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Review

A review of impacts of marine dredging activities on marine mammals

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Marine dredging is an excavation activity carried out worldwide by many industries. Concern about the impact dredging has on marine life, including marine mammals (cetaceans, pinnipeds, and sirenians) exists, but effects are largely unknown. Through consulting available literature, this review aims to expand on existing knowledge of the direct and indirect, negative and positive impacts on marine mammals. In terms of direct effects, collisions are possible, but unlikely, given the slow speed of dredgers. Noise emitted is broadband, with most energy below 1 kHz and unlikely to cause damage to marine mammal auditory systems, but masking and behavioural changes are possible. Sediment plumes are generally localized, and marine mammals reside often in turbid waters, so significant impacts from turbidity are improbable. Entrainment, habitat degradation, noise, contaminant remobilization, suspended sediments, and sedimentation can affect benthic, epibenthic, and infaunal communities, which may impact marine mammals indirectly through changes to prey. Eggs and larvae are at highest risk from entrainment, so dredging in spawning areas can be detrimental, but effects are minimized through the use of environmental windows. Sensitive environments such as seagrass beds are at risk from smothering, removal, or damage, but careful planning can reduce degradation. Assessing impacts of contaminant remobilization is difficult, but as long as contaminated sediments are disposed of correctly, remobilization is limited in space and time. Effects of suspended sediments and sedimentation are species-specific, but invertebrates, eggs, and larvae are most vulnerable. Positive effects, including an increase in food, result from greater nutrient loads, but are often short term. Dredging has the potential to impact marine mammals, but effects are species and location-specific, varying also with dredging equipment type. In general, evidence suggests that if management procedures are implemented, effects are most likely to be masking and short-term behavioural alterations and changes to prey availability.

Keywords: aggregate dredging, anthropogenic noise, behavioural response, marine mammals, sedimentation, turbidity.

Introduction

Dredging is a worldwide excavation activity that involves removing sediment from a sea, river, or lakebed and depositing it at a new location. Uses are vast and include construction of ports, waterways, dykes, and other marine infrastructure, land reclamation, flood and storm protection, extraction of mineral resources to provide material for the construction industry (e.g. for road construction), and in environmental remediation of contaminated sediments (see reviews by Brunn *et al.*, 2005; Thomsen *et al.*, 2009; CEDA, 2011; Tillin *et al.*, 2011; WODA, 2013). Here, we focus on dredging in the marine environment, except fisheries.

Four main types of dredger, cutter suction dredgers (CSDs), trailing suction hopper dredgers (TSHDs), grab dredgers, and backhoe dredgers, are used commonly for dredging operations (Figure 1).

Regulations, project requirements, and nature of the seabed determine which dredger is used; processes vary substantially between types. Hydraulic dredgers, such as CSDs and TSHDs, use suction to move material from the seabed to a barge, hopper, or pipeline. CSDs are best suited to removing hard substrates, as a rotating cutter head breaks up material on the seabed before its removal by suction pipe. TSHDs, on the other hand, are ideal for removing loose sediments,

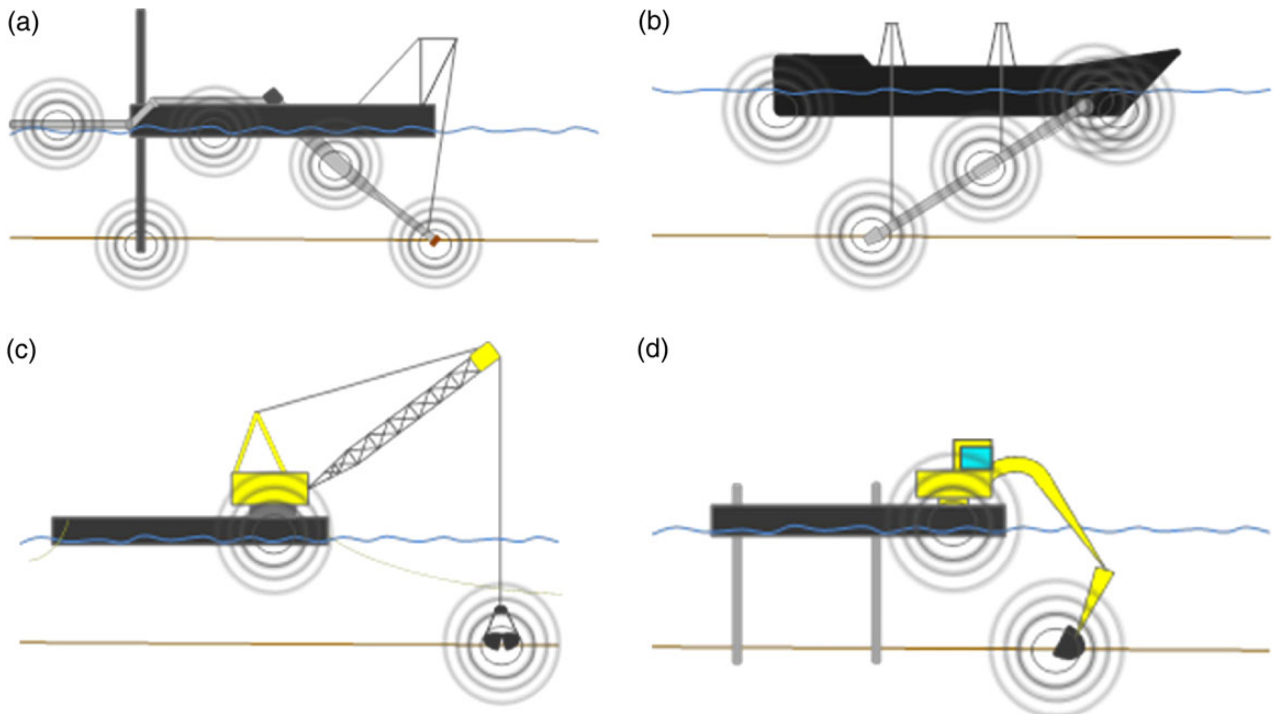

Figure 1. Common examples of dredgers and possible sound sources (a) CSD, (b) TSHD, (c) grab, and (d) backhoe (adapted from CEDA, 2011; WODA, 2013).

as the suction pipe or drag head is dragged behind the vessel and removes material while in transit. Grab and backhoe dredgers are mechanical and moored on site. Rather than using suction, grab dredgers use a crane-operated clamshell bucket to scrape material off the seabed. Once closed, the bucket is brought to the surface, and sediment deposited onto a separate barge. Backhoe dredgers are similar, but a hydraulic arm operates a bucket from the rear of the vessel (EUDA, 2014).

Marine aggregates are an essential resource. In waters around England and Wales alone, 20 million t of marine sand and gravel are dredged annually (Tillin *et al.*, 2011). Activity is not spaced uniformly, but instead confined to certain areas, or hotspots; in the UK, most dredging occurs around the Southeast coast (Tillin *et al.*, 2011). Expanding to continental Europe, most dredging is carried out in coastal areas of Netherlands and Denmark (Velegrakis *et al.*, 2010). In 2012, total turnover for dredging contractors worldwide was estimated to be €11 370 million, which is more than double the turnover in 2000 (IADC, 2012). Population growth and increasing number and size of infrastructure projects mean demand is growing continually worldwide, so amount of dredging, volume of aggregates, and turnover will most likely increase.

Since dredging impacts the marine environment, sustainable management of the activity is required, based on an in-depth understanding of how dredging affects marine habitats and associated fauna and flora. To date, the positive and negative effects of dredging on marine flora, benthic infauna, and the seabed are relatively well documented (see reviews by Newell *et al.*, 1998; Thrush and Dayton, 2002; Hitchcock and Bell, 2004; Erftemeijer and Lewis, 2006; Tillin *et al.*, 2011; Erftemeijer *et al.*, 2012). Conversely, although many marine mammal species inhabit coastal regions, where intensive construction activities (including dredging) occur (see, for example, Chilvers *et al.*, 2005; Coll *et al.*, 2012; Anderwald *et al.*, 2013; Pirotta *et al.*, 2013), the direct and indirect impacts on marine mammals are less well understood.

As a whole, marine mammals are dispersed widely, but distribution of individual species and populations is patchy, with certain areas comprising higher animal densities than others. Critical areas that provide ideal conditions for essential activities such as breeding, nursing, or feeding can be vital to a populations' ability to survive and grow. Interference with these habitats, which could be caused by dredging, may impact upon local distribution and abundance.

This paper aims to synthesize existing knowledge on the impacts of dredging on marine mammals, in the hope that environmental management of dredging activities will improve. Peer-reviewed scientific publications, books, and non-peer-reviewed consultancy and technical reports have been reviewed and discussed in relation to marine mammals, focusing on cetaceans (whales, dolphins, and porpoises), pinnipeds (eared seals, earless seals, and walruses), and sirenians (dugongs and manatees). For brevity, otters, polar bears, and freshwater cetaceans have not been discussed. For the guidance of impact assessments, a comprehensive reference table detailing hearing ranges, habitat, regional distribution, and diet preferences of all marine mammals, along with documented and predicted effects of dredging, has been provided in the Supplementary material.

Direct impacts

Physical injury or mortality from collisions, noise production, and increased turbidity are the main ways dredging can affect marine mammals directly.

Collisions

Collision with vessels is a known cause of injury and mortality in marine mammals (see reviews by Laist *et al.*, 2001; Jensen and Silber, 2003; Van Waerebeek *et al.*, 2007; Neilson *et al.*, 2012). Vessel movement is associated with all stages of dredging, from transit from the extraction site and dumping grounds to operation of the dredger itself. Thus, collision with dredgers is possible, but only one incident is evident in the literature; it resulted in the death of a southern right whale (*Eubalaena australis*) calf (Best *et al.*, 2001).

Research into marine mammals and vessel collisions in general has demonstrated that the likelihood of collision varies, depending on a number of factors, including vessel type, speed, location, species, and behaviour (Laist *et al.*, 2001; Van Waerebeek *et al.*, 2007).

Although vessel strikes are reported for all marine mammals, most research has focused on mysticetes. Studies have shown that the risk of a collision occurring and the likelihood that it will result in severe or lethal injury increases when vessels exceed 10–14 kn (Laist *et al.*, 2001; Vanderlaan and Taggart, 2007; Gende *et al.*, 2011; Neilson *et al.*, 2012; Lammers *et al.*, 2013). The influence of vessel size or type appears less significant. Right whales (*Eubalaena* spp.), humpback whales (*Megaptera novaeangliae*), and fin whales (*Balaenoptera physalus*) are considered some of the most prone to collisions (Laist *et al.*, 2001; Van Waerebeek *et al.*, 2007), and calves and juveniles are struck most commonly (Laist *et al.*, 2001; Neilson *et al.*, 2012; Lammers *et al.*, 2013). Resting or feeding whales were deemed more at risk by Laist *et al.* (2001), and Panigada *et al.* (2006) reported seasonal changes in collision rate of fin whales, with rates increasing during months when intensive feeding occurs. This is due possibly to the fact that feeding animals are distracted, and less focused on vessel movements (Laist *et al.*, 2001).

Data on vessel collisions need to be assessed with caution, as much of what we know is obtained from historical or anecdotal records that are difficult to verify. Data from strandings are useful, but identifying the cause is often based on speculation from injuries, which may not be obvious or could be attributed to a number of sources. Nevertheless, based on evidence presented, and given that active dredgers are stationary, or move at slow speeds of 1–3 kn (Reilly, 1950), if dredging is well managed, avoids critical habitats, times when animals may be distracted, or areas where calves are abundant, risk of collision between marine mammals and active dredgers is minimal. Collision risk is perhaps greater when dredgers are in transit, as speeds can reach ca. 12–16 kn (Brunn *et al.*, 2005), but in areas already characterized by heavy shipping traffic, the addition of dredging vessels is unlikely to increase the collision risk substantially (Tillin *et al.*, 2011).

Noise levels

Marine mammals, particularly cetaceans, are acoustically reliant animals that utilize sound for detecting prey, navigating, and communicating. Knowledge on the effects of anthropogenic noise on marine mammals has improved due to extensive research over the past two decades, although many information gaps still exist (see, for example, Croll *et al.*, 2001; Gerstein *et al.*, 2006; Southall *et al.*, 2007; Weilgart, 2007; Wright *et al.*, 2007; OSPAR, 2009; Popov *et al.*, 2011; Thomsen *et al.*, 2011; Di Iorio and Clark, 2012). Reported effects include temporary threshold shift (TTS) or permanent threshold shift (PTS), the latter being considered as auditory injury (Nachtigall *et al.*, 2003; Kastak *et al.*, 2005; Lucke *et al.*, 2009; Mooney *et al.*, 2009). Other effects include acoustic masking, which could cause animals to alter the duration, frequency, or sound level of acoustic signals. Masking of important sounds can theoretically impact reproductive success of individual whales, and in turn affect populations (Croll *et al.*, 2001; Clark *et al.*, 2009). Behavioural changes due to noise exposure can happen at large distances from the source, and may be costly biologically, as they could affect energy expenditure, or limit the amount of time spent feeding or resting (see NRC, 2005). It has been hypothesized that noise impacts have the potential to induce stress (Wright *et al.*, 2007; see also Rolland *et al.*, 2012). Stress could reduce the foraging efficiency of marine mammals or increase their susceptibility to disease and the effects of toxins (Geraci and Lounsbury, 2001; Reynolds *et al.*, 2005; Perrin *et al.*, 2009).

Published results of noise for dredgers used most commonly are highlighted in recent reviews such as Thomsen *et al.* (2009), CEDA (2011), and WODA (2013). In general, dredging produces continuous, broadband sound with main energy below 1 kHz. Sound pressure levels (SPLs) can vary widely, for example, with dredger type, operational stage, or environmental conditions.

Greene (1987) undertook noise measurements of two CSDs; received SPLs were 133 dB re 1 μPa and 140 dB re 1 μPa at distances of 0.19 and 0.2 km from the dredgers respectively (bandwidth = 20 Hz–1 kHz). Noise levels of a CSD used in New York and New Jersey harbour were recorded during rock fracturing; the maximum received SPL of 149.3 dB re 1 μPa rms was recorded at a distance of 89 m from the dredger. Based on a 15 log (R/1 m) scaling, the calculated source levels reached 175 dB re 1 μPa at 1 metre (bandwidth = 3 Hz–20 kHz; Reine *et al.*, 2012b).

Noise produced by TSHDs has been measured on a number of occasions, and in general reported sound levels appear higher than ones documented for CSDs. Robinson *et al.* (2011) measured six TSHDs, stating that sound levels below 500 Hz were in line with those expected for a cargo ship travelling at modest speeds (8–16 kn). The maximum broadband source SPL was 189.9 dB re 1 μPa at 1 metre (calculated based on 1/3 octave band levels from 31.6 Hz to 39.8 kHz, as reported by Robinson *et al.*, 2011). Estimated 1/3 octave band source levels above 1 kHz were relatively high, which was probably a result of the coarse aggregate pumped through the dredge pipe. Using an identical approach, de Jong *et al.* (2012) found very similar results to Robinson *et al.* (2011), but 1/3 octave band source levels clearly showed a steady decline beyond 1 kHz. This was due to the material dredged (sand as opposed to gravel).

Noise produced by grab dredgers varies substantially with operational stage. Dickerson *et al.* (2001) measured SPLs at 0.15 km from a grab dredger throughout the entire process. The loudest SPLs of 124 dB re 1 μPa were recorded at peak frequencies of 0.16 kHz, when the bucket made impact with the seabed.

Noise levels emanating from a backhoe dredger operating around the Shetland Islands, UK, were recorded by Nedwell *et al.* (2008). Using a scaling of 10 log (R/1 m), the back-calculated source level was 163 dB re 1 μPa at 1 metre (bandwidth = 20 Hz–100 kHz). In contrast, Reine *et al.* (2012a) calculated source levels of 179 dB re 1 μPa at 1 metre (bandwidth = 3 Hz–20 kHz), but the used scaling was different [15 log (R/1 m)], so results are difficult to compare.

Knowledge about the hearing range of cetacean species is only available partly, but it is assumed generally, that whales and dolphins hear over similar frequency ranges to the sounds they produce, although hearing ranges can extend beyond that of frequencies used for vocalizations (review by Southall *et al.*, 2007). If anthropogenic noise, such as that produced during dredging operations, coincides with species' hearing ranges, it has the potential to affect individuals and populations of marine mammals present within the area at the time. Looking at the overlap between dredging noises on the one hand, and suspected hearing sensitivity of marine mammals on the other, it can be assumed that all marine mammals are prone to noise impacts from dredging, although the issue might be more acute for baleen whales which communicate at very low frequencies (see Thompson *et al.*, 1979; Au *et al.*, 2000; Tervo *et al.*, 2012). Toothed whales (odontocetes; including larger toothed whales, dolphins, and porpoises) produce a variety of sounds for communication and echolocation, including narrowband, frequency-modulated (FM) continuous tonal sounds known as whistles (0.5–>80 kHz), and broadband sonar clicks (0.25–220 kHz) including burst pulse sounds (Au *et al.*, 2000; Gordon and Tyack, 2002). The range of best hearing in the species documented so far is shifted to frequencies well above 10 kHz with sensitivity below 1 kHz being relatively poor (see Southall *et al.*, 2007). Impacts of dredging noise are also a potential concern for pinnipeds, which utilize sound during social interactions and when locating mates (Schustermann *et al.*, 2001; Van Opzeeland *et al.*, 2010). If dredging activities were to occur in breeding areas, masking of biologically important noises could decrease the chances of reproduction in pinnipeds.

Based on the information provided above, reactions of marine mammals to dredging sound are expected to depend on types of dredger used and its state of operation, on the local sound propagation conditions, and the receiver characteristics with regard to the sensitivity and bandwidth of hearing. Given available information, sound levels that marine mammals are exposed to usually are below suspected injury thresholds or PTS (for exposure criteria, see Southall *et al.*, 2007); however, TTS cannot be ruled out if marine mammals are exposed to noise for prolonged periods [for a recent study on effects of long-term exposure in harbour porpoises (*Phocoena phocoena*), see Kastelein *et al.* (2012)]. In the literature, dedicated case studies on the effects of marine dredging activities on specific marine mammal species are rare, and isolating any reactions observed during dredging activities is difficult to achieve. It is thought that bowhead whales (*Balaena mysticetus*) are affected by industrial noise in general, but results from comprehensive studies on their reactions to drilling and dredging noise in the Canadian Beaufort Sea have been inconclusive with conflicting observations recorded. On a number of occasions in the early 1980's, bowhead whales were observed close to operating dredgers and drill ships (Richardson *et al.*, 1985, 1987, 1990). A longer-term comparison of data collected from the Canadian Beaufort Sea suggests that fewer animals were observed in total after 1980, when an increase in industrial activity, including dredging, occurred. It was hypothesized that, either cumulative effects of increased industrial activity led to habitat avoidance or alternatively, a change in prey distribution caused whales to occupy different areas (Richardson *et al.*, 1987).

While carrying out a study on grey whales (*Eschrichtius robustus*) in a lagoon in Baja California, Bryant *et al.* (1984) reported that industrial activities, including dredging, had led most likely to long-term changes in baleen whale distribution. The study reported that grey whales were almost absent completely from the lagoon during the many years of intense shipping and dredging activity, and returned only once shipping had ceased. Shipping itself is potentially a major cause for disturbance in cetaceans (see Southall, 2005; OSPAR, 2009; and recent results in Rolland *et al.*, 2012), so the actual effect of dredging alone could not be determined.

More recently, Anderwald *et al.* (2013) stated that minke whales (*Balaenoptera acutorostrata*) off the coast of Ireland avoided areas of high construction vessel traffic (including dredgers) during installation of a gas pipeline. Data indicated that number of fishing boats was also correlated negatively with minke whale presence, which suggests avoidance was perhaps more related to vessel noise or presence in general, rather than of dredging or construction specifically.

Using passive acoustic monitoring techniques, Diederichs *et al.* (2010) found short-term avoidance in harbour porpoises at ranges of 600 m from a TSHD operating to the west of Sylt (Northern Germany). In the Port of Anchorage, near the head of Cook Inlet (south-central Alaska), declines in the beluga whale (*Delphinapterus leucas*) population have also been investigated in relation to dredging works. Results were inconclusive, with beluga whales often sighted in proximity to operating dredgers, but it was noted that they could have habituated over time (Hoffman, 2010). Most recently, Pirotta *et al.* (2013) noted that bottlenose dolphin (*Tursiops truncatus*) presence in foraging areas in Aberdeen harbour declined as dredging intensity increased. Aberdeen harbour is subject to high shipping activity year round, and thus dolphins are accustomed to high levels of vessel disturbance, so in this case, it was possible for the authors to link avoidance to dredging activity, and not vessel presence in general.

Studies so far suggest that effects of dredging sound on pinnipeds may be limited. Between 2002 and 2003, during observations of dredging operations in Geraldton, Western Australia, it was reported that New Zealand fur seals (*Arctocephalus forsteri*) and Australian sea lions (*Neophoca cinerea*) showed no sign of disturbance reactions, despite the relative closeness of the dredging to popular haul-out sights (EPA, 2007). Similarly, Hawaiian monk seals (*Monachus schauinslandi*) showed no adverse reactions to bucket dredgers around Tern Island (Gilmartin, 2003). Anderwald *et al.* (2013) found that grey seals (*Halichoerus grypus*) showed some level of avoidance to high construction vessel traffic in Ireland, although it should be noted that observations were undertaken from a cliff, so animals possibly taking advantage of increased food close to operating dredgers may have been missed by observers.

Comparisons of various noise measurements with behavioural hearing data of the West Indian manatee (*Trichechus manatus*) by Gerstein *et al.* (2006) found that cavitation from dredger propellers, dredger head vacuuming, and noise from submerged slurry pipelines could mask the noise of other boats, increasing chances of ship strikes. Avoidance reactions from sirenians have also been observed during research into low-frequency noise, with Florida manatees (*T. manatus latirostris*) found to select seagrass (*Thalassia testudinum, Syringodium filiforme, Halodule wrightii*) bed sites with less low-frequency noise (Miksis-Olds *et al.*, 2007).

In conclusion, it is difficult to elucidate specific dredging noise effects on marine mammals, given that many industrial activities occur concurrently. It can be concluded that most effects concern short, perhaps medium-term behavioural reactions and masking of low-frequency calls in baleen whales and seals. Temporary hearing loss is possible if receivers stay for extended periods near the dredger, but auditory injury is unlikely.

Turbidity

Seabed disturbance through extraction, rejection, and disposal of sediments, along with outwash of excess materials, can result in increased turbidity and creation of sediment plumes. Sediment plumes have the ability to extend the impact of dredging over larger areas that would otherwise remain unaffected physically (Hitchcock and Bell, 2004). Research has shown that effects are short lived generally, lasting a maximum of four to five tidal cycles (Hitchcock and Bell, 2004), and are confined mainly to an area of a few hundred metres from the point of discharge (Newell *et al.*, 1998; Hitchcock and Bell, 2004).

Marine mammals often inhabit turbid environments and many utilize sophisticated sonar systems to sense the environment around them (see Au *et al.*, 2000). Evidence that turbidity affects cetaceans or sirenians directly is not evident in the literature, and feeding methods employed by some mysticetes, for example, grey whales and sirenians, create plumes of sediment, indicating that individuals must have some level of tolerance and are able to feed in turbid conditions.

Researchers have explored the effects of turbidity on pinnipeds, which are not known to produce sonar for prey detection purposes. If vision is used to locate prey, increases in turbidity could affect their ability to hunt. In a captive environment, Weiffen *et al.* (2006) tested the visual acuity of harbour seals to increasing levels of turbidity, finding that it decreased substantially, as turbidity increased above 1 formazin turbidity unit (FNU). The same study tested turbidity levels in areas of the North Sea where harbour seals are known to reside; levels ranged from 7 to 40 FNU at a depth of 2 m; however, it is likely that other senses are used instead of, or in combination with, vision (e.g. Dehnhardt *et al.*, 2001). Newby *et al.* (1970) reported apparent blindness, identified by opaque and white corneas, in three harbour seals (*Phoca vitulina*) on Gertrude Island, Puget Sound, Washington. It was suggested that, as blind individuals appeared healthy, their ability to forage was unaffected by blindness. Factors used to make assumption of healthiness are not, however, explained. Similar assumptions were made by McConnell *et al.* (1999), who used satellite relay data loggers (SRDLs) to track foraging areas and trip durations of grey seals in the North Sea. One blind seal was included in the study, but no significant difference in foraging behaviour was found. These results indicate that vision is not essential to pinnipeds' survival, or ability to forage.

To summarize, the limited available information indicates that increased turbidity, as a result of dredging, is unlikely to have a substantial direct impact on marine mammals that often inhabit naturally turbid or dark environments. This is likely because other senses are utilized, and vision is not relied upon solely.

Indirect impacts

Indirect impacts on marine mammals from dredging stem from changes to their physical environment, or to their prey. Physical characteristics, such as topography, depth, waves, tidal currents, sediment particle size, and suspended sediment concentrations, are altered by dredging (see review by Tillin *et al.*, 2011), but changes also occur naturally, as a result of disturbance events such as tides, waves, and storms. Consequently, small changes are unlikely to have a substantial effect on the marine ecosystem, and can even increase biodiversity, but large-scale repeated alterations have the potential to affect the entire foodweb, right up to marine mammals.

Indirect effects can be positive or negative, but are most likely highly species-specific, so it is unclear how effects from dredging influence various marine organisms. Given the varied and vast quantity of data on the subject, literature reviews are not exhaustive, but the aim here is to provide a good indication of how effects of dredging on the marine environment, fauna, and flora may affect marine mammals indirectly, although the high level of site, and species specificity, means assessment of impacts are somewhat subjective.

Negative

Dredging impacts marine organisms negatively through entrainment, habitat degradation, noise, remobilization of contaminants, sedimentation, and increases in suspended sediment concentrations.

Entrainment

All marine organisms associated with the seabed are at risk from entrainment, which is the unintentional removal of organisms by the suction field created by hydraulic dredgers (Reine and Clarke, 1998). At present, no studies address the indirect effects of entrainment on marine mammals specifically, but impacts of entrainment during marine dredging on prey species have been addressed, although mostly in unpublished, non-peer reviewed reports (see reviews by Reine and Clarke, 1998; Nightingale and Simenstad, 2001).

Entrainment rates depend on a number of factors, including depth, dredger type, speed, and strength of suction field. For example, hydraulic dredgers create stronger suction fields than mechanical ones, so are more of a risk to marine life (Reine and Clarke, 1998; Nightingale and Simenstad, 2001). Susceptibility also depends on species. Benthic fauna and demersal fish that are associated strongly with bottom substrates are considered more at risk from entrainment than highly mobile species. Overall, consensus within the literature appears that, entrainment of adult fish and many shellfish species, has minimal population level effects (Reine and Clarke, 1998; Drabble, 2012b).

In agreement with freshwater studies (e.g. Boysen and Hoover, 2009; Hoover *et al.*, 2009, 2011), dredging-related entrainment is considered to be more of an issue for young fish, and eggs and larvae of marine organisms, as their reduced swimming ability means they are unable to actively avoid the suction field (Reine and Clarke, 1998; Nightingale and Simenstad, 2001; Drabble, 2012b). Consequently, dredging in spawning areas can affect survival rate of organisms to adulthood, and therefore population structure and growth. Populations of common sole (*Solea solea*), lemon sole (*Microstomus kitt*), thickback sole (*Microchirus variegatus*), and European plaice (*Pleuronectes platessa*) in the Eastern Channel Region of the UK were monitored by Drabble (2012a) from 2005 to 2008. Baseline data were obtained in 2005, and dredging commenced in 2006. Results indicate a reduction in numbers, and a change in population structure. For example, an abundance of age 1 sole was evident in 2005, but in 2006, few age 2 sole were recorded. In 2008, fish born before dredging dominated samples. Similar results were found for plaice. Natural conditions alone could not account for the alteration, and entrainment was considered a factor, but its role is primarily unknown.

Given that effects are greatest during the egg and larval stages, impacts can be reduced by implementing temporal restrictions on dredging activity, known as environmental windows, which ensure activity is restricted in spawning and nursery grounds at critical times. To put into context of marine mammals, if risk assessments are carried out before dredging, and activities are well managed, reduction in prey numbers is unlikely to be high enough to have substantial population-level impacts.

Habitat degradation

Ecologically important habitats such as seagrass beds and coral reefs that are particularly sensitive to change are at high risk from dredging. Main concerns are physical removal, smothering, and a decrease in light intensity (Erftemeijer and Lewis, 2006; Erftemeijer *et al.*, 2012). Losses of these habitats, as a result of dredging can be substantial. For example, a review of 45 case studies worldwide found that 21 023 ha of seagrass beds were lost as a result of 26 dredging projects over a 50-year period (Erftemeijer and Lewis, 2006), and this is likely an underestimation, as other projects were carried out where extent of loss was not reported (Erftemeijer and Lewis, 2006). Dredging impacts on seagrass beds and coral reefs have been reviewed by Erftemeijer and Lewis (2006) and Erftemeijer *et al.* (2012), respectively.

Seagrass beds are utilized frequently by marine mammals, but impact removal varies considerably. Herbivorous sirenians are reliant entirely on seagrass beds as a food source, so removal can have substantial effects on survival, distribution, and feeding habits (Spain and Heinsohn, 1973 cited in Heinsohn and Spain, 1974; Heinsohn *et al.*, 1977; Marsh *et al.*, 1982; Preen and Marsh, 1995; GBRMPA, 2011). Other species, for example, bottlenose dolphins, feed on prey within seagrass beds (e.g. Scott *et al.*, 1990; Shane, 1990), but are not restricted to them. In fact, Allen *et al.* (2001) stated that bottlenose dolphins in Clearwater, Florida, preferred non-seagrass habitats, suggesting that seagrasses may create an obstruction which could hinder prey location and capture. Prey sizes were also bigger outside of seagrass habitats, so more energetically viable. Irrespective of this, seagrass beds are an essential part of ecosystems, given their primary productivity, and role in nutrient cycling and sediment stabilization (Duarte, 2002; Orth *et al.*, 2006). They also support diverse marine communities, and their structure provides shelter for juvenile marine organisms (e.g. Heck *et al.*, 2003). Changes therefore affect the foodweb at some level, for varying amounts of time, and ability to recover depends on species and extent of loss or damage (Erftemeijer and Lewis, 2006). In terms of smothering, burial depth, sediment type, nutrient load, and whether or not the sediment contains pollutants all influence survival (Zieman and Zieman, 1989; Wilber *et al.*, 2005; Erftemeijer and Lewis, 2006).

Dredging-related impacts on seagrasses reported in recent years have declined generally when compared with the past (Erftemeijer and Lewis, 2006). This is perhaps the result of increased knowledge, the ability to model and predict paths of sediment plumes, and introduction of well-designed and implemented mitigation measures (Erftemeijer and Lewis, 2006). In addition, seagrasses have varying abilities to withstand at least small changes in their environment, which occur as a result of natural processes and anthropogenic activities. Thus, short-term light reductions, or thin smothering from dredging should have only short-term effects. What is clear from the research is that each case needs to be assessed individually. As long as criteria that amalgamate all factors are used during planning stages, impacts of dredging on seagrasses should be short-term, and not sufficient to have detrimental impacts on marine mammals, although minor alterations to prey availability, or distributions may occur.

Noise levels

Sound is utilized by many marine organisms to sense the environment around them and find prey. Consequently, an increase in anthropogenic low-frequency noise, such as that produced by dredging, has the potential to cause adverse effects. The extent to which effects disseminate through the foodweb to marine mammals is unknown, but speculated effects are given, based on available data.

Extensive variability exists between hearing sensitivity of fish species, but in general, they are sensitive to low frequencies (Popper *et al.*, 2003; Popper and Fay, 2011), which puts them at risk from dredging noise. Some level of TTS has been reported in freshwater and marine fish exposed to low-frequency white noise (e.g. Scholik and Yan, 2001; Amoser and Ladich, 2003; Smith *et al.*, 2004a, b) and vessel noise (e.g. Scholik and Yan, 2002; Codarin *et al.*, 2009) in laboratory experiments. Results suggest that those with more specialized hearing experience a greater level of hearing loss. It should be noted, however, that these experiments did not focus on dredging noise, so noise characteristics and exposure durations likely vary from those experienced during dredging activities, which may alter the chance and extent of TTS.

No study has looked at dredging noise specifically, but avoidance of low-frequency vessel noise by some fish species has been reported (e.g. Mitson, 1995; Mitson and Knudsen, 2003; de Robertis and Wilson, 2011; reviewed by de Robertis and Handegard, 2013) and Handegard *et al.* (2003) noted vertical and horizontal avoidance by cod (*Gadus morhua*) of a bottom-trawling vessel. Perhaps noise is not the primary factor causing avoidance reactions, although other factors, such as the presence of vessels themselves, may still be relevant to dredging. Small-scale avoidance of noise is unlikely to have any long-lasting effects on fitness, but if noise was to occur in breeding or feeding grounds, then fish could relocate to other areas; more research is required to assess this possibility. Other behavioural effects include increased motility (Buscaino *et al.*, 2010), reduced feeding efficiency (Voellmy *et al.*, 2014), and masking of communication signals (Codarin *et al.*, 2009).

Noise also has the ability to impact larval organisms that use sounds to orientate towards settlement locations (Simpson *et al.*, 2010; Radford *et al.*, 2011; Holles *et al.*, 2013). Masking of these sounds could prevent larvae settling in ideal locations, or prevent them from finding a place to settle at all (e.g. Simpson *et al.*, 2010, 2011; Holles *et al.*, 2013).

Responses to particle motion of low-frequency sound have also been recorded in cephalopods (*Sepia officinalis, Loligo vulgaris, Loligo pealeii, Octopus vulgaris, Illex coindetii*; Packard *et al.*, 1990; Mooney *et al.*, 2010), which can form an important part of the diet of some marine mammals. Low-frequency noise in the 1 Hz–10 kHz band altered cephalopod breathing rhythms and movement, and in some cases induced acoustic trauma and permanent damage to statocysts' sensory hair cells (Packard *et al.*, 1990; Andre *et al.*, 2011; Solé *et al.*, 2013), that are responsible for the detection of sound (Kaifu *et al.*, 2008; Mooney *et al.*, 2010).

Dredging noise is unlikely to result in direct mortality, or permanent hearing damage of fish, but long-term exposure could theoretically affect fitness of some individuals. Exclusion of prey from foraging areas has potential to impact marine mammals negatively, but extent to which this occurs depends on the significance of the feeding ground, ability to switch prey species, and availability of alternative foraging areas. The level of effect is therefore species- and context-dependent.

Toxins and pollutants

Over time, sediments accumulate toxins and pollutants such as hydrocarbons and heavy metals (Cundy *et al.*, 2003; Taylor *et al.*, 2004). Dredging disturbance of sediments can release contaminants into the water column, which has the potential to change chemical properties of the sediment, and reduce water quality at both extraction and dumping sites for some time after dredging has ceased. Once suspended, contaminants can become available to marine organisms, and potentially accumulate up the food chain. Remobilization and bioavailability of contaminants is site-specific, complex, and affected by a multitude of factors. The fate of remobilized contaminants has not been discussed here, but see reviews by Eggleton and Thomas (2004) and Roberts (2012) for details. Literature on dredging release of contaminants suggests that remobilization is restricted in both time and space, and that as long as highly contaminated sediments are managed strictly, concentrations are not high enough to have detrimental effects on the environment (Roberts, 2012).

Marine mammals are susceptible to bioaccumulation because they feed at high trophic levels, and have a large proportion of lipid-rich blubber which accumulates contaminants readily (Vos *et al.*, 2003). High contaminant levels have been linked to immune system depression, disease breakouts, reproductive effects, developmental effects, and endocrine disruption (see Vos *et al.*, 2003 for a review of toxins and marine mammals).

Dredging release of contaminants may increase the amount consumed by lower trophic levels, including species of marine mammal prey, but laboratory studies indicate that effects on marine organisms are varied and dependent on conditions, such as concentration, exposure duration, and species (Rice and White, 1987; Fichet *et al.*, 1998; Hedge *et al.*, 2009; Knott *et al.*, 2009; reviewed by Roberts, 2012). Negative impacts do, however, have the potential to reduce prey availability.

Marine mammals accumulate high levels of contaminants irrespective of whether dredging occurs. Linking remobilization of contaminants from dredging to effects in marine mammals is challenging. Levels of toxins in blubber before, during, and after dredging are unknown, marine mammals are mobile and exposed to contaminants throughout their entire range, and effects are only likely to be discovered long after dredging ceases. Risks are highest and impacts greatest, when dredging contaminated sediments, but screening ensures they are disposed of responsibly, and not in the open ocean (Roberts, 2012). Although organisms can accumulate contaminants released during dredging for months after it has ceased, lethal effects are unusual and likely to be confined spatially.

Suspended sediment

Natural events, such as storms that disturb sediments, increase turbidity. To cope, marine organisms have evolved varying levels of tolerance, or survival mechanisms; however, dredging-related increases in turbidity may exceed natural levels, or vary in terms of timing, which can put strain on some organisms' ability to survive. Impacts of increased suspended sediment concentrations are highly species-specific, and vary with sediment characteristics (see reviews by Stern and Stickle, 1978; Newcombe and Macdonald, 1991; Clark and Wilber, 2000; Wilber and Clarke, 2001; Berry *et al.*, 2003).

Considerable research has been carried out to assess impacts of suspended sediments on marine organisms, but not all studies have used sediment plume concentrations that resemble those produced during dredging. This means application to dredging is limited, although large variations do exist in plume concentrations because of local conditions (and dredger type). van der Veer (1979) cited in van der Veer *et al.* (1985) recorded suspended sediment concentrations of 6300 mg l^{-1} in the outwash of a suction dredger, while Hitchcock and Dearnaley (1996) reported lower concentrations of 80–340 mg l^{-1} (upper water column) and 480–611 mg l^{-1} (lower water column) within 100 m of a dredger. Levels reported by Hitchcock and Bell (2004) were in-between at 5500 mg l^{-1} close to a dredger, reducing to 450 mg l^{-1} with distance, and Reine *et al.* (2007) stated that maximum concentrations, recorded in proximity to a bucket dredger in Maumee Bay, were 800 mg l^{-1}, although levels decreased rapidly, and were closer to 300 mg l^{-1} at a distance of 24 m.

Turbidity has the potential to impact fish feeding ability, although piscivorous fish that feed on larger prey, detected visually over longer distances, are affected to a greater extent than planktivorous fish, that detect prey visually over short distances (Hecht and van der Lingen, 1992; Utne-Palm, 2002; de Robertis *et al.*, 2003). Other behavioural alterations include changes in habitat choice (e.g. Wenger and McCormick, 2013), altered predator–prey relationships (e.g. Wenger *et al.*, 2013), and increased anti-predator responses (Leahy *et al.*, 2011). High suspended sediments can also cause gill damage in fish (Herbert and Merkens, 1961; Lake and Hinch, 1999; Au *et al.*, 2004; Wong *et al.*, 2013).

Increases in suspended sediment concentrations on invertebrates include abrasion, decreased respiration rates due to clogging of filtration mechanisms, or behavioural alterations. Change in conditions can also affect feeding efficiency of filter-feeders, as the food-to-sediment-ratio is decreased, meaning more energy is required to sort through additional material. Reactions are, as expected, species-specific, but Last *et al.* (2011) stated that changes in behaviours observed in blue mussels (*Mytilus edulis*), queen scallops (*Aequipecten opercularis*), Ross worms (*Sabellaria spinulosa*), and edible crabs (*Cancer pagurus*) exposed to suspended sediment concentrations of 12 and 71 mg l^{-1} have the potential to impact fitness, if conditions are prolonged; however, lethal effects were not observed for either concentration.

The impact of suspended sediment on eggs and larvae of marine organisms has been addressed in many studies under laboratory conditions (e.g. Auld and Schubel, 1978; Kiørboe *et al.*, 1981; Morgan *et al.*, 1983; Griffin *et al.*, 2009; Suedel *et al.*, 2012). Auld and Schubel (1978) and Kiørboe *et al.* (1981) suggest that suspended sediment concentrations have limited effects on egg hatching success, but exposure was not immediate following dispersal. Griffin *et al.* (2009), on the other hand, found that if Pacific herring (*Clupea pallasii*) eggs were exposed to suspended sediments of 250 and 500 mg l^{-1}, within 2 h of dispersal, sediments adhered to the outside of eggs, which led to increased egg-to-egg attachment, and abnormal larval development; ability to attach to surfaces could also be compromised. Outside of the initial 2 h, no significant effect was recorded. The majority of data are collected in laboratories under set conditions that vary from those in the wild; current strength, temperature, and contaminant levels may all have an effect. Effects also vary substantially depending on species, for example, not all species' eggs form an adhesive layer, which influences how sediment particles attach to the outside.

Modelling of sediment plumes can predict where concentrations will be highest, meaning dredging can be planned to avoid sensitive areas, and times such as spawning. If this is the case, lethal and long-lasting impacts on marine organisms should be minimized, but small-scale or short-term effects are to be expected, although they are unlikely to have significant impacts on marine mammals.

Sedimentation

Change in sediment structure as a result of dredging has been reported frequently in the literature (e.g. Kenny and Rees, 1996;

Desprez, 2000; van Dalfsen *et al.*, 2000; Weller *et al.*, 2002; Hitchcock and Bell, 2004; Boyd *et al.*, 2005; Cooper *et al.*, 2005; Robinson *et al.*, 2005; Desprez *et al.*, 2010; Barrio Froján *et al.*, 2011); a fining of the sediment is most common, especially where screening is carried out. Extent of change, and ability to recover, varies substantially, and depends on area, and type of sediment deposited. In general, regularly disturbed habitats characterized by fine sands and fast-growing opportunistic species are affected less, and recover quicker, than stable habitats monopolized by coarse gravels and slow-growing sessile fauna and flora (Tillin *et al.*, 2011). Coarse sediment habitats are also likely to see a greater change in species composition over the long term, as the new finer sediment suits a different range of species than those that occupied the coarser sediments, although it should be noted that sediment composition is not the only driver in determining benthic community composition; other factors have impacts.

In addition to changing community structure, sediment deposition can smother or bury marine organisms associated with the seabed. Non-mobile organisms and early life stages that are unable to move out of the path of dredgers are most at risk. Impacts are highly species-specific and depend on a species' ability to either tolerate or escape burial, both of which vary with sediment characteristics and temperature. This variation is demonstrated by Last *et al.* (2011) through laboratory experiments on a number of species. Some can survive prolonged periods buried in the sediments (e.g. Ross worm), while others suffer high mortality if buried, but are able to emerge from relatively deep sediments [e.g. green sea urchin (*Psammechinus miliaris*)]. Species that form large beds, for example, oysters, are important within the ecosystem as many organisms rely on or are associated with them for colonization or predator protection (Wilber *et al.*, 2005).

Smothering of eggs can cause mass mortality, delayed hatching (see, for example, Berry *et al.*, 2011), or added sediment could reduce the number of settlement locations available to larvae, which increases level of competition (see review by Wilber *et al.*, 2005).

Given that effects of sedimentation vary massively, putting them into context of potential indirect impacts on marine mammals is challenging, although a reduction in the health of benthic communities signifies a reduction in the amount of food available to higher trophic levels, including marine mammals. Avoidance of spawning or nursery areas during dredging is beneficial, and minimizes large-scale losses of species, as will minimizing dredging-related sedimentation around oyster beds or other sensitive habitats. Nevertheless, sedimentation will have some level of impact on marine organisms, and could result in mortality or long-term changes in the environment; however, dredged areas are colonized quickly by opportunistic species, which likely attract higher trophic level species. If re-colonization includes those species consumed by marine mammals, then impact on prey availability should be short-term only, in which case long-lasting, population-level effects are unlikely, but short-term changes to feeding, or distribution are possible.

Positive

Dredging disturbance of sediments has been reported to enhance diversity and abundance of benthic fauna near dredged channels (Jones and Candy, 1981; Poiner and Kennedy, 1984; van Dalfsen and Essink, 2001; Newell *et al.*, 2004; Claveleau and Desprez, 2009). A possible reason for this enhancement is the release of organic nutrients from the sediment plume (Ingle, 1952; Biggs, 1968; Sherk, 1972; Oviatt *et al.*, 1981; Walker and O'Donnell, 1981). This rise in species abundance has the potential to increase the amount of food available temporarily to marine mammals. For example, Anderwald *et al.* (2013) reported larger numbers of bottlenose dolphins during construction activity around Doonanierin Point, Ireland. It cannot be said with certainty that increased prey numbers, as a result of seabed disturbance, attracted the dolphins, as other factors were not explored, but it is a possibility.

Change in topography could also affect marine mammals positively. For example, Allen *et al.* (2001) found that bottlenose dolphins in Anclote Key, Clearwater, Florida, favour previously dredged channels, over other habitat types, stating that the dolphins used the structural features to aid in prey detection and capture.

In terms of marine organisms, increase in food availability can result in increased growth rates. For example, Ingle (1952) reported that oyster species grew quicker in areas of high turbidity. Some fish larvae also benefit, as Boehlert and Morgan (1985) reported that at suspended sediment concentrations of 500–1000 mg l^{-1}, feeding rate of larval Pacific herring was increased significantly above the control (0 mg l^{-1}). Increased turbidity could also increase protection against visual predators, which will find it harder to hunt. Positive effects are often observed only up to a certain concentration, so perhaps extensive dredging could increase suspended sediment concentrations above those that appear positive, and negative effects will resume.

Increases are often short-lived only, and followed by reductions in diversity, biomass, and abundance. Thus, positive effects can be limited, and potentially harmful if marine mammals are attracted to areas of high human activity, where the risk of collision is increased, as is exposure to noise.

Conclusions

There are few studies on the effects of dredging on marine mammals that can be attributed entirely to dredging activities in isolation.

In terms of direct effects on marine mammals, collisions are possible, but improbable given that operating dredgers are either stationary or moving at slow speeds. Dredging noise levels vary greatly, depending not only on dredging methods used, but also on disparities in each method. Limited data that do exist highlight that dredging is unlikely to cause physiological damage to marine mammal auditory systems, but is more likely to lead to masking and behavioural disturbances, and baleen whales could be more at risk than other taxa. Effects of turbidity are often localized with minimal direct impact on marine mammals that inhabit naturally turbid and dark environments.

Indirect effects of dredging on marine mammals are more complex, and considerably less well understood, but studies on potential marine mammal prey species are more numerous. In general, the literature suggests that dredging causes reductions in biomass, abundance, and species diversity for varying lengths of time, depending on surrounding conditions. Marine mammals can likely compensate for small-scale changes in prey abundance by switching prey species, moving to alternative foraging grounds, or increasing time spent foraging, although this maybe more of an issue for small, restricted populations, as movement away from areas of high disturbance may not be possible.

Entrainment in nursery or spawning grounds of prey could cause significant reductions in prey abundance, as could removal of, or damage to, sensitive seagrass systems. No studies have addressed the impact of dredging noise on fish, but research on low-frequency noise exposure suggest that TTS is possible, although avoidance and masking are more likely.

Disturbance of sediments pose some of the greatest risks to marine environments. Remobilization of contaminants can increase uptake by marine organisms, which will disseminate through the foodweb to marine mammals, but effects are usually localized and contaminated sediments disposed of elsewhere. Increased suspended sediment concentrations, and sedimentation can result in long-term loss or permanent changes to the seabed, but negative impact on marine mammals may be reduced if the new species serve the same purpose, and occupy the same trophic levels as those that occupied the habitat before dredging.

Effects of dredging can be positive, due to increased primary production and nutrient enrichment from sediment dispersal and entrainment. Increases in populations are, however, often short term and recovery of habitats to pre-disturbance conditions can take years.

Adverse impacts from dredging can be limited by implementing mitigation measures, such as the use of environmental windows which ensure that dredging activities do not occur in important habitats or at times when marine mammals or their prey are most sensitive, for example, during breeding or spawning seasons. More likely effects include masking, avoidance and short-term changes to behaviour, and prey availability. Context is however important when discussing impacts, because marine mammals are more likely to tolerate disturbance, and remain near active dredgers, if in a prime foraging location, where rewards are high. In this case, reactions may not be obvious to observers, but the absence of a measurable response does not mean longer-term impacts are absent.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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