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REVIEW

Discharged drilling waste from oil and gas platforms and its effects on benthic communities

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ABSTRACT: This review paper identifies the main effects of oil and gas drilling waste on benthic environments. We identified 26 papers and technical reports that surveyed sediment samples from 72 production or exploration platform sites to assess the zone of influence of sediment contamination and biological effects on benthic communities. While oil-based fluids are now rarely used in the marine context, their release has had large-scale (out to 6 km) and persistent (decadal time scale) impacts on benthic communities. The zone of influence of water-based drilling fluids as determined by sediment barium concentration was larger (2 to 20 km) than for synthetic-based fluids (200 to 2000 m). The zone of biological effects on benthic community diversity and abundance ranged from 100 to 1000 m for both water and synthetic fluids. Effects include changes in benthic species diversity, abundance and alterations to community structure. Functional changes included a loss of suspension-feeding species and increases in deposit feeders and polychaetes. In general, this review demonstrates a loss of benthic biodiversity and suspension-feeding communities due to oil exploration and production and the potential for large-scale effects on sensitive communities such as deep-sea, coral and vegetated habitats. Current research gaps and priorities are identified.

KEY WORDS: Benthic community composition · Chemical toxicity · Organic enrichment · Suspended sediments · Oil-based fluids · Synthetic-based fluids · Water-based fluids

INTRODUCTION

In 1935, the first offshore drilling structures were installed in the Caspian Sea. The largest offshore oil industry centres then appeared in the 1950s in the Persian Gulf, on the shelf of Venezuela, in the Gulf of Mexico and off the California (USA) coast (Patin 1999). Especially rapid and large-scale offshore oil and gas developments started in the 1970s with Great Britain, Norway, Italy, Malaysia, Indonesia and Australia numbered among the leading oil-producing countries (Patin 1999). Offshore development results in both exploration and development drilling operations, and it is the effects of drilling waste (spent drilling mud and drill cuttings) on the receiving environment that has been identified as a primary environmental concern during drilling operations (Kingston 1992, Cranford et al. 2001).

There are 4 steps to drilling a well: (1) spudding in, (2) inserting a second string of casing, (3) installing a blow-out preventer and marine riser on top of the well head and (4) drilling the remaining sections of the well to discover oil reserves. 'Spudding in' involves forcing metal tubing called 'casing' into the ground. The second step includes drilling a deep hole inside the casing and then inserting a second casing into the freshly drilled hole. The 2 sections are cemented in place. The diameter and wall thickness of the pipes vary depending on well depth. Up until this point, any drilling fluids and cuttings are dis-

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charged directly at sea. The third step includes the installation of a blow-out preventer on top of the wellhead which controls formation pressures. Additionally, a marine riser is installed that allows all drilling fluids and cuttings to be pumped up through the riser and back to the oil platform or drilling ship. The remaining sections of the well are then drilled to reach the oil reserve.

Drill cuttings are produced by the grinding action of the drill bit and range in size from clay-sized particles to coarse gravel, having a mineralogy reflecting that of the drilled strata (Neff 1987, 2005, Trannum et al. 2010). Drilling muds lubricate the drill string, bring up cuttings from the well hole, control internal pressure and stabilize the well and constitute 5 to 25% of the discharged drill fluids (Trannum et al. 2010).

There are 3 main types of drilling mud: oil-based, synthetic and water-based fluids (OBF, SBF, WBF). In oil-based mud, the dominant fluid is a mineral oil; in synthetic mud it is ester, ether, acetyl or olefin; and in water-based mud, fresh or salt water is used. Drilling muds also contain a weighting material, clay or an organic polymer, various inorganic salts, solids and organic additives (Neff 2005). Barite ($BaSO_4$) has been the most frequently used weighting material. More recently, ilmenite ($FeTiO_3$), which has lower concentrations of trace metals such as mercury, lead and cadmium, is increasingly used as a replacement for barite (Neff 2005).

Because the casing, marine riser and blow-out preventer are not yet installed and the mud and cuttings cannot be returned to the platform for processing and disposal, drilling of the upper well sections is typically performed with less toxic seawater and bentonite ($Al_2O_3 \cdot 4SiO_2 \cdot H_2O$), which are directly discharged at sea. For drilling the other sections, the types of drilling fluids used are well-specific. During the production phase of extraction, drilling fluids can be discharged directly into the marine environment, recycled and partially screened and discharged, reinjected or shipped to shore for land disposal, depending on national regulations. This review considers effects of discharged drilling fluids from both exploration and production wells.

We reviewed scientific papers and unpublished technical reports to summarize the key findings associated with the effects of drilling activities on seafloor communities. The effects associated with OBF, SBF and WBF on benthic communities are summarised using data from Australia, Canada, Italy, Norway and the USA. Most of the publications and technical reports present compliance data collected as part of an environmental effects monitoring (EEM) programme required by the various jurisdictions in which the industry is operating. EEM programmes allow for the verification of environmental effects predictions and the analysis of the effectiveness of mitigative measures but may also identify unforeseen environmental problems that may arise and address them in an effective and timely manner (Duinker 1989). Sediment quality, benthic habitat and communities and fish health are routinely monitored for drilling EEM programmes (e.g. Husky Oil Ltd 2000). Macrobenthic communities are widely used to monitor the effects of marine pollution because certain benthic organisms are sessile and integrate effects of pollutants over time (Gray et al. 1990). This review provides a synthesis of the current knowledge of the effects of oil and gas exploration and production from drilling activities on seafloor communities.

METHODS

We conducted a literature search using combinations of the following terms: 'benthic', 'environmental effects', 'drilling fluids', 'oil' and 'gas', 'production drilling' and 'exploration drilling', using the Web of Science. The search included journals published from 1902 up until the year 2010. We also conducted separate searches for unpublished technical reports. Surprisingly few findings have been published in the open scientific literature on the effects of drilling fluids from platform operations due to the proprietary nature of the data (Olsgard & Gray 1995). Most of the data on the outcomes of research or EEM programmes on the effects of drill cuttings remain confidential to the respective country's environmental authorities or industry, with Norway being an exception. Norway has an open policy whereby all data reported to the Norwegian State Pollution Control Authority are available to the public (Olsgard & Gray 1995). As a result, many studies currently available in the open scientific literature are based on data collected around platforms in Norway. However, in 2000 the U.S. Environmental Protection Agency (EPA) published a review of surveys that assessed water- and synthetic-based drilling fluids primarily from the USA Continental Shelf, the Gulf of Mexico and the North Sea. The review included survey information available from the open literature, technical reports and comments submitted to the EPA as rule-making records. The review, which was used to develop effluent limitations guidelines and standards, provides a valuable source of information not available in the open literature but present in unpublished technical reports. Some of the reports summarized by the EPA were not available publicly, and our requests for the individual reports were denied. In these cases, we had to rely on the summary information provided in EPA (2000).

From our literature search, we identified 26 papers and technical reports that surveyed sediment samples from 72 production or exploration platforms that could be used to assess the zone of influence of sediment contamination and biological effects. One region-wide study reviewed data from a field of 200 wells in the southern Gulf of Mexico (Hernandez Arana et al. 2005). Most sampling designs employed a radial gradient sampling design recommended for point source pollution (Ellis & Schneider 1997), including one or more far-field reference stations, and in some programmes, baseline and several post-drilling surveys were sampled dependent on the nature of the field. Often, a number of transects radiating away from the platform with sites at varying distances would be sampled. The basic design used in the Norwegian sector is a cross, which intersects at the centre of the field with sampling stations placed at geometrically increasing distances from the centre (e.g. 250, 500, 1000, 2000, 4000, 6000 m; see Gray et al. 1990, Olsgard & Gray 1995) (Fig. 1). One axis is usually located along the dominant current, and one or more reference stations are located at distances such as 12 km. Sediment core samples to quantify physical and chemical variables are taken to determine sediment grain size, organic carbon content and heavy metal contamination. Heavy metal analyses routinely determine Fe, C, Zn, Ba, Sr, Cd, Cr and Hg levels. Benthic macrofauna are determined from grab samples such as 0.1 m^2 van Veen grabs and box corers sieved using a 0.5 or 1 mm mesh. Benthic meiofauna are typically determined from multi-core samples (e.g. <0.01 m^2) sieved using a 64 µm or smaller mesh. Benthic epifauna are determined from still camera and video imagery. The type of sampling method used is dependent on the habitat. Some studies also determined body burden levels of heavy metals in tissue samples. In reviewing EEM programmes, we recorded the distance from the production or exploration platform of elevated hydrocarbons, barium and other chemicals. We also summarized changes in benthic communities with distance from platforms, such as abundance, diversity, biomass, species composition or the presence and absence of rare species. Biological information is often presented as the distance of a change in a variable (e.g. abundance, diversity, community composition) relative to background levels (Olsgard & Gray 1995). Background levels are determined from pre-drilling surveys or from far-field reference sites. We also included any information associated with bioaccumulation of heavy metals. Some papers and technical reports also documented the spatial extent of physical or biological effects over time as production activities increased or as wells were decommissioned. Physical effects are related to changes in the sediment grain size and heavy metal accumulation while biological effects are related to changes in benthic communities. In such cases, we included changes in the scale of effects, potential for cumulative impacts with increasing drilling discharge and temporal scales of community recovery. These summary statistics are provided for oil, synthetic and water drilling fluids separately in order to increase our understanding of the environmental effects associated with various drilling programmes.

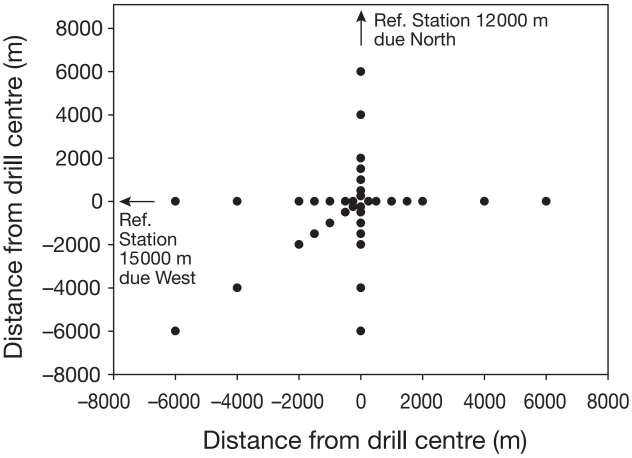

Fig. 1. Sampling design layout commonly used in environmental effects monitoring programmes where sediment and biological samples are taken with distance from drill centres in marine environments. Additional axes (e.g. diagonal axis running southwest in the panel) are often aligned with the predominant currents

RESULTS

For all fluid types (OBF, WBF, SBF), the degree of effects of drilling fluids on benthic and demersal species is highly dependent on a number of local environmental variables (e.g. depth, current and wave regimes, substrate type), and on the nature and volume of the discharges (cutting size, outfall location in water column). However, consistent zones of detection for drilling fluids and biological effects for OBF, WBF and SBF were documented and are summarized below.

Oil-based fluids

Data from 5 technical reports and scientific papers summarizing effects from OBFs in 16 fields in the North Sea are provided in Table 1. Most of the early knowledge about OBFs and cuttings discharge was developed from seabed studies conducted on North Sea sites. Operations began in the 1970s using diesel OBFs. The zones of detection for drilling fluids and biological effects for OBFs varied for development versus single-well operations. In general, elevated barium and total hydrocarbon concentrations in sediment samples ranged from 2000 to 6000 m from the platforms before reaching background levels. Spatial trends show hydrocarbon, barium and trace metal concentrations decreasing with distance from the drill sites. Biological effects, including changes in community composition, were documented from 500 to 6000 m (Fig. 2). Specific studies that document varying levels of chemical and biological effects are discussed in the following paragraphs.

Davies et al. (1984, 1988) summarized various zones of influence where maximum ranges of chemical and biological effects were distinguished for development and single wells in the North Sea. The authors concluded that chemical tracers associated with development wells could be documented out to distances ranging between 800 and 4000 m. They also noted a transition zone in benthic diversity and community structure that could occur between 200 and 2000 m from platforms. Close to the cuttings discharge was an area with few or no macrobenthic species, although diversity increased rapidly with distance until background species diversity was encountered between ~200 and 2000 m, depending on the oceanographic characteristics and operational history at the particular location. Davies et al. (1988) interpreted the diversity gradient as a classic successional response to disturbance as described by Pearson & Rosenberg (1978), with a peak of opportunist deposit-feeding polychaete species occurring between the severely depleted zone and the progressively more diverse zone farther away from the discharge.

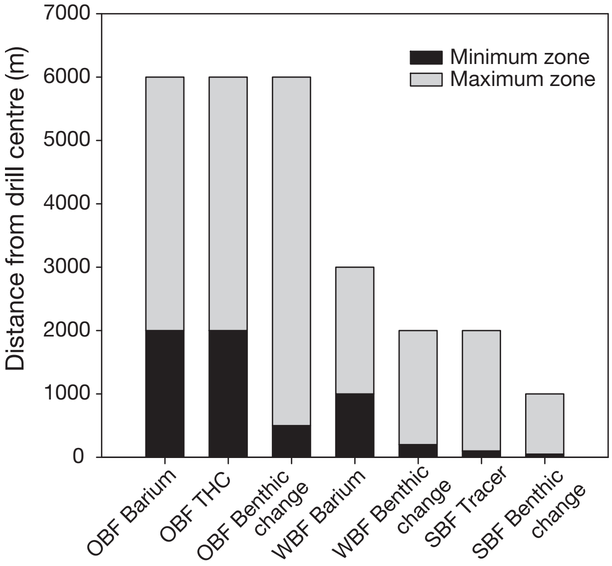

Fig. 2. Maximum and minimum extent of increases or decreases in physical and biological variables from the drill centre in relation to background levels. These 'zones of effects' are identified from all studies reviewed and provide the range of distances reported in the literature. OBF: oil-based fluid, WBF: water-based fluid, SBF: synthetic-based fluid, THC: total hydrocarbon content

Studies of long-term effects indicate that the aerial extent and magnitude of effects of OBF cuttings discharge on benthic communities are highly variable. Olsgard & Gray (1995) documented the persistence of sediment contamination over a period of 6 to 9 yr after termination of cuttings discharge for 3 oil fields on the Norwegian continental shelf. Nearly all stations located 2000 to 6000 m from the drill site showed evidence of elevated barium and total hydrocarbons and sometimes also elevated levels of zinc, copper, cadmium and lead, even after 9 yr. Effects on the fauna several years after cessation of drill-cutting discharges ranged between 1000 and 6000 m from the platform, with only a few contaminated stations at each field not exhibiting faunal effects. Thus, the areas where biological effects were detected were only slightly smaller than the contaminated areas. Sites that were severely polluted were characterised by low diversity and the presence of opportunistic polychaete species. Multivariate analyses linking fauna and environmental variables indicated that pollution effects on community composition were mainly related to the total hydrocarbon content (THC), barium and strontium concentrations, but also to metals like zinc, copper, cadmium and lead. Subsequent to the cessation of discharges, biodegradation of oil and reduced concentrations of THC were observed. Effects on the fauna closely followed the patterns of contamination, including an increase in the spatial area around the platforms where the fauna was affected several years after cessation of drill-cutting discharges. Olsgard & Gray (1995) con-

Table 1. Summary of studies identified that assessed the scale of effects of oil-based fluids (OBFs) on sediments and benthic communities. nd: no data, MDS: multidimensional scaling, PAHs: polycyclic aromatic hydrocarbons, SG: sampling gear, SS: sieve size. Distances relate to the maximum extent of increases or decreases in physical or biological variables from the drill centre in relation to background levels

Location	Depth and sediment type	Well information	Barium	Hydrocarbon	Trace metals	Biotic community change	Source
North Sea. Synthesis from 9 unpublished data reports	Depth: nd. Sand with some silt for most sites	nd	nd	2000–3000 m	nd	500–1000 m, decreases in Shannon Wiener diversity & number of species. 750 m, increases in densities of opportunistic species. SG: 0.1 m^2 grab. SS: 0.5 to 1 mm	Davies et al. (1984)
North Sea. Ekofisk and Eldfisk platforms	Depth: nd. Fine or very fine sand	903 tons oil-based drilling mud discharged from 1984–1985 at Ekofisk. nd for Eldfisk	2000–3000 m	2000–3000 m	nd	2000–3000 m at Ekofisk. 1500 m at Eldfisk. Changes in benthic community composition along a pollutiion gradient including a loss of rare species and increases in abundance of pollution tolerant species near platforms, based on MDS ordination. SG: 0.1 m^2. Day grab. SS: 1 mm	Gray et al. (1990)
Dutch sector, North Sea	42 m. Mud / sand	Exploration well	nd	No gradient detected	nd	1000 m, decreased biomass (g wet wt m^{-2}), number of species, Hills diversity and number of individuals (total per sample). SG: 0.07 m^2 box corer. SS: 1 mm	Kröncke et al. (1992)
Murchison oil field, North Sea	150 m. Sand with minor amounts of gravel, silt, clay	26 development wells. Wells drilled between 1980 and 1984 using WBFs, diesel-based muds and low-toxicity oil-based muds. Estimated total of 23 000 tons of cuttings	nd	1000 m, PAHs ranged from 100 µg g^{-1} at 100–250 m to ~0.6 µg g^{-1} at 2000 m	nd	2000 m, decreased abundance (ind. 0.5 m^{-2}), total number of species 0.5 m^{-2}, Shannon-Wiener diversity and Pielou's evenness with recovery at 1000 m in 1982 and at 2000 m in 1985. SG: 0.1 m^2 van Veen grab. SS: 0.5 mm	Mair et al. (1987)
North Sea. Valhall, Gyda and Veslefrikk platforms	Valhall 65–69 m, Gyda 65 m, Veslefrikk 171–186 m. Sand and silt	Valhall 15 654 tons, Gyda 19 927 tons, Veslefrikk 5241 tons	4000–6000 m	4000–6000 m	Valhall: Sr, Cu 6000 m; Gyda: Cd 4000 m	Valhall 6000 m, Gyda 2000 m, Veslefrikk 1000 m. Changes in benthic community along a pollution gradient including a loss of rare species and increases in the abundance of pollution tolerant species near platforms, based on MDS ordination. SG: 0.1 m^2 van Veen grab. SS: 1 mm	Olsgard & Gray (1995)

cluded that effects on benthos persisted longer than the ambient hydrocarbon levels were actually elevated, suggesting that metals or other components of the drill cuttings were also contributing to long-term biological effects. Results from the Dutch North Sea monitoring programme also indicated that localized hydrocarbon contamination and biological effects were detectable as long as 8 yr after drilling (Daan et al. 1996).

As a result of these studies, the use of OBF cutting discharge release was phased out in the 1990s for the North Sea, although OBFs are still used in difficult drilling conditions, under strict regulation (Hurley & Ellis 2004). The work from the North Sea also informed the regulations of OBFs in the other regions considered in this review. For example, in Canada, low-toxicity mineral oils (LTMOs) were last used in 1989 off Newfoundland and in the mid-1990s off Nova Scotia and the Beaufort Sea (Hurley & Ellis 2004). Oil and gas exploration and development drilling programmes now generally use WBFs and SBFs.

Water-based fluids

Data from 14 scientific papers and technical reports summarizing effects from WBFs are provided in Table 2. These papers represent data from 41 wells and 1 region-wide study of 200 wells. The minimum and maximum distances of changes in physical and biological variables relative to background values are also summarized in Fig. 2. For example, the WBF barium column provides the range of reported distances of elevated barium concentrations in sediment around wells discharging WBFs. In general, elevated barium concentrations in sediment samples ranged between 1000 and 3000 m from the platforms before reaching background levels. Biological effects, including changes in community composition, were documented from 250 to 2000 m (Fig. 2). Specific studies discussed in the following paragraphs document varying levels of chemical and biological effects.

The most clearly documented point source effects of these discharges include alterations in the concentration of barium in sediments. Observations of the zone of detection of WBF for both single- and multi-well facilities, using barium as a tracer for drilling fluids, suggest that average measured background levels are reached at 1000 to 3000 m (Houghton et al. 1980, Mariani et al. 1980, Meek & Ray 1980, Menzie et al. 1980, Ray & Meek 1980, CSA 1986, Boothe & Presley 1989, Jenkins et al. 1989) (Table 2). However, drilling fluid solids can be transported over longer distances to regional areas of deposition, albeit at low concentrations, based on a study of 8 exploration wells located on the Georges Bank, Atlantic USA, in 80 to 140 m depths (Bothner et al. 1985, Neff et al. 1989). Barium was detected in the fine fraction of sediment 65 km west (downstream) and 35 km east of an exploratory drilling site after drilling was completed, with resuspension of drilling mud barite being identified as an important sediment transport mechanism (Bothner et al. 1985).

Increases in a suite of other trace metals associated with WBFs (As, Cd, Cr, Cu, Hg, Pb, Zn) have also been observed. These increases were more spatially limited (generally within 250 to 500 m of the drill site), when compared to the scale of detection for barium concentrations. However, increases in trace metals (specifically Cr) were detected between 1000 and 2000 m from the drill centre for sites on the Gulf of Mexico at depths ranging from 76 to 160 m (CSA 1986). At deeper-water sites (>80 m), a comparison of metal enrichments immediately after cessation of drilling and 5 to 10 yr after the last discharges showed that similar concentrations were observed, confirming the relative stability of the contaminant field over time frames of years, possibly decades, at deeper sites (Kennicutt et al. 1996).

Biological effects have been detected at distances of 200 to 2000 m (US DOI 1977, Lees & Houghton 1980, Menzie et al. 1980, Montagna & Harper 1996, Green 2003). Alterations to benthic community structure are virtually always observed within 300 m of the drill site. Effects include a reduction in species diversity and increases in the abundance of a few opportunistic species. Functional changes were also observed, including a loss of suspension-feeding species and increases in deposit feeders. Changes have been ascribed to physical alteration in sediment texture and organic enrichment effects more frequently than to toxic effects. However, systematic studies of the relative contribution of varying stressors to observed effects have not been conducted. Sedimentation can be very high near oil and gas rigs because drill cuttings tend to settle onto the seabed when discharged directly at sea. The new sediment composition reflects the grain size of the drill cuttings and not the overlying sediments. Organic enrichment occurs due to the addition of usable carbon to the ecosystem (see Patin 1999). The total quantity of oil discharged by the offshore industry via cuttings, produced waters and accidental spills can be high, representing inputs of carbon into the marine environment. For example, in the North Sea the total oil input from

Table 2 (this and the following 2 pages). Summary of studies identified that assessed the scale of contamination effects of water-based fluids (WBFs) on sediments and benthic communities. Tissue BA: tissue bioaccumulation of heavy metals, TH: total hydrocarbon, nd: no data, MDS: multidimensional scaling, CAP: Canonical analysis of principal components, PAHs: polycyclic aromatic hydrocarbons, SG: sampling gear, SS: sieve size. *Denotes technical reports that are not publicly available and were summarized based on data from the EPA (2000) report. Distances relate to the maximum extent of increases or decreases in physical or biological variables from the drill centre in relation to background levels

Location	Depth and Sediment type	Well information	Barium	Hydrocarbon	Trace metals	Biotic community change	Tissue BA (m)	Source
Southern Gulf of Mexico, Campeche Shelf. Grouped stations in relation to the number of oil platforms within a 5 km radius from high density (4 to 12), to low density (1 to 3), to no oil platforms.	Regional, shelf-wide study. Across-shelf transect 12–135 m. Along-shelf transect 30–50 m. Relatively homogeneous muddy shelf environment	Area of 8000 km^2 including 200 oil platforms with a range of functions. 'Little is known about the amount of drilling fluids that have been discharged since exploration started in 1974' (p. 103)	Elevated Ba levels next to platforms, decreasing with distance to the wells	Elevated TH levels next to platforms, decreasing with distance to the wells. PAHs of petroleum origin detected at distances from 700 to 25 500 m	Elevated Ni levels next to platforms, decreasing with distance to the wells	Stations located in areas of high oil platform densities had significantly lower abundance/biomass and different species assemblage composition than stations located in areas of low platform density. Oil-impacted area relatively extensive. ANOVA on mean abundance and biomass grouped by oil rig density. MDS, CAP and meta-analysis used for community composition and regional scale analyses. SG: 0.01 m^2 core. SS: 0.5 mm	nd	Hernández Arana et al. (2005)
Northwest Gulf of Mexico (19 km offshore)	30–100 m. Silt / clay	6 exploration and development wells. 196 m^3 of drill cuttings	2- to 11-fold increase for all sites out to 500 m	nd	Pb increase within 500 m, Hg increase within 250 m	nd	nd	Boothe & Presley (1989)
Georges Bank, Atlantic Continental Shelf	nd	8 exploratory wells drilled over a 3 yr period	6000 m, 25% of barite deposited within 6 km. Ba transport detected at 35 to 65 km	nd	No drilling-related changes of 11 metals from bulk sediment samples	nd	nd	Bothner et al. (1985)
Gulf of Mexico	76–160 m	nd	7.5-fold increase in Ba at 4 km	nd	60% increase in Cr at 4000 m, 2-fold increase in % Fe at 500 m	nd	nd	*CSA (1986)
Gainesville Area, Florida Continental Shelf	21 m	Assessing impacts of a proposed exploratory drilling programme	4000 m, increase in Ba ratio 90%	nd	4000 m, 90% increase in Ba:Fe ratio. 300 m, 11% increase in Cr	Absence of seagrass within 300 m. Seagrass standing crop, biomass, blade count inhibited beyond 300 m to 3.7 km. 77% decrease in seagrass blade count at 3.7 km. Still camera data, live monitoring stations	nd	*CSA (1988)

(continued on next page)

Table 2 (continued)

Location	Depth and Sediment type	Well information	Barium	Hydro-carbon	Trace metals	Biotic community change	Tissue BA (m)	Source
Pensacola Gulf of Mexico	50–60 m. Hard bottom	Single exploratory well	2000 m, 3-fold increase in Ba	nd	Cr levels were 8- to 10-fold higher than reference levels, within 500 m	Reduced bryozoan coverage within 2000 m of discharge. SG: video and still camera data	nd	*CSA (1989)
Minerva-2A well, Southern Victoria Coast, Australia	60 m. Coarse, well sorted sediment	Exploratory well drilled over a 3 wk period	nd	nd	nd	200 m, decreases in abundance (density declines exceeded 70 %) and diversity (36 %). Loss of rare species. Community composition at the well-headsite remained modified 11 mo after drilling. ANOVA tests for diversity/abundance changes (total number of species & ind. site^{-1}). MDS used for community change. SG: 0.1 m^2 Smith-McIntyre grab and video. SS: 1 mm	nd	Currie & Isaacs (2005)
Cook Inlet, Alaska Continental Shelf	62 m. Sand and gravel	Single well	Ba levels elevated out to 400 m	nd	nd	nd	nd	Houghton et al. (1980)
Mid-Atlantic Continental Shelf	120 m. Medium/fine sands with a silt-clay content of 16–25 %	Single exploratory well	1.6 km, 21-fold increase in Ba	nd	3.6-fold increase in Pb at 200 m. 2.5-fold increase in Ni at 100 m.	150 m, lower species diversity and abundance. SG: grab sampler, size unknown. SS: 0.5 mm	Ba increase in tissues at 1.6 to 2.6 km: molluscs 20-fold, polychaetes 40-fold, brittlestars 133-fold	Menzie et al. (1980)
Northwestern Adriatic Sea, Barbara and Calipso Platforms	Barbara 68.5 m, muddy sand. Calipso 75 m, muddy	Two gas-producing platforms. Neither cuttings nor formation waters were discharged at sea. No water discharged during the production phase. Barbara installed in 1999, Calipso installed in 2002, production ongoing	nd	Barbara: PAH levels increased in the second year of monitoring. Calipso: PAH concentrations were higher around the structure, with decreases noted in third monitoring year	Barbara: peaks in Cd, Zn, Pb, Hg recorded around the platform during the first year after installation. Calipso: Cu, Pb, Ba and Zn elevated	Initial defaunation at Barbara and within 120 m radius at Calipso. General recovery in terms of abundance, species richness and diversity was observed at both platforms after 1 yr. During third year, mussel mound developed at both platforms. Diversity (Simpson Index), permutation ANOVA used for community change. SG: 0.1 m^2 van Veen. SS: 0.5 mm	nd	Manoukian et al. (2010)

Table 2 (continued)

Location	Depth and Sediment type	Well information	Barium	Hydro-carbon	Trace metals	Biotic community change	Tissue BA (m)	Source
Continental Shelf, Gulf of Mexico	29–157 m	3 platforms	Elevated within close proximity to platform (distance not provided)	Elevated within close proximity to platform (distance not provided)	Cd, Hg, Pb, Zn measured and used in a principal components analysis, but no distance information available	100 m, increases in deposit-feeding nematodes and polychaetes in the meiofauna. SG: 0.25 m^2 box core. SS: 500 µm	nd	Montagna & Harper (1996)
Georges Bank, North Atlantic USA	80–140 m. Sand with minor amounts of gravel, silt, clay	8 exploratory wells. 9200 t of drill cuttings. 5000 t of drilling fluid solids. Wells were studied for a period of 3 yr	Statistically significant increases in Ba in the fine fraction of the sediment were detected ~65 km west (down current) and 35 km east of the 80 m drilling site	nd	Elevated Cr concentrations within 200 m	No changes in benthic communities detected. Measured diversity from grabs (Shannon Wiener Index) and epifauna density from photographic images (ind. m^{-2}). The dominant fauna were polychaetes. SG: 0.1 m^2 van Veen grab. SS: 0.3 mm	nd	Neff et al. (1989)
Santa Maria Basin, California Continental Shelf	105–213 m. Hard-bottom site (105–213 m) Soft-bottom site (123–169 m)	7 wells drilled from Nov 1987 to Jan 1989 (hard-bottom site)	nd	nd	nd	Sediment flux related to decreased coral coverage. SG: still camera data and sediment flux traps	nd	*Steinhauer & Imamura (1990)
Mustang Island Continental Shelf	36 m. Sand	Single exploratory well	1000 m, 2.5-fold increase in Ba	nd	nd	1000 m, decreases in total abundance of epifauna. SG: 9.1 m semi-balloon trawl	nd	US DOI (1977)

these sources in 1990 was estimated at 20 000 t yr^{-1} (Patin 1999).

The greatest biological effects of WBFs were documented for sensitive seagrass communities and hard-bottom communities. Data on seagrasses are limited to a single shallow-water USA study (CSA 1988) which documented a greater spatial scale of biological effects than studies conducted on unvegetated soft-sediment habitats. Approximately 9 wk after drilling operations commenced, seagrasses were completely absent within 300 m of the drill site. At a distance of 3700 m from the drill site, blade biomass and blade numbers showed only 25% growth compared to the increases shown at the reference station (CSA 1988).

Two case studies also documented effects out to greater spatial scales for hard-bottom epibenthic habitats (CSA 1989, Steinhauer & Imamura 1990) than the spatial scale of effects documented for soft-bottom habitats. The first study documented reductions in epibenthic community coverage that occurred out to 2000 m from a single exploration well (CSA 1989). This field survey used photographic and video data to detect community change, whereby total biotic coverage of epibenthic communities decreased by 55% between pre- versus post-drilling surveys. Reference station values decreased in total biotic coverage by 19% between survey times. Overall decreases at both drill site and reference stations were primarily due to dramatic (i.e. 95%) decreases in bryozoan coverage between surveys. Because only 1 pre- and 1 post-drilling survey were conducted, it is more difficult to separate out effects related to natural variability over time, compared to changes in community composition with respect to drilling activities; however, the report does provide evidence for drilling-related effects on sensitive hard-bottom epibenthic communities. A second study that also collected photographic information for a hard-bottom habitat provided evidence that increased sediment flux from drilling activities was related to decreased coral coverage for the solitary cup coral *Caryophyllia* sp. (Steinhauer & Imamura 1990). The zones of effects for these 2 studies that represent sensitive communities were larger than for soft-bottom infaunal benthic communities.

Besides documented changes in species composition or abundances, another impact on benthic communities was associated with chemical toxicity as measured by body burden. Elevated concentrations of barium in tissues of polychaetes, brittle stars (primarily *Amphioplus macilentus*) and bivalves (primarily *Lucinoma filosa*) were detected as far as 1600 m from a single well discharging WBFs (Menzie et al. 1980). These species cover a range of trophic modes including detritivores (brittle stars) as well as deposit- and suspension-feeding modes.

A region-wide study provides information on the potential for cumulative effects where multiple wells are drilled in an area (Hernández Arana et al. 2005). In the southern Gulf of Mexico, a regional shelf-wide study was conducted that sampled across an 8000 km^2 area that included 200 oil platforms with a range of functions. Little is known about the amount of drilling fluids and produced water that have been discharged since oil exploration started in 1974. The objective was to determine the effect of oil-related activity in a region known to have a highly variable benthic community composition due to temporal and spatial variability of its natural environment. A transect design along gradients of natural variables and disturbance intensities, including active oil platforms, was implemented during the rainy and winter storm seasons of 1999 to 2000. Two transects running across the shelf and 2 running along the shelf were sampled. Twelve stations were allocated along each transect, with a total of 48 stations sampled in the study. Contamination from oil-related activities extended beyond the immediate surroundings of the point source. Results from ordination analysis clustered stations with high concentrations of oil hydrocarbon and metals together, independent of season, and these stations did not exhibit the ambient pattern of depth and grain-size gradients across and along the shelf. Specifically, the study grouped stations in relation to the number of oil platforms within a radius of 5 km from high density (4 to 12), low density (1 to 3) and no oil platforms and was able to demonstrate elevated barium and hydrocarbon concentrations with polycyclic aromatic hydrocarbons (PAHs) of petroleum origin detected at distances ranging from 700 to 25 500 m. Stations located in areas of high oil platform densities, or close to oil-related activities, had significantly lower abundance or biomass and different species composition than those stations located in areas of low platform density or farther away from oil-related activities (Hernández Arana et al. 2005). These effects were generally independent of natural differences between the sampling dates. The authors also used an index of multivariate dispersion that indicated increased variability in benthic community composition for the group of stations located within 0 to 3 km of an oil field, indicating increased levels of stress (Warwick et al. 1990, Warwick & Clarke 1993). Finally, for all 48 stations sampled, a fossil fuel pollution index was measured and demonstrated that 12 stations sampled in 1999 and 19 stations sampled in 2000 had PAHs of petroleum origin. The nearest distance to oil platforms for these stations ranged from 1300 to 22 500 m for stations in 1999 and 700 to 25 500 m for stations in 2000, indicating that the distance of effects for petroleum origin hydrocarbons could range out to 25.5 km. It was therefore concluded that oil-related activities in the southern Gulf of Mexico have a significant effect on the macrofaunal assemblages and that effects are comparatively extensive and occur at a regional scale (Hernández Arana et al. 2005).

Little information is available on recovery time scales for benthic habitats after exposure to WBFs. The few studies of benthic community change around single wells suggest that communities returned to baseline conditions 1 yr after the cessation of drilling (Currie & Isaacs 2005, Manoukian et al. 2010). In some cases, sensitive species, such as the burrowing brittle star *Amphioplus macilentus*, remained depressed 1 yr after drilling (Menzie et al. 1980). Currently, there is limited information on recovery time scales, as multiple wells operate in a region.

Synthetic-based fluids

Seven studies summarizing information from a total of 15 wells were reviewed to assess environmental effects associated with SBFs. The area of detection and scale of biological effects resulting from discharged SBFs were smaller than that resulting from the release of WBFs. Maximum concentrations of synthetic tracers from SBFs in sediment were detected at distances ranging from 100 to 2000 m from the discharge location (Tables 3 & 4). Biological effects associated with the release of SBF cuttings were generally detected at distances of 50 to 500 m from well sites (Smith & May 1991, Candler et al. 1995, Schaanning 1995, DeBlois et al. 2005), although reductions in the abundance of a few taxa (such as bivalves and echinoderms) were detected out to 1000 m (Daan et al. 1996; Table 3). Jensen et al. (1999) documented effects of various SBFs (ester, ether, olefin) on benthic community abundance and diversity (Table 5). Their study was based on previously collected field data from biological and chemical surveys of 9 oil and gas fields in the North Sea and the Norwegian Sea. The maximum distance with reduced number of species ranged from 250 to 500 m, while the maximum change in abundances of benthic organisms was typically 500 to 1000 m (Table 5). The change in the density of individuals up to 1000 m was generally due to changes in the abundance of indicator species such as the polychaetes *Chaetozone setosa*, *Capitella capitata*, *Pseudopolydora paucibranchiata*, *Raricirrus beryli* and *Octobranchus floriceps*. The authors also compared the zone of effects of different SBFs on benthic communities. Statistically significant correlations were found between reduced diversity in the benthic fauna and high concentrations of barium, olefin and ester in the bottom sediments surrounding several fields (Jensen et al. 1999). In most cases, there was a stronger correlation between the reduction in diversity and high concentrations of olefin and/or ester than with barium, which may indicate that possible toxic and anoxic effects are greater than effects due to sedimentation and physical disturbance as a result of dispersion of cuttings and barium.

Research on SBFs suggests that changes in benthic communities occur primarily due to the level of nutrient enrichment from synthetic materials and the ensuing development of benthic anoxia. Specifically, organic enrichment causes oxygen depletion due to the biodegradation of the discharged SBFs. This biodegradation results in predominantly anoxic conditions in the sediment (EPA 2000). All synthetic fluids have high theoretical oxygen demands and are likely to produce a substantial sediment oxygen demand when discharged in the amounts typical of offshore drilling operations. The actual oxygen demand of a compound will depend on the biodegradability of the compound and the specific organisms metabolizing the compound. Existing field data suggest that these materials will be substantially degraded on a time scale of 1 to a few years; however, the distribution and fate of these materials has not been extensively documented (EPA 2000). The relative impact of the various types of SBFs is also speculative given the paucity of field data for laboratory versus field conditions (EPA 2000). Further research on biological effects of SBFs, recovery trajectories and effects associated with differing SBFs is required.

RESEARCH GAPS AND RECOMMENDATIONS

The extraction of fossil fuels from offshore fields has increased rapidly in the last 5 decades, becoming the leading activity in the exploitation of marine mineral resources. As a result, thousands of offshore platforms have proliferated over the world's oceans, and more will likely be implemented in the future

Table 3. Summary of studies identified that assessed the scale of contamination effects of synthetic-based fluids (SBFs) on sediments and benthic communities. nd: no data, bbl: barrels of oil, MMS: minerals management service, PAO: polyalphaolefin, TPH: total petroleum hydrocarbon, SG: sampling gear, SS: sieve size. *Denotes technical reports that are not publicly available and were summarized based on data from the EPA (2000) report. Distances relate to the maximum extent of increases or decreases in physical or biological variables from the drill centre in relation to background levels

Location	Depth and Sediment type	Well information	Synthetic tracer	Hydrocarbon	Trace metals	Biotic community change	Source
Gulf of Mexico	nd	Discharge of PAO, 441 bbl of cuttings, 354 bbl adhering SBF	200 m	Authors used TPH to determine the presence of PAO-based fluid. TPH measured above 1000 mg kg^{-1} out to 200 m	nd	50 m, benthic community composition significantly different at stations within 50 m, persisting 2 yr after discharge ceased. No information in EPA document on units or sieve size	*Candler et al. (1995)
North Sea Dutch Sector	30 m; Fine sand and silt	447 tons of an ester-based SBF discharged from 1 drill site	200 m, ester-based fluid concentrations reached background levels	nd	nd	500 m, gradual increase in abundance with distance. Depression of a dominant bivalve and the echinoderm *Echinocardium cordatum*, which is highly sensitive to organic enrichment, occurred over greater spatial scales out to 1000 m. Recovery of species abundance apparent 11 mo after drilling ceased. Used logit regression to test for gradients in individual species. SG: 0.16 m^2 van Veen. SS: 1 mm	Daan et al. (1996)
Newfoundland, Canada, Terra Nova Field	94 m	Synthetic-based mud. Pure Drill 1A-35	nd	Hydrocarbons gradually declined to low levels at 3000 m from drill centres (1 mg kg^{-1})	No project-related effects noted for trace metals	No distance gradients among years for total abundance, biomass, richness or diversity. Slight evidence for enrichment effects of project activities on spionids and bivalves, and negative effects on syllids and cirratulids. Total abundance (total organisms per station), biomass (wet weight per station) Simpson's diversity, MDS community change. SG: 0.1 m^2 box corer. SS: 0.5 mm	DeBlois et al. (2005)
Northern Gulf of Mexico Outer Continental Shelf	565 m	6263 bbl of SBF discharged from 1 well	Sampled at 25 m intervals out to 75 m. Effects were detected out to 75 m. Concentrations at the 75 m station were 165051 mg kg^{-1} for 1997 and 198320 mg kg^{-1} for 1998. High concentrations of SBF may be due to slower biodegradation rates than those noted in the North Sea	nd	nd	Benthic survey data from 1998 indicate an increase in polychaetes and gastropods as compared to MMS background data. Polychaete densities were nearly 40× higher than background data, gastropod densities were nearly 3000× higher than background data. Note no reference samples were collected, so comparison is with MMS data. SG: core samples and video transects to quantify large invertebrates	Fechhelm et al. (1999)

Table 3 (continued)

Location	Depth and Sediment type	Well information	Synthetic tracer	Hydro-carbon	Trace metals	Biotic community change	Source
North Sea Ula Well	67 m	Discharge of PAO-based SBF. 97 tons of synthetic esters discharged	1000 m, average concentration of synthetic ester out to 1 km was 16546 mg kg^{-1} compared to 2.3 mg kg^{-1} at reference station	nd	nd	100 m, benthic organisms impacted within 100 m. Impacts on benthic communities persisted 2 yr after drilling ceased. No information in EPA document on units or sieve size	*Schaanning (1995)
North Sea Ula Well	67 m	Single well discharging ester-based synthetic fluid	Ester concentrations elevated within 200 m. 85300 mg kg^{-1} at 50 m, 46400 at 100 m and 208 mg kg^{-1} at 200 m in 1990. Levels dropped to 0.2 mg kg^{-1} at 50 and 100 m, and 1.3 mg kg^{-1} at 200 m by 1991	500 m, hydrocarbons elevated to 774 mg kg^{-1} at 100 m and 86 mg kg^{-1} at 200 m in 1990. Levels dropped to 13 mg kg^{-1} at 100 m and 7 mg kg^{-1} at 200 m in 1991	nd	Reduced abundance and diversity within 100 m. No information in EPA document on units, sieve size or abundance diversity measures	*Smith & May (1991)

(Pulsipher & Daniel 2000), representing a threat for coastal, shelf and deep-sea systems (Terlizzi et al. 2008). The magnitude of effects on benthic assemblages varies depending on the complex interactions among local environmental factors and specific features of platforms (Terlizzi et al. 2008). In summary, the use of OBFs has been phased out for most marine drilling programs due to the large spatial extent of biological effects (up to 6000 m) and documented recovery trajectories of up to 8 yr (Olsgard & Gray 1995, Hurley & Ellis 2004). For WBFs and SBFs, the maximum zone of benthic effects ranged from 50 to 1000 m from platforms or wells depending on discharge volumes of drilling fluids, hydrodynamic regimes, water depth and the sensitivity of benthic habitats within the region. The scale of documented effects on hard-bottom benthic communities was generally larger than for soft-sediment habitats. It is hoped that the information provided in this review will be used to guide sustainable environmental management of offshore drilling and production activities in the marine environment. In reviewing the existing literature, a series of research questions regarding the environmental effects of the offshore oil industry that still remain unanswered have also been identified. These include questions on (1) long-term chronic impacts on ecosystems, (2) effects of drilling programmes on deep-sea and hard-bottom habitats and (3) cumulative impacts of oil and gas activities in a marine context. These needs are discussed below, including recommendations regarding management frameworks that could be developed to facilitate decisions when an area is developed for oil production, including how and where exploration and development drilling should be permitted.

This review identifies that there is limited fundamental research to understand long-term chronic impacts of drilling activities on benthic ecosystems. Long-term impacts on marine populations can occur as a consequence of low-level but chronic exposure to petroleum hydrocarbons, drilling fluids, metals and other chemicals associated with drilling activities. A number of mechanisms may operate to impact a given biological community, including chemical toxicity, organic enrichment and physical interference from particles in suspension (Patin 1999, Cranford 2004). An increasing amount of ecotoxicology experiments have been published that research the chemical toxicity of drilling wastes for various organisms in laboratory experiments (see review by Holdway 2002). However, it is generally not possible in the laboratory to investigate and understand the responses of whole ecosystems over the actual time

Table 4. Summary statistics for all studies providing the distance (m) of elevated sediment contaminants and benthic community change resulting from drilling muds. Data are summarised by spatial zone of influence from greatest to least distance of physical and biological effects. nd: no data

Barium/ synthetic based fluids (m)	Total hydrocarbon content (m)	Biological change (m)	Source
Oil-based fluids			
6000	6000	6000	Olsgard & Gray (1995) – Valhall
4000	4000	2000	Olsgard & Gray (1995) – Gyda
4000	4000	1000	Olsgard & Gray (1995) – Veslefrikk
3000	3000	3000	Gray et al. (1990)
nd	3000	1000	Davies et al. (1984)
nd	1000	2000	Mair et al. (1987)
nd	No gradient	1000	Kröncke et al. (1992)
Water-based fluids			
65000	nd	No effect	Neff et al. (1989)
nd	700 to 25500	Region-wide effects	Hernández Arana et al. (2005)
6000	nd	nd	Bothner et al. (1985)
4000	nd	3700 (Seagrass)	CSA (1988)
4000	nd	2000 (Bryozoan)	CSA (1989)
4000	nd	nd	CSA (1986)
1000	nd	1000	US DOI (1977)
1600	nd	150	Menzie et al. (1980)
500	nd	200	Booth & Presley (1989)
400	nd	nd	Houghton et al. (1980)
nd	nd	200	Currie & Isaacs (2005)
nd	nd	120	Manoukian et al. (2010)
nd	nd	100	Montagna & Harper (1996)
Synthetic-based fluids			
nd	3000	Mild stimulatory/ inhibitory effects	DeBlois et al. (2005)
200	nd	500 to 1000	Daan et al. (1996)
1000	nd	100	Schaanning (1995)
200	500	100	Smith & May (1991)
200	200	50	Candler et al. (1995)

and spatial scales involved, and it is essential that more holistic and field-based research programmes also be employed to understand ecosystem-level impacts.

Laboratory studies have also been conducted to determine potential long-term effects of particles in suspension on filter-feeding populations. For example, research conducted on scallops indicates that physical interference by bentonite and barite particles in drilling wastes can affect growth and reproduction at environmentally relevant concentrations (Cranford 2004). Benthic boundary layer transport models were used to simulate the dispersion of drilling wastes around drilling platforms under typical exploration drilling scenarios (Hannah et al. 1995, 2006), and concentrations known to affect scallops were predicted to occur over large areas (several km).

In a review of the long-term consequences of oil and gas production in the Gulf of Mexico, Peterson et al. (1996) argued that our understanding of the consequences of sublethal environmental changes associated with offshore hydrocarbon production is limited. Understanding chronic and sublethal effects on biological communities was also identified as the most important research priority to improve public decision making on proposals to develop additional hydrocarbon resources (Peterson et al. 1996). Further, prominent concerns regarding the ecological consequences of the industry are the long-term consequences of chronic contamination (NRC 1991, 1992, Patin 1999).

Another research gap identified here is the limited knowledge of how oil and gas operations will impact deep-sea habitats. Most studies on the effects of oil and gas operations have been conducted in soft-sediment benthic habitats on continental shelf environments. As oil and gas operations move into deeper waters, the species assemblages and habitats encountered change. There is growing concern that as exploration drilling programmes move into deeper waters, potential interactions with unique hard-bottom and coral habitats are likely to increase (Probert et al. 1997, Reed 2002, Hurley & Ellis 2004). Deep-water oil reserves have been identified in the Gulf of Mexico, Brazil, Africa, Atlantic Canada, New Zealand and Arctic regions, and these areas are slated for potential development. While in some regions extensive information is compiled on habitat distributions of key species in these areas, in general there is limited knowledge of the distribution, habitat, age composition and biological aspects of deep-water species such as corals (Mortensen et al. 2002). The greatest concern for coral species from oil and gas activities identified to date is the potential for smothering from drill cuttings (Roberts et al. 2006), and presumably this will also be a major factor for other hard-bottom epifaunal species. Laboratory experiments indicate the potential for polyp mortality caused by drill cuttings (Larsson & Purser 2011) as well as alterations in feeding behaviours, coral physiology and disruption of calcification (Dodge & Szmant-Froelich 1985). The tolerance of

Table 5. Benthic abundance and diversity data taken from Norwegian drilling fields discharging both ether/olefin and ester/olefin synthetic-based fluids (data from Jensen et al. 1999). nd: no data, max.: maximum, ind.: individual

Field	Year	Depth (m)	Max. distance with reduced diversity (m)	Change in ind. density (m)
Stratfjord North	1996	260–289	500	1000
Stratfjord East	1997	146–207	500	1000
Tordis	1996	190–222	250	1000
Snorre	1996	294–340	500	500
Heidrun	1997	228–350	250	550
Balder	1997	120–126	250	500
Froy	1997	108–115	250	500
Vigdis	1996	nd	250	500

individual species to the constituents of drill cuttings has also been found to be highly variable (Rogers 1999). Given the amounts of drilling fluids and cuttings that can be released into the water column from a drilling programme and the knowledge that sedimentation and chemical toxicity are destructive to hard-bottom and coral assemblages, we identify that this is an area requiring careful monitoring and research as oil and gas activities move into these deep-water habitats.

Finally, the cumulative impact of multiple oil and gas operations within a region requires more detailed research. Data collected from EEM programmes are specific to the platform or well being drilled and are usually collected as part of compliance monitoring to ensure the scale of effects does not exceed predictions made in the environmental assessment (EA). However, research to address cumulative impacts is necessary to provide information on factors such as the potential of benthic communities to recover in areas where multiple wells are in operation. We found only 1 study that assessed cumulative impacts of oil and gas activities in a region of multiple wells (Hernández Arana et al. 2005). Stations located in areas of high oil platform densities had significantly lower abundance and biomass and different species assemblage composition than those stations located in areas of low platform densities, and the authors therefore concluded that drilling-related activities affected the area over relatively extensive regional scales. Extensive contaminated areas and overlapping influences from neighbouring oil fields are expected in areas with a long history of oil exploration (Olsgard & Gray 1995). The regional scale study conducted in the southern Gulf of Mexico supported this assumption (Hernández Arana et al. 2005). The consequences of shifts in species assemblage composition that have been summarized in this study will require further research to determine impacts at the ecosystem level. The likely ability of benthic communities to recover will also be affected as the scale of disturbed communities becomes larger. Research designed to understand and manage cumulative impacts will become more important as industry activities grow in a region.

Research to assess cumulative impacts will also need to evaluate multiple stressors such as climate change, resource depletion and pollution in a spatial framework in order to fully assess the long-term impacts of oil and gas activities in a marine context. Management focused on impacts of a single stressor is inefficient and often ineffective because co-occurring human activities lead to multiple simultaneous impacts on communities and individual species (Halpern et al. 2008a,b). Therefore, spatial information on human activities and species distribution is needed that can assist in ecosystem-based management decisions. Formalized frameworks to inform management decisions regarding the licensing of exploration and production programmes will also be necessary. Many countries have already developed legislation and frameworks for oil and gas activities operating within their jurisdiction. One example is based on a review of Canadian environmental effects monitoring programmes for exploration drilling which recommended a 'decision tree' process based on 3 scenarios. The scenarios ranged from the situation where no known sensitive habitats are present and where there is sufficient existing information from previous EA work, to the scenario where exploration drilling is slated to occur in sensitive areas (see Hurley & Ellis 2004). Formalized decision frameworks could be integrated within larger-scale spatial planning approaches to ensure that (1) effects of multiple anthropogenic stressors on the marine environment are considered and, (2) that sensitive habitats are protected when managing the expansion of exploration and production activities within the marine environment.

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