Environmental Impacts of the Deep-Water Oil and Gas Industry

Erik E. Cordes et al.

The industrialization of the deep sea is expanding worldwide. Increasing oil and gas exploration activities in the absence of sufficient baseline data in deep-sea ecosystems has made environmental management challenging. The following report excerpt reviews the types of activities that are associated with global offshore oil and gas development in water depths over 200 m, the typical impacts of these activities, and some of the more extreme impacts of accidental oil and gas releases.

Effects of Routine Activities

Routine oil and gas activities can have detrimental environmental effects during each of the main phases of exploration, production, and decommissioning (Figure 1). During the exploration phase, impacts can result from indirect (sound and traffic) and direct physical (anchor chains, drill cuttings, and drilling fluids) disturbance. Additional direct physical impacts occur in the production phase as pipelines are laid and the volume of discharged produced water increases. Lastly, decommissioning can result in a series of direct impacts on the sea floor and can re-introduce contaminants to the environment. It is critical that all of the potential impacts of routine operations are accounted for when designing management strategies, whether local or regional, for offshore oil and gas activities.

Impacts from deep-water oil and gas development activities begin during seismic surveys that are used to reveal the subsurface geology and locate potential reservoirs. These impacts include underwater sound and light emissions and increased vessel activity. Sound levels produced during seismic surveys vary in intensity, but in some cases, soundwaves from these surveys have been detected almost 4000 km away from the survey vessel (Nieukirk et al., 2012). Impact assessments of acoustic disturbance have primarily focused on marine mammals. Reported effects include disruption of behavior (e.g., feeding, breeding, resting, migration), masking of sounds used for communication and navigation, localized displacement, physiological stress, as well as physical injury including temporary or permanent hearing damage (Gordon et al., 2004; Southall et al., 2008; Moore et al., 2012). Marine mammal exposure experiments and noise propagation modeling suggest that hearing damage may occur within a few 100 m to km from the sound source, with avoidance behaviors more variable but generally detected over greater distances (Southall et al., 2008). In contrast, the potential effects of sound on fish and invertebrates

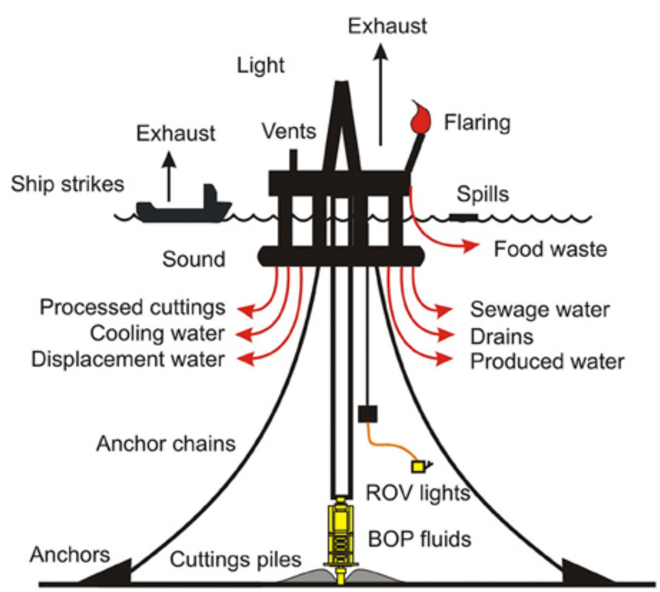

Figure 1. Diagram of impacts from typical deep-sea drilling activity

remain poorly understood, but may be significant (Hawkins et al., 2014). For example, significant developmental delays and body malformations have been recorded in scallop larvae exposed to seismic pulses (de Soto et al., 2013). Exposure to underwater broadband sound fields that resemble offshore shipping and construction activity can also influence the activity and behavior of key bioturbating species in sediments (Solan et al., 2016).

Operations at oil fields introduce considerable amounts of artificial light (e.g., electric lighting, gas flares) that can potentially affect ecological processes in the upper ocean, such as diel vertical migration of plankton (Moore et al., 2000). Artificial night light also attracts numerous species, including squid, large predatory fishes, and birds (Longcore and Rich, 2004). Underwater lighting, such as used on remotely operated vehicles, is likely to be of comparatively modest impact, though it may be significant in the case of species with extremely sensitive visual systems (Herring et al., 1999).

Once the installation of infrastructure commences, direct impacts on habitats and associated fauna increase. Placement of infrastructure on the seafloor, such as anchors and pipelines, will directly disturb the seabed and cause a transient increase in local sedimentation. Typically, 8–12 anchors are used to moor a semi-submersible drilling rig. The spatial extent of anchor impacts on the seabed varies depending on operating depth, but is typically between 1.5 and 2.5 times the water depth of the operation (Vryhof Anchors BV, 2010). As anchors are set, they are dragged along the seabed, damaging benthic organisms and leaving an anchor scar on the seafloor. The impact of anchors in the deep sea is of greatest concern in biogenic habitats, such as those formed by corals and sponges, which are fragile and have low resilience to physical forces (Hall-Spencer et al., 2002; Watling, 2014). Anchor operations have been shown to impact coral communities directly through physical disturbance and increased local sedimentation, with an estimated 100 m wide corridor of influence (Ulfsnes et al., 2013). The laying of pipelines also alters local seabed habitat conditions by adding hard substratum, which in turn may support sessile epifauna and/or attract motile benthic organisms (Lebrato and Jones, 2009). Ulfsnes et al. (2013) estimated a 50 m wide corridor of impact for pipeline installations, including dislocation of existing hard substrata. Corrosion and leakage of pipelines also poses the risk of exposing deep-sea fauna to potentially damaging pollution.

The drilling process involves the disposal of waste, including drill cuttings and excess cement, fluids (drilling mud), produced water, and other chemicals that may cause detrimental ecological effects (Gray et al., 1990). Drill cuttings are the fragments of rock that are created during the drilling process. The chemical composition of drilling muds is diverse, and has changed from the more toxic oil-based muds (currently restricted in many jurisdictions) to more modern synthetic and water-based fluids. The types of fluids most commonly used currently are generally regarded to be less toxic than oil-based fluids, but they are not without adverse biological effects (Daan and Mulder, 1996; Breuer et al., 2004; Bakhtyar and Gagnon, 2012; Gagnon and Bakhtyar, 2013; Edge et al., 2016). Produced water is contaminated water associated with oil and gas extraction process, with an estimated global production ratio of 3:1 water:oil over the lifetime of a well (Khatib and Verbeek, 2002; Neff, 2002; Fakhru'l-Razi et al., 2009). However, it should be noted that this is a global average, and these estimates vary greatly between hydrocarbon fields with the ratio of water to oil increasing over the lifetime of a single well. Produced water is primarily composed of formation water extracted during oil and gas recovery, but may also contain seawater that has previously been injected into the reservoir along with dissolved inorganic salts, dissolved and dispersed hydrocarbons, dissolved minerals, trace metals, naturally occurring radioactive substances, production chemicals, and dissolved gases (Hansen and Davies, 1994; Neff, 2002; Fakhru'l-Razi et al., 2009; Bakke et al., 2013). As a major source of contaminants from oil and gas extraction activity, produced water is typically treated in accordance with strict regulations before being discharged (e.g., OSPAR, 2001).

The spatial footprint of discharge varies with the volume of discharge, depth of discharge, local hydrography, particle size distribution, rates of settlement and floc formation, and time since discharge (Neff, 2005; Niu et al., 2009). Although volumes are likely to vary greatly depending on the local conditions during the active stage of drilling, discharges from one deep-water well at 900 m depth off the coast of Brazil were ~270 m^3 of cuttings, 320 m^3 of water-based fluids, and 70 m^3 of non-aqueous fluids (Pivel et al., 2009). These types of discharges may produce cuttings accumulations up to 20 m in thickness within 100–500 m of the well site (Breuer et al., 2004; Jones et al., 2006; Pivel et al., 2009). Visual assessment at 10 recent deep-water well sites between 370 and 1750 m depth, drilled using current best practice in the NE Atlantic, recorded visual cuttings accumulations present over a radius of 50–150 m from the well head (Jones and Gates, 2010).

Potential impacts on seabed communities can result from both the chemical toxicants and the physical disturbance. Reduction in oxygen concentration, organic enrichment, increased hydrocarbon concentrations, and increased metal abundance can alter biogeochemical processes and generate hydrogen sulfide and ammonia (Neff, 2002). At present, little information is available on the effects of these processes at the microbial level. At the metazoan level, community-level changes in the density, biomass, and diversity of protistan, meio-, macro-, and megafaunal assemblages have been recorded in several studies (Gray et al., 1990; Currie and Isaacs, 2005; Jones et al., 2007; Netto et al., 2009; Santos et al., 2009; Lanzen et al., 2016). These changes have been linked with smothering by drilling cuttings and increased concentrations of harmful metals (e.g., barium) and hydrocarbons (Holdway, 2002; Breuer et al., 2004; Santos et al., 2009; Trannum et al., 2010).

Detected ecological changes attributed to current practices have typically been found within 200–300 m of the well-head (Currie and Isaacs, 2005; Gates and Jones, 2012), but can occasionally extend to 1–2 km for sensitive species (Paine et al., 2014). Previous drilling practices, where oil-based drilling muds were used for the entire drilling process (use of such methods are currently heavily regulated in most jurisdictions), appeared to generate benthic impacts to >5 km from the discharge point (Olsgard and Gray, 1995). More recent evidence based on current drilling techniques suggests that the effects of produced water on benthic organisms will be limited to 1–2 km from the source (Bakke et al., 2013). Seafloor coverage of drill cuttings as low as 3 mm thickness can generate detectable impacts to the infauna (Schaaning et al., 2008). However, even beyond the area of observable cuttings piles, quantitative changes in meiofaunal abundance and community composition have been observed (Montagna and Harper, 1996; Netto et al., 2009). Changes in assemblage structure have also been observed beyond the areas of visually apparent seafloor disturbance as a result of increased scavenging and opportunistic feeding on dead animals (Jones et al., 2007; Hughes et al., 2010). Despite occasional observations of increased scavenger abundance in impacted areas, it has been suggested that the fauna of cuttings-contaminated sediments represent a reduced food resource for fish populations (e.g., smaller body size, loss of epifaunal species, shift from ophiuroids to polychaetes; Olsgard and Gray, 1995).

Cold-water corals (Figure 2) have been the focus of numerous impact studies. Discharges from typical operations have the potential to impact cold-water coral communities in deep waters through smothering and toxic effects (Lepland and Mortensen, 2008; Purser and Thomsen, 2012; Larsson et al., 2013). In laboratory studies, the reef-framework-forming stony coral *Lophelia pertusa* had significant polyp mortality following burial by 6.5 mm of drill cuttings, the maximum permissible under environmental risk assessment in Norway (Larsson and Purser, 2011). As a result, at the Morvin field in Norway, where drilling took place near a *Lophelia* reef, a novel cuttings-transport system was developed to discharge cuttings some 500 m from the well and down-current from the most significant coral reefs (Purser, 2015). The discharge location was determined to minimize impacts based on cuttings dispersion simulation modeling (Reed and Hetland, 2002). Subsequent monitoring at nine reefs between 100 m and 2 km from the discharge site suggested this mitigation measure appeared to have been generally successful. Although concentrations of drill cuttings >25 ppm were observed at several of the monitored reefs, no obvious visual impacts to the coral communities were reported (Purser, 2015). However, this concentration of drill cuttings had been shown to have a significant negative effect on *L. pertusa* growth in laboratory experiments (Larsson et al., 2013).

Impacts from oil and gas operations may be compounded in some settings by other anthropogenic disturbances, particularly as human impacts on the deep-sea environment continue to increase (e.g., Glover and Smith, 2003; Ramirez-Llodra et al., 2011; Kark et al., 2015). Climate and ocean change, including higher temperatures, expansion of oxygen minimum zones, and ocean acidification, will exacerbate the more direct impacts of the oil and gas industry through increased metabolic demand. Multiple stressors can operate as additive effects, synergistic effects, or antagonistic effects (Crain et al., 2008). While studies of the interactions between climate variables (temperature, oxygen, pH, CO_2) and drilling impacts are rare or non-existent, multiple stressors typically have antagonistic effects at the community level, but synergistic effects at the population level (Crain et al., 2008). At the most basic level, experimental work has shown that increased temperature generally increases the toxicity of petroleum hydrocarbons and other compounds (Cairns et al., 1975; Tatem et al., 1978), which suggests that the ecological impacts that have been recorded to date may expand in magnitude and distance as climate change proceeds.

Deep-water fisheries have a significant impact on deep-sea species, with detrimental effects extending to habitats and ecosystems beyond the target populations (Benn et al., 2010; Clark et al., 2016). Some authors note that the physical presence of oil and gas infrastructure may protect fished species or habitats by *de facto* creating fisheries exclusion zones (Hall, 2001; Love et al., 2006), by establishing new reef habitat (sensu Montagna et al., 2002), and by functioning as fish aggregating devices (Hinck et al., 2004). Although the value of oil and gas infrastructure in secondary production and fisheries, particularly in deep waters, is controversial (Bohnsack, 1989; Baine, 2002; Ponti, 2002; Powers et al., 2003; Fabi et al., 2004; Kaiser and Pulsipher, 2006), there is some evidence to suggest that this can occur (Claisse et al., 2015). Oil industry infrastructure may therefore have some positive effects, even in deep water (Macreadie et al., 2011), principally in terms of creating refugia from fishing impacts (e.g., Wilson et al., 2002).

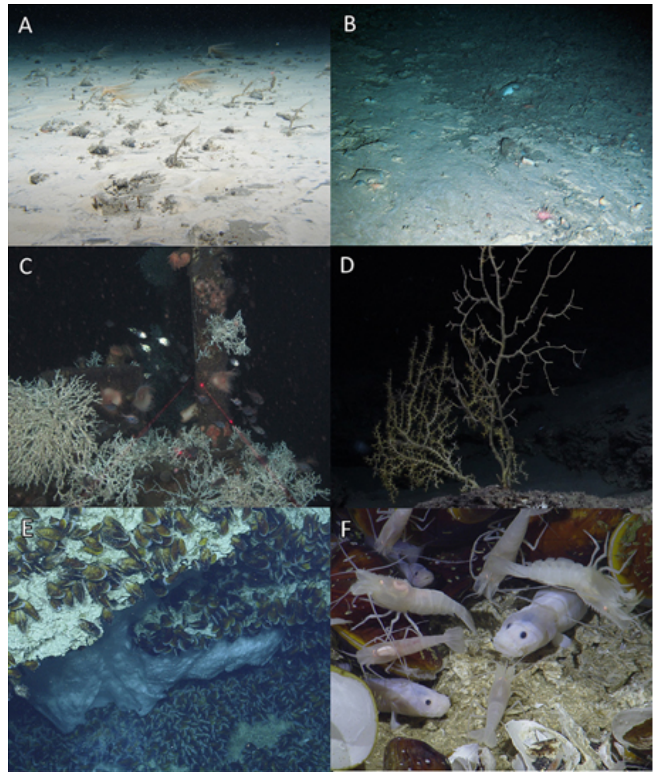

Figure 2. Deep-sea communities near drilling activities. (A) Benthic communities shortly after smothering by (light colored) cuttings at the Tornado Field (1050 m depth), Faroe-Shetland Channel, U.K. (B) Edge of cuttings pile at the Laggan field, Faroe-Shetland Channel, U.K. (Figure 4D from Jones et al., 2012a). (C) Atlantic roughy, Hoplostethus occidentalis, among L. pertusa *around the abandoned test-pile near Zinc at 450 m depth in the Gulf of Mexico. Image courtesy of the Lophelia II program, U.S. Bureau of Ocean Energy and Management and NOAA Office of Ocean Exploraiton and Research. (D) Appearance in 2013 of a* Paramuricea biscaya *colony damaged during the Deepwater Horizon oil spill in 2010. Image courtesy of ECOGIG, a GoMRI-funded research consortium and the Ocean Exploration Trust. (E,F): Methane-seep communities from an area within the exclusive economic zone of Trinidad and Tobago that is targeted for future oil and gas development. The Ocean Exploration Trust is acknowledged for use of these photos from the E/V* Nautilus *2014 Expedition.*

Oil-field infrastructure can also provide hard substratum for colonization by benthic invertebrates, including scleractinian corals and octocorals (Hall, 2001; Sammarco et al., 2004; Gass and Roberts, 2006; Larcom et al., 2014). The widely-distributed coral *L. pertusa* (Figure 2) has been recorded on numerous oil field structures in the northern North Sea (Bell and Smith, 1999; Gass and Roberts, 2006), as well as on infrastructure in the Faroe-Shetland Channel (Hughes, 2011), and the northern Gulf of Mexico (Larcom et al., 2014). These man-made structures may enhance population connectivity (Atchison et al., 2008) and provide stepping stones for both native and potentially invasive species, which has been demonstrated for shallow-water species that may not normally be able to disperse across large expanses of open water (Page et al., 2006; Coutts and Dodgshun, 2007; Sheehy and Vik, 2010). Therefore, the increased connectivity provided by these artificial structures may be viewed both positively and negatively, and it is difficult to make predictions about the potential benefits or harm of the increased availability of deep-sea hard substrata.

Effects of Accidental Discharges

Oil and gas operations have the potential to result in accidental releases of hydrocarbons, with the likelihood of an accidental spill or blowout increasing with the depth of the operations (Muehlenbachs et al., 2013). The U.S. NOAA Office of Response and Restoration records, on average, 1–3 spills per week within the U.S. EEZ, but most of these are relatively small and occur near the shore. On the U.S. outer continental shelf between 1971 and 2010, there were 23 large spills of more than 1000 barrels (160,000 L) of oil, or an average of one every 21 months (Anderson et al., 2012). In addition, on a global scale there were 166 spills over 1000 barrels that occurred during offshore transport of oil in the period between 1974 and 2008, or one every 2.5 months (Anderson et al., 2012). The greatest risk to the marine environment comes from an uncontrolled release of hydrocarbons from the reservoir, known as a blowout (Johansen et al., 2003). Risk modeling suggests that an event the size of the Deepwater Horizon incident can be broadly predicted to occur on an interval between 8 and 91 years, or a rough average of once every 17 years (Eckle et al., 2012). Several major offshore oil blowouts have occurred, including the IXTOC-1 well in the Bahia de Campeche, Mexico where 3.5 million barrels of oil were released at a water depth of 50 m over 9 months (Jernelov and Linden, 1981; Sun et al., 2015) and the Ekofisk blowout where 200,000 barrels (32 million liters) of oil were released at a water depth of 70 m (Law, 1978). While all of these examples represent accidental discharges, the frequency at which they occur in offshore waters suggests that they can be expected during “typical” operations.

The best-studied example of a major deep-sea blowout was at the Macondo well in the Gulf of Mexico in 2010 (Joye et al., 2016). This blowout discharged ~5 million barrels (800 million liters) of oil at a water depth of ~1500 m (McNutt et al., 2012). About half of the oil traveled up to the surface, while the rest of the gaseous hydrocarbons and oil suspended as microdroplets remained in a subsurface plume centered around 1100 m depth, that traveled ~50 km from the well-head (Camilli et al., 2010). The surface oil slicks interacted with planktonic communities and mineral particles to form an emulsion of oiled marine snow (Passow et al., 2012). This material was subsequently observed as a deposited layer on the deep-sea floor that was detected in an area of ~3200 km^2 (Chanton et al., 2014; Valentine et al., 2014). Impacts at the seabed, as revealed by elevated hydrocarbon concentrations and changes to the nematode-copepod ratio, were detected in an area of over 300 km^2, with patchy impacts observed to a radius of 45 km from the well site (Montagna et al., 2013; Baguley et al., 2015). This oiled marine snow was also implicated in impacts on mesophotic and deep-sea coral communities (White et al., 2012; Silva et al., 2015; Figure 2).

Deep-sea coral communities were contaminated by a layer of flocculent material that included oil fingerprinted to the Macondo well, and constituents of the chemical dispersant used in the response effort (White et al., 2012, 2014). Impacts on corals were detected at a number of sites, extending to 22 km from the well, and to water depths (1950 m) exceeding that of the well-head (Hsing et al., 2013; Fisher et al., 2014a).

Dispersants or chemical emulsifiers are applied to oil spills in an effort to disperse surface slicks. Globally, there have been over 200 documented instances of dispersant use between 1968 and 2007 (Steen, 2008). Dispersant use can cause increases in environmental hydrocarbon concentrations (Pace et al., 1995) and direct toxic effects (Epstein et al., 2000). Dispersants increase the surface area for oil-water interactions (Pace et al., 1995), ostensibly increasing the biological availability of oil compounds (Couillard et al., 2005; Schein et al., 2009), potentially enhancing toxic effects (Chandrasekar et al., 2006; Goodbody-Gringley et al., 2013; DeLeo et al., 2016). However, in the case of the Deepwater Horizon accident, dispersant use was shown to impede hydrocarbon degradation by microorganisms (Kleindienst et al., 2015). Chemically-dispersed oil is known to reduce larval settlement, cause abnormal development, and produce tissue degeneration in sessile invertebrates (Epstein et al., 2000; Goodbody-Gringley et al., 2013; DeLeo et al., 2016). Dispersant exposure alone has proved toxic to shallow-water coral larvae (Goodbody-Gringley et al., 2013) and deep-sea octocorals (DeLeo et al., 2016). Some of the potentially toxic components of dispersants may persist in the marine environment for years (White et al., 2014), but there are few *in situ* or even *ex situ* studies of effects of dispersants on deep-sea organisms.

Recovery from Impacts

Typical impacts from drilling may persist over long time scales (years to decades) in the deep sea. In deep waters, the generally low-energy hydrodynamic regime may lead to long-term persistence of discharged material, whether it be intentional or accidental (Neff, 2002; Chanton et al., 2014). Sediment contamination by hydrocarbons, particularly PAHs, is of particular concern, as these compounds can persist for decades, posing significant risk of prolonged ecotoxicological effects. Hydrocarbons from the Prestige spill, off the Galician coast, were still present in intertidal sediments 10 years post-spill (Bernabeu et al., 2013), and petroleum residues from the oil barge *Florida* were still detectable in salt marsh sediments in West Falmouth, MA, after 30 years (Reddy et al., 2002). In the Norwegian Sea (380 m depth), there was a reduction in the visible footprint of drill cuttings from a radius of over 50 m to ~20 m over 3 years, but chemical contamination persisted over the larger area (Gates and Jones, 2012). In the Faroe-Shetland Channel (500–600 m), visible drill cuttings reduced from a radius of over 85–35 m over a 3-year period, while an adjacent 10 year-old well-site exhibited visually distinct cuttings piles at a radius of only 15–20 m (Jones et al., 2012a). Recovery of benthic habitats may take longer at sites where bottom water movements limit dispersal of cuttings (Breuer et al., 2004).

Much of the deep-sea floor is characterized by comparatively low temperatures and low food supply rates. Consequently, deep-sea communities and individuals generally exhibit a slower pace of life than their shallow-water counterparts (reviewed in Gage and Tyler, 1991; McClain and Schlacher, 2015). Deep-water corals and cold-seep communities (Figure 2) represent anomalous high-biomass ecosystems in the deep sea and frequently occur in areas of economic interest because of their direct (energy and carbon source) or indirect (substratum in the form of authigenic carbonate) association with oil and/or gas-rich fluids (Masson et al., 2003; Coleman et al., 2005; Schroeder et al., 2005; Cordes et al., 2008; Bernardino et al., 2012; Jones et al., 2014). Cold-seep tubeworms and deep-water corals exhibit slow growth and some of the greatest longevities among marine metazoans, typically decades to hundreds of years, but occasionally to thousands of years (Fisher et al., 1997; Bergquist et al., 2000; Andrews et al., 2002; Roark et al., 2006; Cordes et al., 2007; Watling et al., 2011). Recruitment and colonization dynamics are not well-understood for these assemblages, but recruitment appears to be slow and episodic in cold-seep tubeworms (Cordes et al., 2003), mussels (Arellano and Young, 2009), and deep-sea corals (Thresher et al., 2011; Lacharité and Metaxas, 2013; Doughty et al., 2014).

Because of the combination of slow growth, long life spans and variable recruitment, recovery from impacts can be prolonged. Based on presumed slow recolonization rates of uncontaminated deep-sea sediments (Grassle, 1977), low environmental temperatures, and consequently reduced metabolic rates (Baguley et al., 2008; Rowe and Kennicutt, 2008), Montagna et al. (2013) suggested recovery of the soft-sediment benthos from the *Deepwater Horizon* well blowout might take decades. For deep-sea corals, recovery time estimates are on the order of centuries to millennia (Fisher et al., 2014b). However, in some cases re-colonization may be relatively rapid, for example, significant macrofaunal recruitment on cuttings piles after 6 months (Trannum et al., 2011). Altered benthic species composition may, nevertheless, persist for years to decades (Netto et al., 2009). Direct studies of recovery from drilling in deep water are lacking and the cumulative effects of multiple drilling wells are not well-studied.

Assessment of Environmental Impacts

Environmental impacts of oil and gas operations may influence species, populations, assemblages, or ecosystems by modifying a variety of ecological parameters (e.g., biodiversity, biomass, productivity, etc.). At the project level, potential impacts are generally assessed through some type of formal process, termed an environmental impact assessment (EIA). These typically involve the identification, prediction, evaluation, and mitigation of impacts prior to the start of a project. Key standard components of an EIA include: (i) description of the proposed development, including information about the size, location, and duration of the project, (ii) baseline description of the environment, (iii) description of potential impacts on the environment, (iv) proposed mitigation of impacts, and (v) identification of knowledge gaps. Mitigation in current oil and gas projects is recommended to follow the mitigation hierarchy: avoid, minimize, restore, and offset (World Bank, 2012). Environmental management strategies, particularly those to avoid and minimize the environmental impacts of projects, are set during the EIA process and may become conditions of operation. As a result, this element of the EIA process is particularly important in preemptively avoiding serious impacts to the marine environment (Beanlands and Duinker, 1984). Establishing appropriate baseline data and control reference sites are critical to both an effective EIA development and subsequent assessment and monitoring of EIA predictions.

EIAs include predictions of how an ecological "baseline" condition may change in response to development and activities. The reliability of EIA predictions depends largely on the quality of existing ecological data (e.g., spatial and temporal coverage, measures of natural variation, taxonomic resolution, types of fauna observed, and collected, etc.) and empirical data or model predictions of how ecological features react to human stressors. Even in the best-known deep-sea environments, the need for planned, coherent, and consistent ecological data to inform EIAs may necessitate substantial new survey operations. For example, in the Gulf of Mexico, region-wide assessments of deep-sea community structure are available for different groups of fauna (e.g., Rowe and Menzel, 1971; Cordes et al., 2006, 2008; Rowe and Kennicutt, 2008; Demopoulos et al., 2014; Quattrini et al., 2014). However, following the Deepwater Horizon incident, baseline data were still found to be lacking in the immediate vicinity of the impacts, and for many key components of the ecosystem, including microbial communities and processes (Joye et al., 2016).

Testing EIA predictions and the effectiveness of implemented mitigation measures with well-designed and consistent environmental monitoring is a critical next step. Generally, some form of "before-after/control-impact" (BACI) monitoring approach is appropriate (Underwood, 1994), as this will enable the detection of accidental impacts in addition to impacts anticipated from typical operations (Wiens and Parker, 1995; Iversen et al., 2011). However, this often receives less attention and resources than the EIA itself, and most jurisdictions have minimal requirements for monitoring programs. Long-term monitoring in the deep sea is generally rare (e.g., Hartman et al., 2012), and long-term environmental monitoring of deep-water oil and gas developments is extremely limited. A significant exception is found in the two observatory systems that were installed in deep waters off Angola to record long-term natural and anthropogenic changes in the physical, chemical, and biological environment and to allow an understanding of the pace of recovery from unforeseen impacts (Vardaro et al., 2013). Monitoring should also be carried out after production has ceased and throughout de-commissioning.

Authors: Erik E. Cores (Temple University), Daniel O. B. Jones (University of Southampton), Thomas A. Schlacher (University of the Sunshine Coast), Diva J. Amon (University of Hawaii), Angelo F. Bernardino (Universidade Federal do Espírito Santo), Sandra Brooke (Florida State University), Robert Carney (Louisiana State University), Danielle M. DeLeo (Temple University), Katherine M. Dunlop (Heriot-Watt University), Elva G. Escobar-Briones (Instituto de Ciencias del Mar y Limnología), Andrew R. Gates (University of Southampton), Luciana Génio (Universidade de Aveiro, University of Oregon), Judith Gobin (University of the West Indies), Lea-Anne Henry (Heriot-Watt University), Santiago Herrera (University of Toronto), Sarah Hoyt (Duke University), Mandy Joye (University of Georgia), Salit Kark (University of Queensland), Nélia C. Mestre (University of Algarve), Anna Metaxas (Dalhousie University), Simone Pfeifer (University of Southampton), Kerry Sink (South African National Biodiversity Institute), Andrew K. Sweetman (Heriot-Watt University), and Ursula Witte (University of Aberdeen)

This report is adapted from Environmental Impacts of the Deep-Water Oil and Gas Industry: A Review to Guide Management Strategies. The full report, along with citation links, can be accessed here: https://www.frontiersin.org/articles/10.3389/fenvs.2016.00058/full

Literature Cited

Anderson, C. M., Mayes, M., and LaBelle, R. P. (2012). Oil Spill Occurrence Rates for Offshore Spills. Herndon, DC: Bureau of Ocean Energy Management.

Andrews, A. H., Cordes, E. E., Mahoney, M. M., Munk, K., Coale, K. H., Cailliet, G. M., et al. (2002). Age, growth and radiometric age validation of a deep-sea, habitat-forming gorgonian (Primnoa resedaeformis) from the Gulf of Alaska. Hydrobiologia 471, 101–110. doi: 10.1023/A:1016501320206

Arellano, S. M., and Young, C. M. (2009). Spawning, development, and the duration of larval life in a deep-sea cold-seep mussel. Biol. Bull. 216, 149–162. doi: 10.2307/25470737

Atchison, A. D., Sammarco, P. W., and Brazeau, D. A. (2008). genetic connectivity in corals on the flower garden banks and surrounding oil/gas platforms, Gulf of Mexico. J. Exp. Mar. Biol. Ecol. 365, 1–12. doi: 10.1016/j.jembe.2008.07.002

Baguley, J. G., Montagna, P. A., Cooksey, C., Hyland, J. L., Bang, H. W., Morrison, C., et al. (2015). Community response of deep-sea soft-sediment metazoan meiofauna to the Deepwater Horizon blowout and oil spill. Mar. Ecol. Prog. Ser.528, 127–140. doi: 10.3354/meps11290

Baguley, J. G., Montagna, P. A., Hyde, L. J., and Rowe, G. T. (2008). Metazoan meiofauna biomass, grazing, and weight-dependent respiration in the Northern Gulf of Mexico deep sea. Deep Sea Res. II 55, 2607–2616. doi: 10.1016/j.dsr2.2008.07.010

Baine, M. (2002). The North Sea rigs-to-reefs debate. ICES J. Mar. Sci. 59 (Suppl.), S277–S280. doi: 10.1006/jmsc.2002.1216

Bakhtyar, S., and Gagnon, M. M. (2012). Toxicity assessment of individual ingredients of synthetic-based drilling muds (SBMs). Environ. Monit. Assess. 184, 5311–5325. doi: 10.1007/s10661-011-2342-x

Bakke, T., Klungsøyr, J., and Sanni, S. (2013). Environmental impacts of produced water and drilling waste discharges from the Norwegian offshore petroleum industry. Mar. Environ. Res. 92, 154–169. doi: 10.1016/j.marenvres.2013.09.012

Beanlands, G. E., and Duinker, P. N. (1984). Lessons from a decade of offshore environmental impact assessment. Ocean Manag. 9, 157–175. doi: 10.1016/0302-184X(84)90001-5

Bell, N., and Smith, J. (1999). Coral growing on North Sea oil rigs. Nature 402, 601. doi: 10.1038/45127

Benn, A. R., Weaver, P. P., Billett, D. S. M., van den Hove, S., Murdock, A. P., Doneghan, G. B., et al. (2010). Human activities on the deep seafloor in the North East Atlantic: an assessment of spatial extent. PLoS ONE 5:e12730. doi: 10.1371/journal.pone.0012730

Bergquist, D. C., Williams, F. M., and Fisher, C. R. (2000). Longevity record for deep-sea invertebrate. Nature 403, 499–500. doi: 10.1038/35000647

Bernabeu, A. M., Fernández-Fernández, S., Bouchette, F., Rey, D., Arcos, A., Bayona, J. M., et al. (2013). Recurrent arrival of oil to Galician coast: the final step of the Prestige deep oil spill. J. Hazard. Mater. 250, 82–90. doi: 10.1016/j.jhazmat.2013.01.057

Bernardino, A. F., Levin, L. A., Thurber, A. R., and Smith, C. R. (2012). Comparative composition, diversity and trophic ecology of sediment macrofauna at vents, seeps and organic falls. PLoS ONE 7:e33515. doi: 10.1371/journal.pone.0033515

Bohnsack, J. A. (1989). Are high densities of fishes at artificial reefs the result of habitat limitation or behavioral preference? Bull. Mar. Sci. 44, 631–645.

Breuer, E., Stevenson, A. G., Howe, J. A., Carroll, J., and Shimmield, G. B. (2004). Drill cutting accumulations in the Northern and Central North Sea: a review of environmental interactions and chemical fate. Mar. Pollut. Bull. 48, 12–25. doi: 10.1016/j.marpolbul.2003.08.009

Cairns, J. Jr., Heath, A. G., and Parker, B. C. (1975). The effects of temperature upon the toxicity of chemicals to aquatic organisms. Hydrobiologia 47, 135–171. doi: 10.1007/BF00036747

Camilli, R., Reddy, C. M., Yoerger, D. R., Van Mooy, B. A. S., Jakuba, M. V., Kinsey, J. C., et al. (2010). Tracking hydrocarbon plume transport and biodegradation at deepwater horizon. Science 330, 201–204. doi: 10.1126/science.1195223

Chandrasekar, S., Sorial, G. A., and Weaver, J. W. (2006). Dispersant effectiveness on oil spills – impact of salinity. ICES J. Mar. Sci. 63, 1418–1430. doi: 10.1016/j.icesjms.2006.04.019

Chanton, J., Zhao, T., Rosenheim, B. E., Joye, S., Bosman, S., Brunner, C., et al. (2014). Using natural abundance radiocarbon to trace the flux of petrocarbon to the seafloor following the deepwater horizon oil spill. Environ. Sci. Technol. 49, 847–854. doi: 10.1021/es5046524

Claisse, J. T., Pondella, D. J. II Love, M., Zahn, L. A., Williams, C. M., and Bull, A. S. (2015). Impacts from partial removal of decommissioned oil and gas platforms on fish biomass and production on the remaining platform structure and surrounding shell mounds. PLoS ONE 10:e0135812. doi: 10.1371/journal.pone.0135812

Clark, M. R., Althaus, F., Schlacher, T. A., Williams, A., Bowden, D. A., and Rowden, A. A. (2016). The impacts of deep-sea fisheries on benthic communities: a review. ICES J. Mar. Sci. 73 (Suppl. 1), i51–i69. doi: 10.1093/icesjms/fsv123

Coleman, F. C., Figueira, W. F., Ueland, J. S., and Crowder, L. B. (2005). Global impact of recreational fisheries-Response. Science 307, 1562–1563.

Cordes, E. E., Bergquist, D. C., Shea, K., and Fisher, C. R. (2003). Hydrogen sulphide demand of long-lived vestimentiferan tube worm aggregations modifies the chemical environment at deep-sea hydrocarbon seeps. Ecol. Lett. 6, 212–219. doi: 10.1046/j.1461-0248.2003.00415.x

Cordes, E. E., Bergquist, D. C., Predmore, B. L., Dienes, P., Jones, C., Fisher, G., et al. (2006). Alternate unstable states: convergent paths of succession in hydrocarbon-seep tubeworm-associated communities. J. Exp. Mar. Biol. Ecol. 339, 159–176, doi: 10.1016/j.jembe.2006.07.017

Cordes, E. E., Carney, S. L., Hourdez, S., Carney, R. S., Brooks, J. M., and Fisher, C. R. (2007). Cold seeps of the deep Gulf of Mexico: community structure and biogeographic comparisons to Atlantic equatorial belt seep communities. Deep Sea Res. I 54, 637–653. doi: 10.1016/j.dsr.2007.01.001

Cordes, E. E., McGinley, M. P., Podowski, E. L., Becker, E. L., Lessard-Pilon, S., Viada, S. T., et al. (2008). Coral communities of the deep Gulf of Mexico. Deep Sea Res. I 55, 777–787. doi: 10.1016/j.dsr.2008.03.005

Couillard, C. M., Lee, K., Légaré, B., and King, T. L. (2005). Effect of dispersant on the composition of water-accommodated fraction of crude oil and its toxicity to larval marine fish. Environ. Toxicol. Chem. 24, 1496–1504. doi: 10.1897/04-267R.1

Coutts, A. D., and Dodgshun, T. J. (2007). The nature and extent of organisms in vessel sea-chests: a protected mechanism for marine bioinvasions. Mar. Pollut. Bull. 54, 875–886. doi: 10.1016/j.marpolbul.2007.03.011

Crain, C. M., Kroeker, K., and Halpern, B. S. (2008). Interactive and cumulative effects of multiple human stressors in marine systems. Ecol. Lett. 11, 1304–1315. doi: 10.1111/j.1461-0248.2008.01253.x

Currie, D. R., and Isaacs, L. R. (2005). Impact of exploratory offshore drilling on benthic communities in the Minerva gas field, Port Campbell, Australia. Mar. Environ. Res. 59, 217–233 doi: 10.1016/j.marenvres.2004.05.001

Daan, R., and Mulder, M. (1996). On the short-term and long-term impact of drilling activities in the Dutch sector of the North Sea. ICES J. Mar. Sci. 53, 1036–1044. doi: 10.1006/jmsc.1996.0129

de Soto, N. A., Delorme, N., Atkins, J., Howard, S., Williams, J., and Johnson, M. (2013). Anthropogenic noise causes body malformations and delays development in marine larvae. Sci. Rep. 3:2831. doi: 10.1038/srep02831

DeLeo, D. M., Ruiz-Ramos, D. V., Baums, I. B., and Cordes, E. E. (2016). Response of deep-water corals to oil and chemical dispersant exposure. Deep Sea Res. II 129, 137–147. doi: 10.1016/j.dsr2.2015.02.028

Demopoulos, A. W., Bourque, J. R., and Frometa, J. (2014). Biodiversity and community composition of sediment macrofauna associated with deep-sea Lophelia pertusa habitats in the Gulf of Mexico. Deep Sea Res. I 93, 91–103. doi: 10.1016/j.dsr.2014.07.014

Doughty, C. L., Quattrini, A. M., and Cordes, E. E. (2014). Insights into the population dynamics of the deep-sea coral genus Paramuricea in the Gulf of Mexico. Deep Sea Res. II 99, 71–82. doi: 10.1016/j.dsr2.2013.05.023

Eckle, P., Burgherr, P., and Michaux, E. (2012). Risk of large oil spills: a statistical analysis in the aftermath of Deepwater Horizon. Environ. Sci. Techonol. 46, 13002–13008. doi: 10.1016/j.marpol.2013.12.002

Edge, K. J., Johnston, E. L., Dafforn, K. A., Simpson, S. L., Kutti, T., and Bannister, R. J. (2016). Sub-lethal effects of water-based drilling muds on the deep-water sponge Geodia barretti. Environ. Pollut. 212, 525–534. doi: 10.1016/j.envpol.2016.02.047

Epstein, N., Bak, R. P. M., and Rinkevich, B. (2000). Toxicity of 3rd generation dispersants and dispersed Egyptian crude oil on Red Sea coral larvae. Mar. Pollut. Bull.40, 497–503. doi: 10.1016/S0025-326X(99)00232-5

Fabi, G., Grati, F., Puletti, M., and Scarcella, G. (2004). Effects on fish community induced by installation of two gas platforms in the Adriatic Sea. Mar. Ecol. Prog. Ser. 273, 187–197. doi: 10.3354/meps273187

Fakhru'l-Razi, A., Pendashteh, A., Abdullah, L. C., Biak, D. R. A., Madaeni, S. S., and Abidin, Z. Z. (2009). Review of technologies for oil and gas produced water treatment. J. Hazard. Mater. 170, 530–551. doi: 10.1016/j.jhazmat.2009.05.044

Fisher, C. R., Urcuyo, I. A., Simpkins, M. A., and Nix, E. (1997). Life in the slow lane: growth and longevity of cold-seep vestimentiferans. Mar. Ecol. 18, 83–94. doi: 10.1111/j.1439-0485.1997.tb00428.x

Fisher, C. R., Hsing, P.-Y., Kaiser, C. L., Yoerger, D. R., Roberts, H. H., Shedd, W. W., et al. (2014a). Footprint of deepwater horizon blowout impact to deep-water coral communities. Proc. Natl. Acad. Sci. U.S.A. 111, 11744–11749. doi: 10.1073/pnas.1403492111

Fisher, C. R., Demopoulos, A. W. J., Cordes, E. E., Baums, I. B., White, H. K., and Bourque, J. R. (2014b). Coral communities as indicators of ecosystem-level impacts of the deepwater horizon spill. Bioscience 64, 796–807. doi: 10.1093/biosci/biu129

Gage, J. D., and Tyler, P. A. (1991). Deep-Sea Biology: A Natural History of Organisms at the Deep-Sea Floor, 1st Edn. Cambridge: Cambridge University Press.

Gass, S. E., and Roberts, J. M. (2006). The occurrence of the cold-water coral Lophelia pertusa (Scleractinia) on oil and gas platforms in the North Sea: colony growth, recruitment and environmental controls on distribution. Mar. Pollut. Bull. 52, 549–559. doi: 10.1016/j.marpolbul.2005.10.002

Gates, A. R., and Jones, D. O. B. (2012). Recovery of benthic megafauna from anthropogenic disturbance at a hydrocarbon drilling well (380 m Depth in the Norwegian Sea). PLoS ONE 7:e44114. doi: 10.1371/journal.pone.0044114

Glover, A. G., and Smith, C. R. (2003). The deep-sea floor ecosystem: current status and prospects of anthropogenic change by the year 2025. Environ. Conserv. 30, 219–241. doi: 10.1017/S0376892903000225

Goodbody-Gringley, G., Wetzel, D. L., Gillon, D., Pulster, E., Miller, A., and Ritchie, K. B. (2013). Toxicity of deepwater horizon source oil and the chemical dispersant, Corexit® 9500, to coral larvae. PLoS ONE 8:e45574. doi: 10.1371/journal.pone.0045574

Gordon, J. G., Gillespie, D., Potter, J., Frantzis, A., Simmonds, M., Swift, R. J., et al. (2004). A review of the effects of seismic survey on marine mammals. Mar. Technol. Soc. J. 37, 14–34. doi: 10.4031/002533203787536998

Grassle, J. F. (1977). Slow recolonisation of deep-sea sediment. Nature 265, 618–619. doi: 10.1038/265618a0

Hall-Spencer, J., Allain, V., and Fosså, J. H. (2002). Trawling damage to Northeast Atlantic ancient coral reefs. Proc. Biol. Sci. 269, 507–511. doi: 10.1098/rspb.2001.1910

Hall, C. M. (2001). Trends in ocean and coastal tourism: the end of the last frontier? Ocean Coast. Manag. 44, 601–618. doi: 10.1016/S0964-5691(01)00071-0

Hansen, B. R., and Davies, S. H. (1994). Review of potential technologies for the removal of dissolved components from produced water. Chem. Eng. Res. Des. 72, 176–188.

Hartman, S. E., Lampitt, R. S., Larkin, K. E., Pagnani, M., Campbell, J., Lankester, T., et al. (2012). The Porcupine Abyssal Plain fixed-point sustained observatory (PAP-SO): variations and trends from the Northeast Atlantic fixed-point time series. ICES J. Mar. Sci. 69, 776–783. doi: 10.1093/icesjms/fss077

Hawkins, A. D., Pembroke, A. E., and Popper, A. N. (2014). Information gaps in understanding the effects of noise on fishes and invertebrates. Rev. Fish Biol. Fish. 25, 39–64. doi: 10.1007/s11160-014-9369-3

Herring, P. J., Gaten, E., and Shelton, P. M. J. (1999). Are vent shrimps blinded by science? Nature 398, 116–116.

Hinck, J. E., Bartish, T. M., Blazer, B. S., Denslow, N. D., Gross, T. S., Myers, M. S., et al. (2004). Biomonitoring of Environmental Status and Trends (BEST) Program: Environmental Contaminants and Their Effects on Fish in the Rio Grande Basin. MO Scientific Investigations Report 2004–5285. U.S. Geological Survey, Columbia Environmental Research Center, Columbia.

Hsing, P. Y., Fu, B., Larcom, E. A., Berlet, S. P., Shank, T. M., Govindarajan, A. F., et al. (2013). Evidence of lasting impact of the deepwater horizon oil spill on a deep Gulf of Mexico coral community. Elementa 1:000012. doi: 10.12952/journal.elementa.000012

Hughes, S. J. M., Jones, D. O. B., Hauton, C., Gates, A. R., and Hawkins, L. E. (2010). An assessment of drilling disturbance on Echinus acutus var. norvegicus based on in-situ observations and experiments using a remotely operated vehicle (ROV). J. Exp. Mar. Biol. Ecol. 395, 37–47. doi: 10.1016/j.jembe.2010.08.012

Hughes, D. J. (2011). “Cold Water Corals on Oil Platforms,” in Scottish Association for Marine Science, Annual Report 2010–11, eds R. Turnewitsch and A. Miller (Oban: Scottish Marine Institute), 12.

Iversen, P. E., Green, A. M. V., Lind, M. J., Petersen, M. R. H., Bakke, T., Lichtenhaler, R., et al. (2011). Guidelines for Offshore Environmental Monitoring on the Norwegian Continental Shelf. Oslo: Norwegian Climate and Pollution Agency.

Jernelov, A., and Linden, O. (1981). Ixtoc I: a case study of the world's largest oil spill. Ambio 10, 299–306.

Johansen, Ø., Rye, H., and Cooper, C. (2003). DeepSpill–field study of a simulated oil and gas blowout in deep water. Spill Sci. Technol. Bull. 8, 433–443. doi: 10.1016/S1353-2561(02)00123-8

Jones, D. O. B., and Gates, A. R. (2010). “Assessing the effects of hydrocarbon drilling activity on deep-water Megafauna in The Northern North Atlantic. A rapid universal assessment method?,” in SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Society of Petroleum Engineers, Rio de Janeiro.

Jones, D. O. B., Hudson, I. R., and Bett, B. J. (2006). Effects of physical disturbance on the cold-water megafaunal communities of the Faroe-Shetland Channel. Mar. Ecol. Prog. Ser. 319, 43–54. doi: 10.3354/meps319043

Jones, D. O. B., Wigham, B. D., Hudson, I. R., and Bett, B. J. (2007). Anthropogenic disturbance of deep-sea megabenthic assemblages: a study with Remotely-operated vehicles in the Faroe-Shetland Chanel, NE Atlantic. Mar. Biol. 151, 1731–1741. doi: 10.1007/s00227-007-0606-3

Jones, D. O. B., Gates, A. R., and Lausen, B. (2012a). Recovery of deep-water megafaunal assemblages from hydrocarbon drilling disturbance in the Faroe-Shetland Channel. Mar. Ecol. Prog. Ser. 461, 71–82. doi: 10.3354/meps09827

Jones, D. O. B., Walls, A., Clare, M., Fiske, M. S., Weiland, R. J., O'Brien, R., et al. (2014). Asphalt mounds and associated biota on the Angolan margin. Deep Sea Res. I 94, 124–136. doi: 10.1016/j.dsr.2014.08.010

Joye, S. B., Bracco, A., Ozgokmen, T., Chanton, J. P., Grosell, M., MacDonald, I. R., et al. (2016). The Gulf of Mexico ecosystem, six years after the Macondo Oil Well Blowout. Deep Sea Res. II 129, 4–19. doi: 10.1016/j.dsr2.2016.04.018

Kaiser, M. J., and Pulsipher, A. G. (2006). Capital Investment Decision Making and Trends: Implications on Petroleum Resource Development in the U.S. Gulf of Mexico. Fairbanks: University Of Alaska.

Kark, S., Brokovich, E., Mazor, T., and Levin, N. (2015). Emerging conservation challenges and prospects in an era of offshore hydrocarbon exploration and exploitation. Conserv. Biol. 29, 1573–1585. doi: 10.1111/cobi.12562

Khatib, Z., and Verbeek, P. (2002). “Water to value – produced water management for sustainable field development of mature and green fields,” in Proceedings of the SPE International Conference on Health, Safety and Environment in Oil and Gas exploration and Production (Kuala Lumpur).

Lacharité, M., and Metaxas, A. (2013). Early life history of deep-water gorgonian corals may limit their abundance. PLoS ONE 8:e65394. doi: 10.1371/journal.pone.0065394

Larcom, E. A., McKean, D. L., Brooks, J. M., and Fisher, C. R. (2014). Growth rates, densities, and distribution of Lophelia pertusa on artificial structures in the Gulf of Mexico. Deep Sea Res. I 85, 101–109. doi: 10.1016/j.dsr.2013.12.005

Larsson, A. I., van Oevelen, D., Purser, A., and Thomsen, L. (2013). Tolerance to long-term exposure of suspended benthic sediments and drill cuttings in the cold-water coral Lophelia pertusa. Mar. Pollut. Bull. 70, 176–188. doi: 10.1016/j.marpolbul.2013.02.033

Law, R. J. (1978). Determination of petroleum hydrocarbons in water, fish and sediments following the Ekofisk blow-out. Mar. Pollut. Bull. 9, 321–324. doi: 10.1016/0025-326X(78)90241-2

Lebrato, M., and Jones, D. O. B. (2009). Mass deposition event of Pyrosoma atlanticum carcasses off Ivory Coast (West Africa). Limnol. Oceanogr. 54, 1197–1209. doi: 10.4319/lo.2009.54.4.1197

Lepland, A., and Mortensen, P. B. (2008). Barite and barium in sediments and coral skeletons around the hydrocarbon exploration drilling site in the Traena Deep, Norwegian Sea. Environ. Geol. 56, 119–129. doi: 10.1007/s00254-007-1145-4

Longcore, T., and Rich, C. (2004). Ecological light pollution. Front. Ecol. Environ. 2, 191–198. doi: 10.1890/1540-9295(2004)002[0191:ELP]2.0.CO;2

Love, M. S., Schroeder, D. M., Lenarz, W., MacCall, A., Bull, A. S., and Thorsteinson, L. (2006). Potential use of offshore marine structures in rebuilding an overfished rockfish species, bocaccio (Sebastes paucispinis). Fish. Bull. 104, 383–390.

Macreadie, P. I., Fowler, A. M., and Booth, D. J. (2011). Rigs-to-reefs: will the deep sea benefit from artificial habitat? Front. Ecol. Environ. 9, 455–461. doi: 10.1890/100112

Masson, D. G., Bett, B. J., Billett, D. S. M., Jacobs, C. L., Wheeler, A. J., and Wynn, R. B. (2003). The origin of deep-water, coral-topped mounds in the northern Rockall Trough, Northeast Atlantic. Mar. Geol. 194, 159–180. doi: 10.1016/S0025-3227(02)00704-1

McClain, C. R., and Schlacher, T. A. (2015). On some hypotheses of diversity of animal life at great depths on the sea floor. Mar. Ecol. 36, 849–872. doi: 10.1111/maec.12288

McNutt, M. K., Camilli, R., Crone, T. J., Guthrie, G. D., Hsieh, P. A., Ryerson, T. B., et al. (2012). Review of flow rate estimates of the Deepwater Horizon oil spill. Proc. Natl. Acad. Sci.U.S.A. 109, 20260–20267. doi: 10.1073/pnas.1112139108

Montagna, P. A., and Harper, D. E. Jr. (1996). Benthic infaunal long-term response to offshore production platforms in the Gulf of Mexico. Can. J. Fish. Aquat. Sci. 53, 2567–2588. doi: 10.1139/f96-215

Montagna, P. A., Baguley, J. G., Cooksey, C., Hartwell, I., Hyde, L. J., Hyland, J. L., et al. (2013). Deep-sea benthic footprint of the deepwater horizon blowout. PLoS ONE 8:e70540. doi: 10.1371/journal.pone.0070540

Montagna, P. A., Kalke, R. D., and Ritter, C. (2002). Effect of restored freshwater inflow on macrofauna and meiofauna in upper Rincon Bayou, Texas, U. S. A. Estuaries 25, 1436–1447. doi: 10.1007/BF02692237

Moore, M. V., Pierce, S. M., Walsh, H. M., Kvalvik, S. K., and Lim, J. D. (2000). Urban light pollution alters the diel vertical migration of Daphnia. Verhandlungen Int. Verein Limnol. 24, 1–4.

Moore, S. E., Reeves, R. R., Southall, B. L., Ragen, T. J., Suydam, R. S., and Clark, C. W. (2012). A new framework for assessing the effects of anthropogenic sound on marine mammals in a rapidly changing arctic. Bioscience 62, 289–295. doi: 10.1525/bio.2012.62.3.10

Muehlenbachs, L., Cohen, M. A., and Gerarden, T. (2013). The impact of water depth on safety and environmental performance in offshore oil and gas production. Energy Policy 55, 699–705. doi: 10.1016/j.enpol.2012.12.074

Neff, J. M. (2002). Bioaccumulation in Marine Organisms: Effect of Contaminants from Oil Well Produced Water. Amsterdam: Elsevier.

Neff, J. M. (2005). Composition, Environmental Fates, and Biological Effect of Water-Based Drilling Muds and Cuttings Discharged into the Marine Environment: Asynthesis and Annotated Bibliography. Duxbury, MA: Petroleum Environmental Research. Forum and API.

Netto, S. A., Gallucci, F., and Fonseca, G. (2009). Deep-sea meiofauna response to synthetic-based drilling mud discharge off SE Brazil. Deep Sea Res. II 56, 41–49. doi: 10.1016/j.dsr2.2008.08.018

Nieukirk, S. L., Mellinger, D. K., Moore, S. E., Klinck, K., Dziak, R. P., and Goslin, J. (2012). Sounds from airguns and fin whales recorded in the mid-Atlantic Ocean, 1999–2009. J. Acoust. Soc. Am. 131, 1102–1112. doi: 10.1121/1.3672648

Niu, H., Li, Z., Lee, K., Kepkay, P., and Mullin, J. V. (2009). "Lagrangian simulation of the transport of oil-mineral-aggregates (OMAs) and assessment of their potential risks," in Proceedings of the 32 AMOP Technical Seminar on Environmental Contamination and Response, Vol. 2. (Ottawa, ON: Environment Canada), 940.

Olsgard, F., and Gray, J. S. (1995). A comprehensive analysis of the effects of offshore oil and gas exploration and production on the benthic communities of the Norwegian continental shelf. Mar. Ecol. Prog. Ser. 122, 277–306. doi: 10.3354/meps122277

OSPAR (2001). OSPAR Recommendation 2001/1 for the Management of Produced Water from Offshore Installations (Consolidated Text). OSPAR Recommendation 2001/1 adopted by OSPAR2001 (OSPAR01/18/1, Annex 5). Amended by OSPAR Recommendation 2006/4 (OSPAR 06/23/1, Annex 15) and OSPAR Recommendation 2011/8 (OSPAR 11/20/1, Annex 19). Available online at: http://www.ospar.org/work-areas/oic

Pace, C. B., Clark, J. R., and Bragin, G. E. (1995). "Comparing crude oil toxicity under standard and environmentally realistic exposures," in Proceedings of the 1995 International Oil Spill Conference (Washington, DC: American Petroleum Institute), 1003–1004.

Page, H. M., Dugan, J. E., Culver, C. S., and Hoesterey, J. C. (2006). Exotic invertebrate species on offshore oil platforms. Mar. Ecol. Prog. Ser. 325, 101–107. doi: 10.3354/meps325101

Paine, M. D., DeBlois, E. M., Kilgour, B. W., Tracy, E., Pocklington, P., Crowley, R. D., et al. (2014). Effects of the Terra Nova offshore oil development on benthic macro-invertebrates over 10 years of development drilling on the Grand Banks of Newfoundland, Canada. Deep Sea Res. II 110, 38–64. doi: 10.1016/j.dsr2.2014.10.015

Passow, U., Ziervogel, K., Asper, V., and Diercks, A. (2012). Marine snow formation in the aftermath of the Deepwater Horizon oil spill in the Gulf of Mexico. Environ. Res. Lett. 7:035301. doi: 10.1088/1748-9326/7/3/035301

Pivel, M. A. G., Freitas, C. M. D. S., and Comba, J. L. D. (2009). Modeling the discharge of cuttings and drilling fluids in a deep-water environment. Deep Sea Res. II 56, 12–21. doi: 10.1016/j.dsr2.2008.08.015

Ponti, M. (2002). Drilling platforms as artificial reefs: distribution of macrobenthic assemblages of the "Paguro" wreck (Northern Adriatic Sea). ICES J. Mar. Sci. 59, S316–S323. doi: 10.1006/jmsc.2002.1225

Powers, S. P., Grabowski, J. H., Peterson, C. H., and Lindberg, W. J. (2003). Estimating enhancement of fish production by offshore artificial reefs: uncertainty exhibited by divergent scenarios. Mar. Ecol. Prog. Ser. 264, 265–277. doi: 10.3354/meps264265

Purser, A., and Thomsen, L. (2012). Monitoring strategies for drill cutting discharge in the vicinity of cold-water coral ecosystems. Mar. Pollut. Bull. 64, 2309–2316. doi: 10.1016/j.marpolbul.2012.08.003

Quattrini, A. M., Etnoyer, P. J., Doughty, C., English, L., Falco, R., Remon, N., et al. (2014). A phylogenetic approach to octocoral community structure in the deep Gulf of Mexico. Deep Sea Res. II 99, 92–102. doi: 10.1016/j.dsr2.2013.05.027

Ramirez-Llodra, E., Tyler, P. A., Baker, M. C., Bergstad, O. A., Clark, M. R., Escobar, E., et al. (2011). Man and the last great wilderness: human impact on the deep sea. PLoS ONE 6:e22588. doi: 10.1371/journal.pone.0022588

Reddy, C. M., Eglinton, T. I., Hounshell, A., White, H. K., Xu, L., Gaines, R. B., et al. (2002). The West Falmouth oil spill after thirty years: the persistence of petroleum hydrocarbons in marsh sediments. Environ. Sci. Technol. 36, 4754–4760. doi: 10.1021/es020656n

Roark, E., Guilderson, T. P., Dunbar, R. B., and Ingram, B. (2006). Radiocarbon-based ages and growth rates of Hawaiian deep-sea corals. Mar. Ecol. Prog. Ser. 327, 1–14. doi: 10.3354/meps327001

Rowe, G. T., and Kennicutt, M. C. (2008). Introduction to the deep Gulf of Mexico Benthos program. Deep Sea Res. II 55, 2536–2540. doi: 10.1016/j.dsr2.2008.09.002

Rowe, G. T., and Menzel, D. W. (1971). Quantitative benthic samples from the deep Gulf of Mexico with some comments on the measurement of deep-sea biomass. Bull. Mar. Sci. 21, 556–566.

Sammarco, P. W., Atchison, A. D., and Boland, G. S. (2004). Expansion of coral communities within the Northern Gulf of Mexico via offshore oil and gas platforms. Mar. Ecol. Prog. Ser. 280, 129–143. doi: 10.3354/meps280129

Santos, M. F. L., Lana, P. C., Silva, J., Fachel, J. G., and Pulgati, F. H. (2009). Effects of non-aqueous fluids cuttings discharge from exploratory drilling activities on the deep-sea macrobenthic communities. Deep Sea Res. II 56, 32–40. doi: 10.1016/j.dsr2.2008.08.017

Schaaning, M. T., Trannum, H. C., Øxnevad, S., Carroll, J., and Blake, T. (2008). Effects of drill cuttings on biogeochemical fluxes and macrobenthos of marine sediments. J. Exp. Mar. Biol. Ecol. 361, 49–57. doi: 10.1016/j.jembe.2008.04.014

Schein, A., Scott, J. A., Mos, L., and Hodson, P. V. (2009). Oil dispersion increases the apparent bioavailability and toxicity of diesel to rainbow trout (Oncorhynchus mykiss). Environ. Toxicol. Chem. 28, 595–602. doi: 10.1897/08-315.1

Schroeder, W. W., Brooke, S. D., Olson, J. B., Phaneuf, B., McDonough, J. J. III, and Etnoyer, P. (2005). "Occurrence of deep-water Lophelia pertusa and Madrepora oculata in the Gulf of Mexico," in Cold-Water Corals and Ecosystems (Berlin; Heidelberg: Springer), 297–307.

Sheehy, D., and Vik, S. F. (2010). The role of constructed reefs in non-indigenous species introductions and range expansions. Ecol. Eng. 36, 1–11. doi: 10.1016/j.ecoleng.2009.09.012

Silva, M., Etnoyer, P. J., and MacDonald, I. R. (2015). Coral injuries observed at mesophotic reefs after the Deepwater Horizon oil discharge. Deep Sea Res. II 129, 96–107. doi: 10.1016/j.dsr2.2015.05.013

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene, C. R. Jr., et al. (2008). Marine mammal noise exposure criteria: initial scientific recommendations. Bioacoustics 17, 273–275. doi: 10.1080/09524622.2008.9753846

Steen, A. (2008). Frequency of dispersant use worldwide. Int. Oil Spill Conf. Proc. 2008, 645–650. doi: 10.7901/2169-3358-2008-1-645

Sun, S., Hu, C., and Tunnell, J. W. Jr. (2015). Surface oil footprint and trajectory of the Ixtoc-I oil spill determined from Landsat/MSS and CZCS observations. Mar. Pollut. Bull. 101, 632–641. doi: 10.1016/j.marpolbul.2015.10.036

Tatem, H. E., Cox, B. A., and Anderson, J. W. (1978). The toxicity of oils and petroleum hydrocarbons to estuarine crustaceans. Estuarine Coast. Mar. Sci. 6, 365–373. doi: 10.1016/0302-3524(78)90128-7

Thresher, R. E., Tilbrook, B., Fallon, S., Wilson, N. C., and Adkins, J. (2011). Effects of chronic low carbonate saturation levels on the distribution, growth and skeletal chemistry of deep-sea corals and other seamount megabenthos. Mar. Ecol. Prog. Ser. 442, 87–99. doi: 10.3354/meps09400

Trannum, H. C., Nilsson, H. C., Schaanning, M. T., and Øxnevad, S. (2010). Effects of sedimentation from water-based drill cuttings and natural sediment on benthic macrofaunal community structure and ecosystem processes. J. Exp. Mar. Biol. Ecol. 383, 111–121. doi: 10.1016/j.jembe.2009.12.004

Trannum, H. C., Nilsson, H. C., Schaanning, M. T., and Norling, K. (2011). Biological and biogeochemical effects of organic matter and drilling discharges in two sediment communities. Mar. Ecol. Prog. Ser. 442, 23–36. doi: 10.3354/meps09340

Ulfsnes, A., Haugland, J. K., and Weltzien, R. (2013). Monitoring of Drill Activities in Areas with Presence of Cold Water Corals. Det Norske Veritas (DNV) Report: 2012–1691. Det Norsk Veritas, Stavanger.

Underwood, A. J. (1994). On beyond BACI: sampling designs that might reliably detect environmental disturbances. Ecol. Appl. 4, 3–15.

Valentine, D. L., Fisher, G. B., Bagby, S. C., Nelson, R. K., Reddy, C. M., Sylva, S. P., et al. (2014). Fallout plume of submerged oil from Deepwater Horizon. Proc. Natl. Acad. Sci. U.S.A. 111, 15906–15911. doi: 10.1073/pnas.1414873111

Vardaro, M., Bagley, P., Bailey, D., Bett, B., Jones, D., Clarke, R., et al. (2013). A Southeast Atlantic deep-ocean observatory: first experiences and results. Limnol. Oceanogr. 11, 304–315. doi: 10.4319/lom.2013.11.304

Vryhof Anchors BV (2010). Anchor Manual 2010: The Guide to Anchoring. AC Capelle a/d Yssel.

Watling, L., France, S. C., Pante, E., and Simpson, A. (2011). Biology of deep-water octocorals. Adv. Mar. Biol. 60, 41–122. doi: 10.1016/B978-0-12-385529-9.00002-0

Watling, L. (2014). Trawling exerts big impacts on small beasts. Proc. Natl. Acad. Sci. U.S.A. 111, 8704–8705. doi: 10.1073/pnas.1407305111

White, H. K., Hsing, P.-Y., Cho, W., Shank, T. M., Cordes, E. E., Quattrini, A. M., et al. (2012). Impact of the Deepwater Horizon oil spill on a deep-water coral community in the Gulf of Mexico. Proc. Natl. Acad. Sci. U.S.A. 109, 20303–20308. doi: 10.1073/pnas.1118029109

White, H. K., Lyons, S. L., Harrison, S. J., Findley, D. M., Liu, Y., and Kujawinski, E. B. (2014). Long-Term Persistence of Dispersants following the Deepwater Horizon Oil Spill. Environ. Sci. Technol. Lett. 1, 295–299. doi: 10.1021/ez500168r

Wiens, J. A., and Parker, K. R. (1995). Analyzing the effects of accidental environmental impacts: approaches and assumptions. Ecol. Appl. 5, 1069–1083.

Wilson, K. D. P., Leung, A. W. Y., and Kennish, R. (2002). Restoration of Hong Kong fisheries through deployment of artificial reefs in marine protected areas. ICES J. Mar. Sci. 59, S157–S163. doi: 10.1006/jmsc.2002.1186

World Bank (2012). IFC Performance Standards on Environmental and Social Sustainability. Washington, DC: World Bank. Available online at: http://documents.worldbank.org/curated/en/101091468153885418/IFC-performance-standards-on-environmental-and-social-sustainability