable; however, it varies between species and locations and so it is important to ensure any stoppages coincide with the actual spawning event for all relevant species at that location for it to be most effective. Furthermore, cessation of dredging can be costly and can delay the completion of projects. Therefore, studies of coral reproduction are required to predict the appropriate window in which turbidity-generating activities should be suspended to reduce pressure and/or to satisfy Ministerial Conditions attached to the environmental approvals, whilst not un-necessarily restricting construction activities.

Although our knowledge of coral reproduction throughout WA is incomplete, a general pattern is evident that can largely be attributed to variation in (i) community composition, (ii) latitude and (iii) the timing of the full moon. The most obvious differences in reproductive patterns of coral communities was driven by the abundance of brooding versus spawning corals. Within the spawning assemblages, differences in the times of spawning are often due to the varying abundances of Acropora and some non-Acropora species. There is a clear pattern of latitudinal variation in spawning corals. The primary period of spawning on all WA reefs (apart from the southwest region) is in autumn, often culminating in the mass spawning of a relatively high proportion of species and colonies during March and/or April. Within the main seasons of spawning, temporal variation in spawning times is not well understood, particularly for the multi-specific spawning in spring. Available data indicates that autumn spawning will be split between March and April (and possibly February) in almost all years, with the majority of spawning occurring during the neap tide period, seven to nine nights after the full moon within a given month. March is normally the month with the highest spawning activity however in some years, spawning may be more evenly split between March and April or may occur predominantly in April. The effect of the timing of the full moon on the spring spawning period has been far less studied and is less understood.

The review made recommendations for pre-development surveys and monitoring to improve the application of the coral spawning CEWS. For example:

- Prior to designing a sampling regime, the literature specific to reefs within the different regions of WA should be read thoroughly as this provides background to the patterns of reproduction for corals more widely.
- Pre-development surveys of coral reproduction would benefit from first quantifying the community composition. Doing so allows the methods and sampling design for reproductive assessments to be driven by the relative cover of different coral groups, and data on abundance and reproduction can be combined to quantify the significance of periods of reproductive output within a year.
- Although identification to the finest taxonomic resolution is always desirable, it may only be practical for species that are particularly abundant and are easily identifiable from photographs and *in situ*. For other species, it is more important to ensure identifications at higher taxonomic levels are correct.
- In most instances, a single sample prior to a predicted date of spawning is insufficient to quantify reproduction during a given period. Without comprehensive data, surveys from previous years provide few insights into future spawning events, requiring substantial sampling effort to be repeated prior to every period of interest. In the worst instances, focusing only on the participation by species in a single month risks perpetuating a paradigm of mass spawning or missing a significant period of reproductive output.
- The presence of mature testes, eggs (pigmented) or larvae (in brooding species), followed by their subsequent disappearance, is the best basis for making strong inferences about the timing of spawning. The optimal time of sampling will depend on the assemblage.

5.2.3 Priority information gaps for further study

The review highlighted significant data gaps:

- Latitudinal patterns: The most data on timing of coral reproduction on WA coral reefs has been collected as part of the environmental impact assessment and monitoring programs associated with large-scale developments. This leaves the coral reproduction understudied on many reefs including the inshore Kimberley and temperate reefs. The remoteness and difficulty in accessing reefs for sampling and the complexity of reproductive patterns also contribute to these spatial gaps.
- Background literature and methods: Some gaps in current knowledge have resulted from errors in sampling. A good knowledge of the primary literature on coral reproduction, and the advantages and disadvantages of different methods is required before studies are designed and executed.
- Biases in species sampling and identification: For many coral species on WA reefs, modes of reproduction, sexuality, cycles of gametogenesis, and the time of maturation for eggs and sperm prior to spawning are largely unknown. If species are common on a reef, it is important that their mode of reproduction and sexuality are known before sampling methods and design are streamlined.
- Unknown spawning window durations: The extent to which spawning is protracted over days to weeks, around the main night(s) of spawning, or weeks to months around the main month of spawning, is unknown for most reefs. Without a knowledge of the proportion of species and colonies releasing gametes on a predicted night of mass spawning, then the proportion of gametes, larvae and new recruits that are protected from turbidity generating activities during a shut-down period cannot be estimated.

5.3 The effects of dredging-related pressures on coral fertilisation, larval development and settlement

5.3.1 Key findings and conclusions

Fertilisation: Our experiments revealed a novel threat to reproductive success, whereby suspended sediments adhered to the mucous membrane of the egg-sperm bundles, reducing their ascent or preventing them from reaching the water surface (Figure 3). This was referred to as the ballasting effect. Our experimental observations of this mechanism were successfully modelled to predict the reduction in egg–sperm encounters as a function of suspended sediment concentration (SSC), particle grain size, and depth of the adult colony and used to derive observable effects concentrations (Table 1). These SSCs and grain sizes can occur during dredging programs but are commonly associated with upper-percentiles of sediment plumes from dredging or natural resuspension events and occur close to dredging activities.

Table 1 Concentration–response thresholds for suspended sediment on the ascent of *Montipora digitata* egg-sperm bundle and egg-sperm encounter rates.

Experiment	**Water depth (m)**	**Suspended sediment concentration**	
		EC_{10} (mg L^{-1})	EC_{50} (mg L^{-1})
Bundle ascent	10	71	211
Egg-sperm contact		53	131
Bundle ascent	15	47	141
Egg-sperm contact		35	87

Source: Ricardo GF, Jones RJ, Negri AP, Stocker R (2016b) That sinking feeling: Suspended sediments can prevent the ascent of coral egg bundles. Sci Rep 6:21567

The second series of experiments investigated how elevated SSCs may directly impact the fertilisation of coral eggs at the water's surface. Some sediments were shown to adhere to sperm, forming sediment–sperm flocs (**Error! Reference source not found.** 3b,c), and this resulted in the sperm concentrations falling below the threshold required for fertilisation. This was referred to as the *sperm limitation* effect and we consider this mechanism to be the primary mode of action whereby fertilisation is reduced in the presence of sediments. Fertilisation was found to be more sensitive to organic-clay rich sediments, with observations clearly showing binding of mineral clays to sperm. For all sediment types, the effect was more pronounced at sub-optimal sperm concentrations. Collectively, these findings demonstrate that high SSCs can remove sperm from the water's surface during coral spawning events, reducing the window for fertilisation with potential flow-on effects for recruitment. The experimentally derived thresholds of effects of suspended sediment on fertilization of coral eggs are provided in Table 2.

Table 2. Concentration–response thresholds for suspended sediment on fertilisation of *Acropora tenuis*.

Experiment	**Sediment type**	**PSD**[1]	**Sperm mL^{-1} conc.**	**EC_{10} ($mg\ L^{-1}$)**	**EC_{50} ($mg\ L^{-1}$)**
Fertilisation success	Inshore GBR 1	Very fine silt	10^4	2.5	5.8
			10^5	54	125
	Inshore GBR 2		10^4	47	75
	Inshore WA (siliciclastic)			40	205
			10^5	80	414
	Offshore GBR (carbonate)		10^4	214	>800
			10^5	>820	>820
	Bentonite clay	Clay	10^4	4.6	6.9

[1] Particle size distribution (PSD) using the Wentworth classification scheme for grain size

Source: Ricardo GF, Jones RJ, Clode PL, Humanes A, Negri AP (2015) Suspended sediments limit coral sperm availability. Sci Rep 5:18084

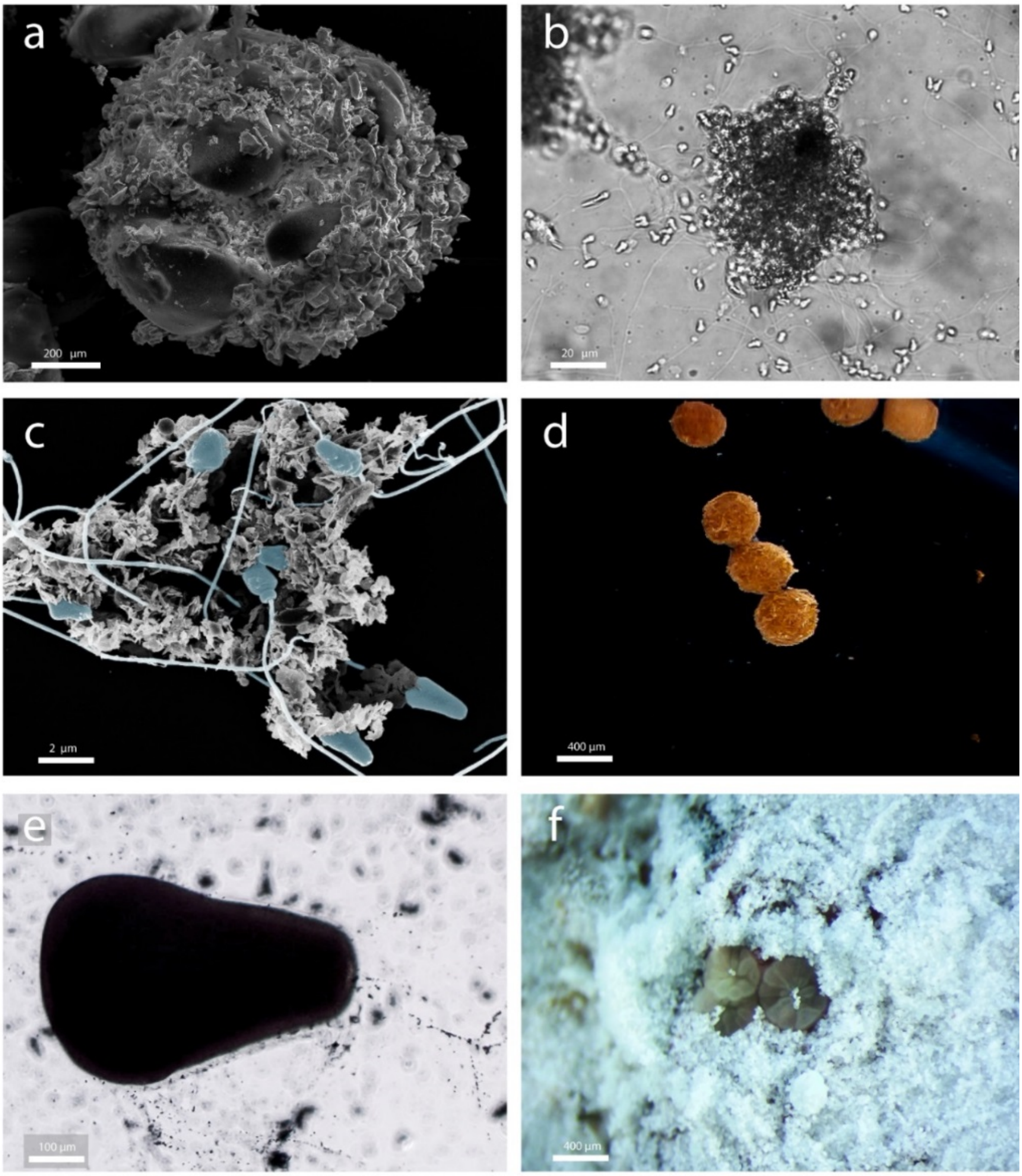

Figure 3. Sediment impacting corals across various developmental stages. (a) An egg-sperm bundle covered in coarse-silt sediment. Approximately 50 grains of coarse-silt are capable of sinking an egg-sperm bundle. (b) Sperm aggregating on a siliciclastic sediment floc. (c) A high magnification false-coloured image of a sediment–sperm floc. Sperm coloured in blue. Thin ~1 µm plate-like grains (mineral clays) can be observed coating sperm within the floc. (d) Embryos developing inside mucous cocoons after being exposed to high concentrations of suspended siliciclastic sediments. (e) A larva clearing sediment with mucous strands and ciliary beating. (f) A few larvae that successfully managed to burrow and undergo metamorphosis on sediment-covered surfaces.

Embryo and larval development: Elevated suspended sediment concentration was considered the most relevant dredging-related hazard for the pelagic stages of the larvae involving early embryogenesis at the surface and larval development at the surface and in the water column. Predicted thresholds for suspended sediment concentrations on the various stages of embryo and larval development are provided in Table 3. The survivorship and subsequent metamorphosis of embryos was unaffected by exposures to very high suspended sediment concentrations. A novel adaption was identified in which embryos form a mucous coating that protects the developing embryos until they are capable of swimming. This was referred to as the cocooning effect and was common in embryos but not in larvae (Figure 3d). Embryo cocooning occurred at elevated concentrations of suspended siliciclastic sediment and the development stage continued successfully with ciliated ~36-h-old larvae able to escape the cocoons, and these continued to develop normally and undergo settlement. Ciliated (>36-h-old) larvae were also observed to secrete mucus (Figure 3e) and were unaffected by very high suspended sediment concentrations. These results show that embryogenesis and larval development are comparatively insensitive to elevated suspended sediments (of the types used), and mucous secretion and cilia beating effectively protect coral embryos and larvae from elevated SSCs.

Table 3. Concentration–response thresholds effects of suspended sediment on coral embryos and larvae.

<table>
<tr><th>Experiment</th><th>Sediment type</th><th>Exposure duration (h)</th><th>Species</th><th>EC$_{10}$ (mg L^{-1})</th><th>EC$_{50}$ (mg L^{-1})</th></tr>
<tr><td>Embryo survival</td><td rowspan="2">Siliciclastic</td><td rowspan="4">30</td><td rowspan="9">Acropora millepora</td><td colspan="2" rowspan="2">>75</td></tr>
<tr><td>Settlement (pre-exposed embryos)</td></tr>
<tr><td>Embryo survival</td><td rowspan="2">Carbonate</td><td colspan="2" rowspan="2">>78</td></tr>
<tr><td>Settlement (pre-exposed embryos)</td></tr>
<tr><td>Cocoon formation (pre-exposed embryos)</td><td rowspan="3">Siliciclastic</td><td>12</td><td>35</td><td>134</td></tr>
<tr><td>Larval survival</td><td rowspan="9">60</td><td colspan="2" rowspan="2">>747</td></tr>
<tr><td>Settlement (pre-exposed larvae)</td></tr>
<tr><td>Larval survival</td><td rowspan="2">Carbonate</td><td colspan="2" rowspan="2">>802</td></tr>
<tr><td>Settlement (pre-exposed larvae)</td></tr>
<tr><td>Larval survival</td><td rowspan="2">Siliciclastic</td><td rowspan="4">Acropora tenuis</td><td colspan="2">>747</td></tr>
<tr><td>Settlement (pre-exposed larvae)</td><td>300</td><td>>747</td></tr>
<tr><td>Larval survival</td><td rowspan="3">Carbonate</td><td colspan="2" rowspan="2">>802</td></tr>
<tr><td>Settlement (pre-exposed larvae)</td></tr>
<tr><td>Larval survival</td><td>Pocillopora acuta</td><td colspan="2">>915</td></tr>
</table>

Source: Ricardo G, Jones R, Clode P, Negri A (2016a) Mucous Secretion and Cilia Beating Defend Developing 1 Coral Larvae from Suspended Sediments. PLoS ONE 11(9): e0162743.doi:10.1371/journal.pone.0162743

Larval settlement: The next series of experiments revealed a strong effect of sediments that deposit or accumulate on substrates, preventing larval settlement (Table 4). Larvae preferentially settled on upward facing surfaces, but very low levels of fine deposited sediment i.e. <~5 mg cm^2 day, equivalent to a thin veneer of sediment (<~100 µm), deterred settlement and caused a change in larval settlement preference to sediment-free, downward facing surfaces. The poorly illuminated undersides may be sub-optimal for longer-term post-settlement survival, but this was beyond the scope of these experiments. When only upward-facing surfaces were presented, 10% of settlement was inhibited at very low sediment deposition levels. We found that light attenuation typical of dredging plume conditions did not affect settlement success on healthy calcareous red algae (CRA) surfaces; however, these surfaces were negatively affected (bleached) by temporarily smothering with low sediment levels and the larvae were very reluctant to settle on these damaged surfaces. This is the first direct link between the degradation of CRA by sediment smothering, and a decrease in larval settlement. This was referred to as the *substrate health effect*. The study shows that even a thin veneer of sediment can have consequences for larval settlement due to a reduction of optimal available substrate, and that sediment smothering can impact the substrate health, thereby also affecting settlement (Figure 3f). Benthic habitats with low complexity will be more likely to suffer from blanketing of upper settlement surfaces with films of sediments that reduce settlement directly or through impacting the health and effectiveness of preferred settlement substrata. While grooves and overhangs may provide alternative settlement sites, these may not be optimal and recruits settling at these sites may also be subject to additional stress from turbidity and sediment infilling.

Table 4. Concentration–response thresholds for deposited sediment impacts on coral larval settlement of *A. millepora*.

Experiment	**Sediment type**	**Sediment treatment**	**PSD**[1]	**Surface**		**Cue**	**EC_{10} (mg cm^{-2})**	**EC_{50} (mg cm^{-2})**
				Structure	**Aspect**			
Settlement (sediment)	Carbonate	Deposited sediment	Fine silt	Flat	Upper	CRA	1.3	11
			Coarse silt				2.9 (2015) 16 (2016)	11 (2015) 48 (2016
	Siliciclastic		Fine silt				4.2	13
			Coarse silt				0.9	7.1
	Carbonate		Coarse silt	Grooves			29	88
Settlement (sediment on multi-surface prism)							69	104
Settlement (post-smothered CRA)				Flat			7.2	33

[1] Particle size distribution (PSD) using the Wentworth classification scheme for grain size

The sequence of experiments have provided much needed information on cause–effect pathways and empirical data on pressure–response relationships for several of the key early life history stages of corals (Ricardo, 2017). The *ballasting*, *sperm limitation*, *cocooning* and *substrate health* effects outlined above have not been described previously in the scientific literature, indicating just how little is really known for risk assessment purposes. The sediment type and the sperm concentration used in tests were found to substantially affect fertilization success. This probably explains the wide range of fertilisation threshold values (<50 mg L^{-1} to >1000 mg L^{-1}) reported in previous studies.

5.3.2 Implications for management

Projects 7.3–7.5 examined the pressure-response mechanisms experimentally and used well-established ecotoxicological approaches to quantify the relevant thresholds (as EC_{10}s). The three key physical stressors associated with turbidity generating activities are elevated sediment concentrations, light attenuation and sediment deposition, and these stressors had very different effects on the different early life history phases:

- Elevated SSCs primarily impacted on the pelagic processes including bundle ascent, fertilisation and temporarily caused cocoon development in embryos;
- Light attenuation did not affect the early life phases apart from having a weak influence on larval settlement under some circumstances;

- Deposited sediments had a very strong *direct* impact on settlement – driving larval settlement to the sediment-free under-sides of substrata which may be less optimal for post-settlement survival;
- Deposited sediments also had *indirect* impacts on settlement by smothering and causing deterioration in the quality of calcareous red algae, which is a powerful settlement inducer for corals, and therefore could have effects on coral settlement *in situ*.

Clearly some early life stages were sensitive (i.e. fertilization), very sensitive (i.e. settlement) and others were quite insensitive (embryogenesis and larval development) to sediments (Table 5). Dredging activities generating SSCs of tens of mg L^{-1} could affect the egg–sperm bundles and cause *sperm limitation* effects: clearly validating, under some circumstances, the use of the coral spawning *CWES* introduced 25 years ago to protect spawning and fertilisation under the precautionary principle. However, where coral spawning occurs at a distance from the dredging activities, and developing embryos and larvae drift into a turbid plume of similar SSCs, there is comparatively little risk of negative effects on embryo and larval survivorship. The settlement phase is at risk if the options for larval settlement are primarily on upper surfaces that are (or have recently been) coated in an elevated yet thin film of deposited sediments from a dredging plume.

Table 5. Recommended *CEWS* for coral fertilisation, larval development and settlement. Shaded cells represent sensitive stages or processes.

Stage	**Fertilisation**	**Embryo and larval development**	**Settlement**
Sensitivity	Sensitive but depends on SS type	Insensitive to SS	Sensitive to all deposited sediments on upper surfaces
Window timing	Most species over a 5 d peak but uncertainty ±2 d each side due to spawning timing uncertainty	A period of ~4 – 10 d after spawning. Peak competency depends on timing of spawning and the rate of larval development to settlement competency	Settlement takes 12 – 48 h and can occur immediately after reaching competency providing a suitable substrate is present.
Other simultaneous and sensitive processes	CCA smothering on upper surfaces by sediment deposition affects settlement on upper surfaces	CCA smothering on upper surfaces by sediment deposition affects settlement on upper surfaces	CCA smothering on upper surfaces by sediment deposition affects settlement on upper surfaces
Recommended Window duration =21 d (not protective of recruits)	= 9 d (centred on predicted peak spawning)	9 d spawning/fertilisation + 10 d development to competency = 19 d	9 d spawning/fertilisation + 10 d development to competency +2 d for the larvae to metamorphose = 21 d

Currently, the coral spawning *CWES* is set as 3 d before the predicted night of spawning to allow for suspended sediment to settle out of the water column, and 7 d afterwards to allow at least some time for the larvae to settle. This period is long enough to protect successful gamete ascent and fertilisation, and in fact a 9 d window is adequate to protect gametes reaching the surface and fertilisation (Table 5, *~5 d to coincide with the main spawning period of multiple species ±2 d each side of this to account for uncertainty in the timing of peak spawning*). While embryo and larval development are unlikely to need protection from elevated SS, larval settlement on upper surfaces is very sensitive to the effects of depositing sediment which negatively affects the settlement substratum (CCA) and causes a direct barrier for settlement on upper surfaces. If the settlement on the upper surfaces is assumed to be ecologically important and in need of protection, then the *CWES* should to be extended by +10 d to account for development of larvae to be competent to settle and another +2 d to allow for permanent attachment and metamorphosis into juvenile coral polyps (Table 5) (see (Gilmour et al., 2016) and (Jones et al., 2015))

The question then becomes when to close the window, and whether dredging thresholds derived for adult corals should be applied to newly settled recruits (a clear data-gap). These adult thresholds are not designed for sub-millimetre sized, recently metamorphosed corals which are known to be vulnerable to dredging pressures (i.e. deposition). Extending the windows to protect juvenile corals for a few months into the post settlement phase should also be considered in the context of the potential for split spawnings, and the existence in WA of both a major (autumn) and minor (spring) spawning period 6 months apart. These issues are discussed more fully in Project 7.1 (Gilmour et al., 2016).

Taking all the information from Theme 7 into consideration, we suggest that the focus of the *CWES* should be placed on the sensitive stages of fertilisation (9 d) and settlement on upper surfaces (2 d). However, the species-specific interval between these two sensitive stages ranges from 4 – 10 d (settlement of some species may actually overlap with the spawning of others) and depositing sediments during this period have negative effects on upper settlement surfaces and should be included if settlement on upper surfaces is to be protected. This extends to total CWES to 21 d (Table 5). Once the settlement stage is considered complete the *CWES* should be ended, since the hazards posed by suspended and depositing sediments on juvenile corals have not yet quantified (beyond the scope of Theme 7 but currently being investigated by NESP 2.1.9 - Risk assessing dredging activities)

The application of a CWES should also be guided by the likelihood of exposure to harmful SSCs. For example, the thresholds experimentally derived for the bundle ascent and fertilization stages (Table 1, Table 2) could be coupled with hydrodynamic and sediment transport and fate models to predict effects. The models need to take into account the geographical separation of dredging plumes and coral spawn and the likelihood of interaction. Important in this regard is that when the window is opened on the predicted first day of spawning the SSCs need to be below the threshold levels to be compliant. This requires a degree of pre-planning but should not be a prescribed period. Using similar exposure-guided application principals to protect settlement and survival of juvenile corals from depositing sediments is difficult at present as accumulated sediment on upper surfaces is rarely directly measured in the field.

Dredge management plans (for maintenance and capital dredging programs) should continue to address the issue of how to minimize the chances of plumes from turbidity generating activities (including dredge material placement) encountering the early life-history phases. Options for this include deciding when to start dredging (for maintenance dredging) or, depending on the project in question, whether sites furthest away from coral communities can be dredged or used for placement of dredge material during the coral spawning CWES. Other commonly used turbidity minimization techniques could be considered such as restricting or shortening overflow periods, reducing production rates and/or using different types of dredges during the coral spawning CWES.

5.3.3 Priority information gaps for further study

The experiments in Theme 7.3–7.5 provide managers, regulators and industry with a greatly improved understanding of the mechanisms and thresholds by which sediments from dredging can affect the early life stages and processes of coral. However, there are several outstanding residual knowledge gaps relating to: (i) other early life stage events and processes not tested; (ii) limited species and sediment conditions tested, (iii) limitations of field data; and (iv) cumulative and interacting pressures.

Other early life stage events and processes not tested: In the literature review (Project 7.1) we identified over 30 potential cause-effect pathways by which dredging could affect the early life stages of coral. Earlier stages potentially at risk include fecundity and spawning synchrony which could be affected by light attenuation or the physical interaction with elevated SSCs or deposited sediments. Larval dispersal could be affected by energy depletion from removal and avoidance of sediment particles by cilia and mucous production. Latter stages potentially at risk include juvenile survival over the first 12 months and this remains to be tested, especially where larvae are driven to potentially less optimal sites of attachment due to deposited sediments.

Limited species and sediments types tested: The experiments in Projects 7.3–7.5 focussed on *Acropora* spp. as one of the dominant taxa across northern Australia. The sensitivities of gametes, embryos and larvae of different species, including more work on Australian brooding corals, should be investigated in future studies. The sediment types had a large effect on fertilisation thresholds due to differences in the formation of sperm-sediment flocs. Future experimental studies should assess the impacts of sediment type on all early life history stages.

Limitations in field data: Fertilisation success in the presence of sediment is highly dependent on sperm concentrations, and more *in situ* research is needed on likely sperm concentrations during spawning events to further evaluate the significance of this pressure-response pathway. Sediment type also had a large effect on fertilisation success and the selection of suitable thresholds for application in risk assessments clearly need to take sediment type (at the dredging site) into account. The significance of the low thresholds for settlement due to deposited sediments are uncertain as *in situ* data on the scale and duration of deposited sediments and the structure of benthic habitats that influence the proportion of substrate affected are generally unknown.

Cumulative and interacting pressures: Many of the dredging stressors (i.e. SSCs, deposited sediment and light intensity) may act alone or more likely in combination. Cause-effect pathways are thus not mutually exclusive, and together represent a source of cumulative effects. Likewise, many of the cause-effect pathways identified through experimental studies may be affected or altered by changes in environmental and biological conditions (e.g. thermal stress, nutrient enrichment, completion with other benthic biota).

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