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Tolerance to long-term exposure of suspended benthic sediments and drill cuttings in the cold-water coral *Lophelia pertusa*

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ABSTRACT

The cold-water coral *Lophelia pertusa* was exposed to suspended particles (<63 μm) for 12 weeks. Skeletal growth was significantly lower under exposure concentrations of ~25 mg l^{-1} than ~5 mg l^{-1} and there was a trend of lower growth rates when exposed to water-based drill cuttings than to natural benthic sediment. Polyp extension was less in corals exposed to higher material concentrations, which provides a possible explanation for observed skeletal growth differences between particle concentrations. Particle exposure had no significant impact on respiration or proportions of tissue and fatty acids in corals. The volume of additional cleaning mucus released by exposed corals was low and release did not significantly affect coral energy expenditure. Our results indicate that *L. pertusa* polyps can deal comparatively well with enhanced particle deposition rates and suspended matter concentrations. However, a small pilot experiment indicated that coral larvae might be particularly vulnerable to high particle concentrations.

1. Introduction

Cold-water corals form spectacular and diverse ecosystems in the deep sea. The cold-water corals lack symbiotic zooxanthellae and thrive in dark, cold and mostly deep oceanic waters (Roberts et al., 2006). Recent mapping efforts have shown that reefs occur in many parts of the world's oceans (Roberts et al., 2006) but they are especially well developed along the continental slopes off Ireland and on the Norwegian shelf (De Mol et al., 2002; Fosså et al., 2002; Freiwald et al., 2002). *Lophelia pertusa* is the most common framework-forming cold-water scleractinian coral (Roberts et al., 2009). Coral polyps form complex bush-like colonies over time, which can attain heights of up to 2 m from the seafloor (Rogers, 1999) and the carbonate structure provide niches for other species. In the northeast Atlantic, ~1300 species have been observed in association with *L. pertusa* reefs, a level of biodiversity comparable with that observed at tropical reefs (Roberts et al., 2006). The diet of *L. pertusa* is still poorly investigated, but feeding observations and analyses of coral polyp tissue indicate that *L. pertusa* ingest whatever is available in the water column including phytodetritus (Duineveld et al., 2004, 2007; van Oevelen et al., 2009) and various zooplankton species (Dodds et al., 2009; Freiwald, 2002; Kiriakoulakis et al., 2005).

Anthropogenic threats to cold-water coral reefs include bottom trawling and hydrocarbon drilling (Fosså and Skjoldal, 2010; Roberts et al., 2009). Bottom trawling can cause severe mechanical damage to deep-coral ecosystems as nets and equipment break and upturn coral blocks (Althaus et al., 2009; Fosså et al., 2002). In addition to this direct mechanical damage the reef organisms are exposed to increased levels of resuspended sediments (Pilskaln et al., 1998). Palanques et al. (2001) reported a 3-fold increase of suspended sediment concentrations for up to 5 days following bottom trawling on the continental shelf. Increased concentrations of suspended particles may also be generated by offshore drilling activities. Waste material in the form of drill cuttings is discharged into the water column in large amounts, which can lead to increased sedimentation around oil and gas installations (Gass and Roberts, 2006). These drill cuttings are made up of the rock cuttings produced during drilling and attached drilling fluids (Holdway, 2002). Drilling fluids (drilling muds) are pumped down a drill well during the drilling process primarily to lubricate the drill, cool the drill bit and prevent blowouts. Water-based muds are the most commonly discharged to the ocean after use (Holdway, 2002; Trannum et al., 2010). A weighting agent, often a fine-grained mineral powder, is one of the major components of drilling muds and barite ($BaSO_4$) is the most frequently used (Barlow and Kingston, 2001; Holdway, 2002; Trannum et al., 2010). A large part of the used barite is recycled on the drilling platforms for economical reasons, but a percentage of it is lost to the rock layers through which the well is drilled or discharged with the rock cuttings. The barite and fine fractions of rock cuttings can remain in suspension or be

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resuspended into the water column following release, and potentially transported hundreds of kilometres from the source by benthic currents (Lepland et al., 2000).

Effects of sedimentation on tropical scleractinian corals have been studied for many years (reviewed in Fabricius, 2005; Rogers, 1990). Increased sedimentation reduces photosynthetic yields in zooxanthellate corals (Dallmeyer et al., 1982; Philipp and Fabricius, 2003; Riegl and Branch, 1995; Weber et al., 2006). Actions to remove deposited sediments by ciliary movements, mucus secretion and tissue distension (Rogers, 1990) result in enhanced energy expenditures with associated metabolic costs (Dallmeyer et al., 1982; Riegl and Branch, 1995; Telesnicki and Goldberg, 1995). Effects of increased, repeated or prolonged exposure on zooxanthellate corals to sediments are decreased skeletal growth (Bak, 1978; Dikou, 2009; Dodge et al., 1974; Edmunds and Davies, 1989), decreased tissue growth (Anthony et al., 2002), damage or loss of tissue (Bak, 1978; Bak and Elgershuizen, 1976; Stafford-Smith, 1993) and polyp mortality (Philipp and Fabricius, 2003). Not all effects of higher sediment loads are detrimental, both suspended and deposited particulate matter and sediments can be used as nutritional sources by tropical corals (Anthony, 1999a, 2000; Mills et al., 2004; Rosenfeld et al., 1999) and both skeletal and tissue growth rates can be enhanced at certain levels of exposure (Anthony, 1999b; Anthony and Fabricius, 2000). In addition to effects on the adult stage, sediment exposure can inhibit zooxanthellate coral reproduction with documented effects on larval development, larval survival, settlement, metamorphosis, and recruit survival (Fabricius, 2005).

Sedimentation effects on cold-water corals are at present not well investigated. Although reduction of photosynthetic yields is not an issue for zooxanthellate-free cold-water corals, it is likely that clearing their tissues from sediments will involve higher metabolic costs. On the other hand, cold-water corals live heterotophically and therefore the organic matter sources associated with sediments may bear significant nutritional advantages. Available studies on sediment tolerance typically study impacts after relatively short exposure periods (hours to days) and measure immediate effects like oxygen shortage or mortality (Allers et al., in prep.; Brooke et al., 2009). Brooke et al. (2009) found that exposure to environmentally very high concentrations of suspended natural sediments (range of 54–362 mg l^{-1}) resulted in significant polyp mortality in *L. pertusa*. For the same species, Allers et al. (in prep.) observed oxygen depletion at the coral surface, with depletion increasing with sediment coverage thickness and time following sediment deposition. The latter authors also noted that mucus secretion was involved in sediment rejection. Larsson and Purser (2011) reported that deposited natural sediments and water-based drill cuttings were efficiently removed from tissue covered surfaces of *L. pertusa*. However, during repeated exposures, particles remained on bare exposed skeleton regions of coral branches, with accumulation of sediments and subsequent smothering of adjacent coenosarc and polyps. Sub-lethal effects due to enhanced sedimentation that impinge on the energy balance of the coral resulting from reduced feeding, energy expenditure related to mucus production or depletion of energy reserves have not been studied and may only be evident on longer time scales.

Table 1
Sediment properties of natural sediments (NS) and water-based drill cuttings (DC) used in the experiments. OM = organic matter.

Grain size (microns) fraction (%)	NS < 63 μm	DC < 63 μm
<3.0	18.6	11.7
3.0–15.5	61.3	60.8
15.5–30.0	14.2	23.0
30.0–63	5.8	4.5
OM (% DW)	9.2	3.8

The objective of the present study was to assess the effects of suspended particulate matter on the cold-water coral *L. pertusa* at a time-scale of months, with exposures to natural benthic sediments and water-based drill cuttings both investigated. Coral fragments were exposed to two particle concentrations (~5 mg l^{-1} and ~25 mg l^{-1}), and effects were measured on structural and storage fatty acid content in coral tissue and the physiological responses polyp activity, respiration, skeletal growth and polyp mortality. In addition, two small-scale studies were conducted on (1) the effect of sediment exposure on coral mucus production and (2) the effect of drill cutting exposure on *L. pertusa* larval survival.

2. Materials and methods

2.1. Exposure of corals to suspended natural sediments and drill cuttings

2.1.1. Experimental material and preparation

L. pertusa coral fragments were collected on June 29 2009 from the Tisler Reef in the Norwegian section of the Skagerrak a few kilometres north of the Swedish border. The coral pieces were collected from two different locations at N58°60′, E10°58′ on 95 and 110 m depth contours respectively with a ROV (Remote Operated Vehicle, Sperre SubFighter 7500 DC). All coral fragments were of the whitish morph and were transported at *in situ* temperature within hours to the University of Gothenburg field station at Tjärnö, Strömstad, Sweden. In the laboratory, corals were maintained in aquaria with flow-through of sand-filtered seawater (31–33 ppt from 45 m depth in the Koster-fjord) at 8 °C and were fed 5 days a week with *Artemia salina* nauplii. Shortly after collection, the coral fragments were further divided (when necessary) into manageable pieces each containing between 8 and 65 live polyps.

Natural benthic sediment was collected from a soft-bottom plateau (N59°00.8′, E011°07.2′) situated close to the *L. pertusa* reef at Säcken in the northern Koster-fjord, Sweden. Collection was performed at 70–80 m depth using a van Veen grab sampler a few weeks before start of experimental exposure. The sediment was sieved through 1 mm mesh size to remove larger fragments and any macrofauna and was stored refrigerated with overflow of seawater until further sieving and use in the experiment. Drill cuttings were provided by Statoil ASA and originated from oil drilling activities on the Norwegian Continental Shelf. The cuttings were from a 17.5″ drill section, were produced with a water-based mud containing glycol which utilised fine-grained barite as weighting agent. To separate fine mud particles from larger rock fragments, the drill cuttings were thoroughly agitated in water before sieving. Drill cuttings and natural sediments were sieved to a final size of <63 μm and stored refrigerated until used for exposure. During the experiment, several batches of drill cuttings and natural sediments were thus produced. The <63 μm fraction was chosen for experimental investigations as this finer material can be carried some distance from point of origin, be this at trawling or drilling sites. The particle size distributions of final drill cuttings and natural sediments were measured using Laser In-Situ Scattering and Transmissometry (LISST-100X, Sequoia Scientific Inc.; Table 1). The organic matter content in the sediments was estimated by incineration of samples in 450 °C for 5 h. Before incineration, salt was washed from the sediments using fresh water, with remaining fresh water siphoned from the sediments following settlement. Samples were then dried at 60 °C to constant weight and weighed before and after incineration for calculations of organic content (Table 1).

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