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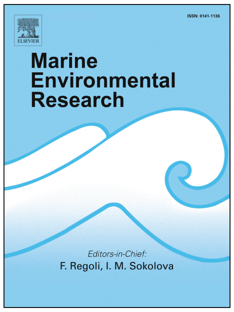

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Historic scale and persistence of drill cuttings impacts on North Sea benthos

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Abstract

Despite its long history of hydrocarbon exploitation, the United Kingdom lacks scientific protocols to monitor ecological impacts of drill cuttings (mixtures between rocky material excavated from wells and drilling mud). The present study used the UK Benthos industry database to apply standardised variance partitioning and measure the scale and persistence of these effects at 19 sites across the UK sector of the North Sea. Generally, effects were limited to within 1 km from the platform, but two platforms historically drilled with oil-based mud were impacted up to 1.2 km away. Impacts persisted for at least 6-8 years in the northern and central North Sea, but were undetectable in the south where cuttings piles do not accumulate. This study underpins new recommendations to implement regional, phase-based approaches to drill cuttings monitoring, and to apply a precautionary approach in considering decommissioning options that will minimise disturbance to cuttings piles.

Keywords

North Sea; benthos; drill cuttings, decommissioning, recovery

1. Introduction

1.1 Operational landscape and environmental impacts of the North Sea oil and gas industry

The North Sea is a mature hydrocarbon province in the northeast Atlantic that continues to be explored for new reserves that are being extracted in new ways via enhanced oil recovery methods (Muggeridge et al. 2014). North Sea oil and gas reserves have been exploited for over five decades, with over 770 subsea installations currently in place in the waters around the United Kingdom alone (Fig. 1a). The proliferation of artificial structures in the sea, or “ocean sprawl”, has necessitated an evolving but complex policy landscape with the dual purpose to manage licensed activities and foster economic growth (Firth et al. 2016). In Europe, policy is underpinned by the Oslo-Paris Convention for the protection of the marine environment of the north-east Atlantic (OSPAR) and the Marine Strategy Framework Directive (MSFD). The North Sea region borders many nations party to OSPAR, yet despite historically high levels of environmental pressure from fisheries and petroleum industries, the environmental status of this region is improving (OSPAR 2010). With regards to the petroleum industry, declining hydrocarbon production levels, improved management, and industry uptake of best available techniques and environmental practices have largely contributed to these improvements.

However, the emerging new era of decommissioning offshore oil and gas installations in the North Sea brings a high degree of uncertainty regarding environmental impacts of infrastructure removal and how these might affect environmental status. With few decommissioned sites to date, there are not many empirical studies on the environmental impacts of decommissioning in the North Sea. This lack of synthesis precludes scientific evidence-led assessments about impacts of different decommissioning scenarios e.g., whether the “rigs-to-reefs” concept could apply in the North Sea (Jørgensen 2012), although decision-making frameworks that incorporate uncertainty are being developed (Fowler et al. 2014). Furthermore, some North Sea nations, such as the United Kingdom, have under-utilised the vast amount of environmental survey data held by industry that could help design monitoring strategies and ensure regional environmental status continues to improve in future. With more than 770 oil and gas installations operational in the UK sector alone, these data could significantly increase the spatial and temporal scales of understanding how to monitor and manage environmental impacts of the industry.

Understanding the scale of industry impacts in the region remains a complex task: the North Sea has been considerably transformed by the oil and gas industry since the late 1960s, but also by fisheries, shipping, and eutrophication over the last century (Kingston 1992; Callaway et al. 2007). The result is that the North Sea's ecological baseline has been lost, making it difficult to understand the scale and persistence of historical impacts of the industry. Trend-based approaches to impact assessment can distinguish background/non-target disturbance or pollution effects from industry-specific impacts. Such approaches provide a means to gain greater understanding the actual scale and persistence of industry-specific impacts.

1.2 Biological impacts of drill cuttings

Industrial discharge of contaminated drill cuttings is a significant source of disturbance and pollution to benthic communities, and can have far-reaching consequences for ecosystems via the rapid transport of aggregates of phytodetritus and cuttings to the seafloor (Pabortsava et al. 2011). Drill cuttings are commonly discharged onto the seafloor in the vicinity of the well head to form a cuttings pile (Breuer et al. 2004). The spatial extent of the cuttings pile depends on the volume of cuttings discharged and the tidal current regime in the area: in areas with strong currents, the cuttings piles often have an elliptical footprint with the long axis of the ellipse aligned with the predominant current direction (Breuer et al. 2004). Physical impacts on the benthos are due to smothering by the discharged cuttings, these effects are usually localised to the vicinity of the well or platform; nevertheless, cuttings piles are overall a significant source of smothering on the UK seabed (Foden et al. 2011). Ecological impacts are often characterised by reduced species diversity, enrichment of opportunistic and/or pollution-tolerant fauna and a loss of more sensitive species (Ellis et al., 2012; Paine et al. 2014a). In the OSPAR region, proposed management of cuttings include options such as allowing natural *in situ* degradation as well as options such as complete removal of cuttings piles.

Toxicity of the discharged cuttings can also impact the benthos. Drill cuttings typically consist of a mixture of the rocky material excavated from the well and the artificially introduced drilling mud. The mud functions as a drill lubricant and contains weighting agents such as barite and associated mineral impurities including metals, and other additives to enhance drill lubrication and prevent blowout (Neff 2009). Over the history of exploration and production in the North Sea, growing concerns from various agencies about toxicity of drill cuttings led to increased regulation of drill mud composition.

Oil-based mud (OBMs) and the discharge of OBM-contaminated cuttings are now prohibited in the OSPAR region, the use of alternative water-based mud (WBMs) help to significantly reduce the environmental footprint of cuttings impacts (Bakke et al. 2013). However, disturbance and remobilisation of historic OBM contaminated cuttings piles is a potential source of pollution that could become more problematical as industry begins to remove subsea structures associated with cuttings piles (Breuer et al. 2004). WBMs have a reduced tendency to aggregate (Niu et al. 2009). However, the flocculation of cuttings may vary considerably depending on specific circumstances, and in some cases, cuttings might be contaminated by the oil contained in the rock reservoir (Niu et al. 2009). Although WBMs are generally assumed to be less toxic than OBMs, emerging experimental evidence suggests that WBMs may have other effects in addition to those associated with simple burial (Trannum et al. 2010, 2011), including sub-lethal effects of barite in particular (Edge et al. 2016).

A broader appraisal of historical impacts and recovery potential from different types of drilling mud, and at individual platforms or wells would contribute significant new information to help assess whether current BEP (Best Environmental Practices) in the OSPAR region continue to move towards minimising environmental impacts. Scientific evidence for partial to full recovery after a couple of decades has emerged (Daan et al. 2006), with evidence for benthos starting to recover after just a few years post-drilling (Tait et al. 2016). However, general estimates of benthic recovery rates in UK waters are mostly based on studies from other areas of the North Sea (Foden et al. 2011). Furthermore, more recent studies are showing chronic “legacy” effects that persist for over a decade (Gates and Jones 2012; Jones et al. 2012). Thus, a broader appraisal of cuttings impact would help prepare and plan for expected scales of impact and recovery in the North Sea and also for ecologically sensitive deepwater environments where benthos recovery from drill cuttings is not well known (Cordes et al. 2016) e.g., the Atlantic Margin and Arctic regions.

1.3 UK Benthos database: a rare industry archive

Decades of industry environmental survey data from the North Sea are held in the UK Benthos database (Fig. 1b), an archive of macrobenthos (>0.5 mm body size), geology and chemistry dating back to 1975. The data include information on drilling history, station locations, macrobenthic species diversity and composition, sediment granulometry, and a range of geochemical data including hydrocarbon content and heavy metal concentrations. These data were originally held in hundreds of separate industry reports held in the archives of individual operators and environmental consultancies. In 2001, all data were digitised and standardised and are regularly updated. The database therefore provides a rare but ideal opportunity for making trend-based assessments of environmental impacts arising from petroleum industry activities.

The first synthesis of environmental baselines and effects of drill cuttings was conducted over a decade ago (Kingston et al. 2001). Although effects of cuttings on benthos were detected, the exact contaminant gradients responsible for these changes could not be identified (Kingston et al. 2001). The study also identified a clear need for longer-term surveys to comprehensively assess the potential for benthos to recover from drill cuttings exposure. As new industry data have continued to become incorporated into the UK Benthos database, the opportunity has arisen to adopt new approaches and provide a current appraisal of historical impacts.

1.4 A community-level multivariate approach

Effects of discharged drill cuttings on benthos located >1 km away from platforms and wells are rarely detected (Bakke et al., 2013), justifying these distant stations as baselines or backgrounds for comparisons. However, benthic communities from these background stations may not be representative of those near the platform or well. The background communities may also vary spatially (Dyer et al. 1983) and temporally due to oceanic changes or impacts from other human activities such as fishing or shipping (Callaway et al. 2007). This makes it difficult to disentangle specific effects of drill cuttings using the standard before-after-control-impact (BACI) approach. Repeated-measure (RM) regression analyses are a good option to disentangle background variability from drill cuttings effects (Paine et al. 2014b), but these require robust experimental design from the outset. To our knowledge, no survey in the UK Benthos database was set up with the intention of conducting RM analyses, with the consequence being that survey data will therefore violate some key statistical assumptions, particularly the need for a large sample size of stations and the same number of replicates taken over multiple years.

An alternative trend-based approach is applied instead to appraise historical impacts of drill cuttings. Partial canonical variance partitioning, a type of direct gradient analysis described in Borcard et al. (2004), is recommended as a good approach to overcome the problem of combining data across what could be quite divergent datasets (Maas-Hebner et al. 2015). The method allows effects of background environmental variability to be fully disentangled from pure effects of contaminant gradients during pre- and post-drilling years. Partial variance partitioning was applied to selected datasets to test whether benthos in the near-field (<1 km) and the far-field (>1 km) were affected by contaminant gradients associated with drilling, and how the strength and statistical significance of these gradients changed with time. The results were then compared across structures to derive a regional appraisal of drill cuttings impacts on benthos and recovery. Recommendations are also proposed on methodological changes to guide further improvements in BEP.

2. Methods

2.1 Survey selection

UK Benthos v.4.06 contains data from 11,353 stations across 351 structures including platforms, wells and manifolds (Fig. 1a), now mapped and made available online during the North Sea Interactive project (BGS 2014). The data originate from numerous separate surveys associated with particular structures and time points, combining data across such different surveys is fraught with statistical issues (Maas-Hebner et al. 2015). The data associated with each structure was assessed to ensure it met several criteria for statistical standards: (i) contains both macrobenthos and environmental data; (ii) include near-field (<1km) and far-field (≥ 1km) stations; (iii) includes pre-and post-drilling survey data; (iv) consistently used the same biological sampling gear including grabs and sieve sizes. This strict selection narrowed the number of usable platform or well datasets from 237 to 19 (Fig. 1b, Table 1). Each station was categorised as being near-field (<1km away) or far-field (>1km away) from the structure, with distance from platform, well or manifold ranging between 0 to 14.4 km away.

2.2 Measurements of benthic contaminant gradients

All statistical analyses were conducted using the software Canoco v5.02 (ter Braak and šmilauer 2012). Species data were square-root transformed when abundance data were available, or presence-absence transformed when colonial benthos had been present. Species data were Hellinger-transformed to suppress spurious statistical effects of rare taxa (Legendre and Gallagher 2001). Each dataset was then split into individual survey years (Table 1).

In some survey years, the number of environmental variables was greater than the number of stations, which posed a statistical challenge: using all variables for direct gradient analysis would spuriously attribute changes in benthos to these variables when in fact the relationship was an artefact. Thus, a forward-selection procedure was applied that would identify a smaller suite of variables to explain most of the variation in benthos (Supplementary Material Table I). For 18 out of the 19 structures, forward-selection was used to identify key environmental variables from each of four categories (total oil content, aromatic hydrocarbons, trace metals, and sediment properties). Holm’s correction for multiple comparison of p-values (Holm 1979) and adjusted R-values (R^2_{adj}) were used to further reduce chances of spurious relationships (Blanchet et al. 2008). This selection step was not needed for the Maureen platform; this site had far more stations each year than numbers of environmental variables. Ordination plots derived from indirect gradient analyses (principal component analysis and detrended correspondence analysis) were used to check the forward-selection procedure, and also to identify any relationships between gradients and species diversity.

The strength and statistical significance of distance (near- or far-field) and environmental gradients on benthic communities were analysed using canonical variance partitioning for each survey year. Two methods of partitioning were used, depending on how species responded to environmental gradients: canonical correspondence analysis (CCA, in the case where species responded to gradients in a non-linear way) and redundancy analysis (RDA, when species responded linearly, e.g., the gradient is not very large relative to the species' niche). Partial variance partitioning was used to separate the amount of variation in benthos explained by purely (i) environmental variables, (ii) the distance category (near- or far-field), and (iii) the interaction between (i) and (ii). Changes in the strength and statistical significance of pure and interactive effects were compared pre- and post-drilling for each structure to examine benthic recovery. Correlations of the top five species either positively or negatively associated with verified contamination gradients were included in ordinations as supplementary evidence for drill cuttings impacts on benthos.

2.3 Measurements of benthos recovery

Recovery was examined by inspecting all post-drilling analyses. Recovery was established when two conditions were met: (1) the pure effects of any of the four categories of variables potentially related to drilling (total oil content, hydrocarbon concentration, metal concentrations, and sediment properties) in the expected direction (i.e., increasing close to the well, manifold or platform) were no longer statistically significant, and (2) the interactive effect was not as strong as either pure effect. At later stages of recovery when the footprint of impacts has shrunk, the interactive effect can become stronger than all other effects because only a small subset of the "near" stations has not recovered. Statistical significance for the interactive effect cannot be measured, see Borcard et al. (2004), only its strength. The number of years post-drilling with effects still persisting was plotted for each structure.

3. Results

3.1 Background variability in relation to drill cuttings

Analysis of datasets from all 19 structures showed that effects of the four categories of variables related to drilling and distance from oil and gas infrastructure differed across space and time. In some cases, this heterogeneity was caused by background variability, but in others, the impacts of drill cuttings were clearly distinguished.

Focussing on background variability, four datasets showed significantly different benthic communities in the near-field versus the far-field before drilling even began: Brae B, Caister, North Alwyn, and well 44_12 (Supplementary Material Table II). A total of 12 pre-drilling surveys also exhibited benthic communities already structured by environmental gradients: Audrey A, Beatrice A, Beryl B, Brae A, Buchan A, Caister, Forties C and E, Maureen A, Nelson, the Strathspey manifold and well 44_12 (Supplementary Material Table II). Pre-drilling environmental gradients were assumed to reflect natural spatial variability in organic enrichment/sediment pollution, or possibly far-field sources unrelated to drilling at the focal platform or well. Inspection of all ordinations from the direct gradient analyses (Supplementary Material Table III) showed that any pre-drilling environmental gradient was either orthogonal (unrelated) to the distance category, or that stations furthest away had higher levels of contaminants than those closest to the structures.

3.2 Direct impacts of drill cuttings

A total of 12 structures showed strong, significant benthic responses to contamination gradients established by drill cuttings (Table 2, Supplementary Material Table II). Gradients relating to normal alkanes, organic content, bioavailable barium, silt/clay fraction, sediment grain size and oil content occurred most frequently, with other significant contaminants including lead, zinc, 4- and 6-ringed PAHs, mercury, and total barium (Fig. 2). Three signs of ecological impacts related to these gradients could be distinguished.

The first sign of ecological impact was a statistically significant post-drilling environmental gradient established in the first post-drilling survey. This sign occurred at all structures except at the Brae B and Murchison platforms (Supplementary Material Table II).

A second sign was that this contamination gradient differed from pre-drilling environmental variability by its directionality and/or magnitude. Unlike pre-drilling gradients that were orthogonal to distance or of small magnitude, inspection of the direct gradient ordinations showed that post-drilling contamination gradients were closely aligned to the distance category (Supplementary Material Table III), with stations closest to the drilling sites exhibiting the highest contaminant/enrichment values. This alignment indicated strong correlations between the benthic communities at these stations and the environmental variables associated with the cuttings pile.

This second sign helped identify post-drilling impacts at Brae B and Murchison platforms, both of which did not exhibit statistically significant post-drilling environmental gradients. In the case of Brae B, the directionality of a zinc gradient completely reversed in the post-drilling survey, with values much higher at stations closest the platforms. As a result, the overall effect of environment became much stronger post-drilling, but the effect was not statistically significant due to an outlier station with a high concentration of normal alkanes unrelated to drilling at the platform (Supplementary Material Table II). In the case of the Murchison platform, environmental gradients remained orthogonal in the post-drilling ordinations (Supplementary Material Table III), but a strong significant effect of distance was discerned in the post-drilling statistical analyses and ordinations but not in the pre-drilling data (Supplementary Material Table II).

A third sign was that post-drilling contamination gradients were always associated with opportunistic and/or pollution-tolerant indicator taxa (Fig. 3). In one instance, at the Caister Platform in the southern North Sea, ordinations from indirect gradient analyses showed that no taxa actually characterised the contamination gradient, but rather the impacted post-drilling community was distinguished by extremely low species diversity (Table 2). Taxa most frequently associated with post-drilling contaminant and/or organic enrichment gradients included the polychaetes *Capitella* spp., *Ophryothrocha* spp., and the bivalve *Thyasira* spp., all of which have been recorded associated with cuttings piles in the North Sea and elsewhere (Ugland et al. 2008). Notably, this community now constitutes its own habitat on the UK continental shelf. It closely corresponds to what is described by the pan-European habitat classification system EUNIS known to characterise organically enriched offshore circalittoral sandy mud associated with deep offshore sandy mud adjacent to oil or gas platforms and organic enrichment from the cuttings piles, specifically, EUNIS habitat type SS.SMu.OMu.CapThy.Odub.

3.3 Maximum ecological footprint of discharged drill cuttings

Maximum ecological footprint was determined by the distance from the structure of the furthest station where the biota remained in alignment with the post-drilling contaminant axis. Out of the 12 datasets where significant ecological impacts were detected, 10 had a maximum ecological footprint limited to less than 1000 m from the structure (Table 2). In 11 out of the 12 time series of data the extent of the ecological footprint was at a maximum at the time of the first post-drilling survey.

Increasing strength of the interactive effect was apparent in some cases, but not all (Supplementary Material Table II). Impacts were occasionally limited to a more restricted footprint, in which case the interactive effect was nearest the structure. For example, the Forties C platform (Supplementary Material Table II) exhibited total oil concentrations four times higher but only at stations within 500 m of the platform (Supplementary Material Table I), resulting in the interactive effect being stronger (R_{adj}=9.6%) than purely environmental (R_{adj}=6.8%) or distance (R_{adj}=2%) effects (Supplementary Material Table II).

Only two datasets exhibited ecological impacts on benthos beyond 1000 m: Forties E and Murchison platforms (Table 2). In both cases, inspection of the direct gradient ordinations showed that stations lined up along a contamination gradient extending out to 1200 m. At Forties E, effects of distance were never strong or significant (Supplementary Material Table II) because post-drilling contamination gradients in total barium spread across many stations near and far. Murchison platform showed more complex trends, with benthos 5 to 7 years post-drilling being strongly and significantly affected by contamination gradients and distance (Supplementary Material Table II), effects that extended out to 1000 m away from the platform (Supplementary Material Table III). After 10 years post-drilling, effects were no longer strong or significant, but just three years later in 1993, strong significant effects of normal alkanes and distance appeared to re-establish, and extended out to 1200 m.

3.4 Recovery periods

Recovery time varied across the North Sea, with only 6 out of 19 sites showing no impacts of drill cuttings i.e., minimum persistence time was zero at the 44_12 well, and the Amethyst (A1, B, C), Buchan A, and Audrey A platforms (Fig. 4). When strong significant impacts were detected, more than 50% of these sites showed effects of cuttings piles persisting for at least 6 years post-drilling (Fig. 4), with most slow-recovery sites being located in the northern North Sea. Benthos in the southern North Sea were not altered by drill cuttings except at the Caister platform, where benthos were profoundly affected by a mercury gradient up to 895 m away (Fig. 4; Supplementary Material Table II).

This regional signal in recovery capacity could relate to the predominant use of potentially more toxic OBMs in the northern North Sea. The present study did not have any sites in the northern North Sea drilled with WBMs to enable a mixed effect of region and drill mud type to be statistically modelled. Alternatively, recovery in the southern North Sea may have been faster due to the stronger current regime in this region, which prevents cutting piles to build up around the structures. When OBM were used, benthos from the northern North Sea were still recovering on average 6.8 years post-drilling, while those in the central North Sea took on average 8.3 years. There were no significant impacts detected in surveys of benthos at sites exposed to OBM in the southern North Sea, at least in communities more than 200 m away from the structure; it was only the Caister platform drilled with WBMs that showed impacts.

Recovery in one instance seemed to have been reset, possibly by a cuttings pile re-disturbance event at the Murchison platform. Recovery at this platform first became evident 10 years post-drilling when the effects of distance and environment became weaker and statistically insignificant, and the interactive effect increased (Supplementary Material Table II). However, a contamination gradient in normal alkanes was re-established by 1993 (Supplementary Material Table II). It was not until the survey in 2006 that effects of distance and environment again became weaker and statistically insignificant and the interactive effect increased (Supplementary Material Table II).

4. Discussion

Despite major advances in the regulatory framework over the operational lifespan of many platforms, the lack of standardised methods in field sampling, statistical analysis, and confounding factors such as natural variability and industry effects have made it difficult for the UK to assess and monitor the wider regional-scale and persistence of drill cuttings impacts on its seafloor communities. This knowledge gap introduces uncertainty about the potential spatial and temporal extent of cuttings piles disturbance during future decommissioning activities.

The empirical variance partitioning approach adopted in the present study is emerging as a technique that allows monitoring results from many offshore extractive industries (oil and gas, renewables, mining) to be extrapolated from a small focal area to extend the relevance of the conclusions to understand the wider region (Borja et al. 2016).

This approach enabled a series of core recommendations to be made concerning the (1) extent and duration of a drill cuttings monitoring program, (2) considerations for decommissioning, (3) standards of industry data collection and analysis, and (4) flexible adaptive approaches. In line with enhanced data sharing and integration opportunities in the future (Shepherd et al. 2015), the assessments in the present study also underscore the critical role that industry data (e.g., UK Benthos) can play in providing new recommendations on drill cuttings monitoring. Recommendations are made with respect to decommissioning scenarios and situations that require special consideration. Special consideration might apply when activities at the platform change, or if new data become available on sensitive or protected species in the area, or if new marine management measures are implemented such as in the case of marine protected areas.

4.1 Duration of monitoring: a regional and phase-based approach

The results of this study provided the first scientific evidence base for establishing a regional and phase-based approach to monitoring the ecological effects of drill cuttings in the UK sector of the North Sea. Recommendations that benthos in the northern and central North Sea are monitored for at least the first 8 years post-drilling are grounded by evidence that across the study, communities in these regions took 6-8 years longer to exhibit recovery signs than their southern North Sea counterparts. Benthos in the southern North Sea should be monitored for at least a year post-drilling, but due to the generally more limited footprint of impacts on benthos in this region, monitoring should include stations within the 200 m diameter of drilling, and pair these with appropriate background stations in the far-field. Evidence of a possible re-disturbance event grounds the recommendation that phased activities that could potentially disturb seafloor communities, e.g., decommissioning, should include a renewed programme of monitoring for the same duration (i.e, 8 years for the central and northern North Sea, one year for the southern North Sea).

This regional approach also makes inherent biological sense because differences between species' sensitivities explain benthos response to drill cuttings, with some species being more naturally tolerant than others. For example, benthic communities beyond the continental shelf of the Caspian Sea were expected to be less impacted by sediment burial and smothering because these species inhabit naturally low oxygen environments (Tait et al. 2016). Similarly, variability in deep-sea foraminiferal communities around cuttings piles off Angola was characterised by differences in species that were naturally tolerant of low oxygen conditions versus those that could not withstand effects of organic enrichment and smothering (Jorissen et al. 2009).

More than half of all the North Sea datasets examined exhibited signs of ecological impacts after one year post-drilling (Fig. 4). However, benthos in the deeper waters of the northern and central North Sea seemed more sensitive to contaminant gradients associated with cuttings piles than those in the more southern North Sea. It is likely that here too differences in species' biology explains recovery. Unlike the thermally stratified waters of the northern and central North Sea, strong tidal mixing and friction in the southern portion of the basin (Sündermann and Pohlmann 2011) would support more disturbance-tolerant taxa. The southern North Sea species are therefore probably more resilient to disturbance in this shallow and relatively more hydrodynamic region. Impacts on benthos in the northern and central regions had on average 6-8 years longer persistence time than benthos in the southern North Sea, which firmly grounds the first recommendation that a conservative minimum time to monitor ecological effects of drill cuttings in the central and northern regions should be at least 8 years.

It was not possible to disentangle the effects of OBM versus WBM on persistence time, or to answer the question of how frequently monitoring should take place for WBMs. Effects on benthos were detected at 12 out of 19 installations, which could reflect the predominant historical use of OBMs in the northern North Sea, and which were long thought to impart effects of greater severity than those caused by WBMs (Olsgard and Gray 1995). However, as more data from WBM drilled sites from the northern and centraol regions are collated into the UK Benthos database, it will be possible for future analyses to evaluate whether a shorter minimum monitoring programme is justified for these regions or whether this should just be the case for sites drilled with WBMs.

After 8 years of post-drill monitoring, operators could relax the intensity or frequency of benthos monitoring and take less costly approaches during late-life production phases. Periodic monitoring of contaminants would still be necessary because metals can continue to accumulate over the history of production at the platform (Kennicutt et al. 1996). Although annual sampling is not essential, it would give the operator a higher resolution database upon which to base decisions about future scaling back of benthos monitoring, and would ensure other events unrelated to field operations are detected and not attributed to industry activity.

4.2 Considerations for decommissioning

Findings from the present study supports recommendations made by others for new evidence to inform future policies regarding decommissioning (e.g., Jørgensen 2012). An abrupt re-disturbance event seems to have occurred at the Murchison platform between 1990 and 1993, re-establishing a significant contaminant gradient that spread up to 1200 m away. Murchison’s planned platform decommissioning programme will leave the drill cuttings *in situ* on the seabed to degrade naturally. The present study demonstrates that at least for the Murchison platform, activities that could significantly disturb cuttings e.g., fishing or cable-laying, must be restricted in the vicinity of the platform for at least another decade. Drill cutting monitoring during the decommissioning phase should therefore revert to a more intensive approach similar to that recommended for the earlier stages of the development. This will allow operators to detect and mitigate activities during this phase, and minimise conflicts with other sectors such as fisheries and telecommunications.

4.3 Standards of industry data collection and analysis

Only 19 out of 351 installations from the UK Benthos v4.06 database had data standardised in such a way that permitted the present study. Moving the industry beyond basic compliance monitoring to ecologically robust standards would permit analyses to be used more effectively and across greater spatial and temporal scales (Hawkins et al. 2017). Recommendations are to ensure surveys: contain at least two years of surveys to establish baseline annual variability; contain data on benthos matched with environmental data; data are collected the same month every year; control (far-field) stations are included; cover all phases of operations life history; gear to collect benthos and environmental data, including mesh size, are standardised; station co-ordinates are provided; numbers of benthos stations each year exceeds numbers of environmental variables; sampling is stratified by distance from the platform, well, or pipeline; stations within 200 m away from the platform are included; and lastly, ideally the same environmental contractor is used for species identification. It is also recommended that an integrated approach to statistical analyses is used. The present study used a combination of direct gradient analyses at the benthic community level but also supplemented these with ordinations, species diversity, and indicator species to detect impacts and persistence time.

4.4 Flexible adaptive approaches

Activities and usage at wells and platforms change with time. Accidental spills, discharges or disturbance events such as those caused by storms, maintenance, additional drilling, or pipeline work could reset recovery. In these cases, it is recommended that operators revert to a monitoring programme similar to the earlier phase. The present study suggested that the cuttings pile around the Murchison platform was disturbed in the early 1990s, and entirely re-set the recovery trajectory. The implication of this evidence is that there must be a recommendation for drill cutting monitoring to evolve in line with changes in usage, which could mean a return to longer or more frequent monitoring programmes on a case-by-case basis.

Conservation management needs are also evolving. As unconventional hydrocarbon exploration in mature basins continues alongside frontier exploration such as in the Atlantic Margin in deep waters to the west of the UK, some licensed blocks now overlap marine protected areas (MPAs) and the sensitivity of many deep-sea species and habitats may require new regulation (OSPAR 2009, Cordes et al. 2016). Latest guidelines on best environmental practice for licensed operations in some MPAs outline how management needs will be measured, assessed and implemented to ensure policy compliance (Scottish Government, 2013). It is therefore highly recommended that the oil and gas industry ensures its monitoring programmes align with these guidelines. Design of monitoring programmes must also consider other drivers of variability in ecosystems. Local-scale variability in sediment parameters, for example, can strongly affect benthic communities, necessitating a robust approach to statistical analyses of drill cutting impacts (Paine et al. 2014b). This ensures that the scale of industry impacts can be put into context with other sources of change acting locally but also at much wider scales such as human activities, natural disturbance events, and climate change. The North Sea has been intensively fished for over a century, and maritime traffic is at an all-time high; both activities strongly shape the communities living in the basin. Profound temporal shifts in plankton, benthos and fish communities in the North Sea are also caused by the North Atlantic Oscillation. This natural climatic phenomenon cycles between years with warmer more saline waters coming into the North Sea and years where cooler less saline waters enter the basin. To add to the complexity, the interactive effects of global climate change and local pollution from the oil and gas industry can have cumulative impacts that heighten the toxicity of contaminants (Coelho et al. 2015). Thus, it is critical that effects of industry activities can be put into context with rapid wider-area changes.

5. Conclusion

This study provided new trend-based assessments to strengthen the UK's capacity to chart progress towards policy targets. Analysis revealed that the spatial scale and temporal persistence of drill cuttings impacts can be measured using existing industry data. The standardised approach across 19 different sites in the North Sea allowed new recommendations to be made. Based on the findings of this study, it is recommended that industry adopt: regional and phase-based approaches to drill cuttings monitoring; drill cuttings monitoring for decommissioned sites that are as intense and frequent as those occurring in earlier phases; more rigorous benthic sampling design; a flexible adaptive approach to monitoring that can account for changes in management regimes and policies and that can also help disentangle natural variability from man-made impacts.

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Geological Survey materials © NERC 2016. All data used for this study are open-access, with the latest database accessible from North Sea Interactive (doi: 10.5285/f9c724ab-006b-4256-8553-928f23736ab2) and the Oil and Gas UK website http://oilandgasuk.co.uk/knowledgecentre/uk_benthos_database.cfm.

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Figure Captions

Fig.1: Occurrence of platforms, manifolds and wells from the oil and gas industry in the North Sea overlaid with UK Benthos v4.06 survey data from the North Sea only, and the 19 study sites examined in the present study. UK Benthos surveys (closed orange diamonds) give good coverage of existing oil and gas installations (open circles) (1a); the 19 study sites (closed black circles) shown against the backdrop of all installations (open circles) (1b).

Fig. 2: Frequency of environmental contaminants being associated with ecological impacts of cuttings piles across the 19 datasets. Concentrations of normal alkanes and sediment organic content were most frequently associated with ecological impacts (39% of the time).

Fig. 3: Frequency of benthic macrofauna associated with environmental gradients related to cuttings piles in the North Sea. The pollution-tolerant polychaete indicators *Capitella* spp. and *Pholoe inornata* were the most commonly encountered taxa, being present 38.5% of the time in association with these gradients.

Fig. 4: Regional differences in temporal persistence of impacts. Black stars indicate OBMs, while empty stars indicate WBMs. The black dashed line is used to show how 50% of the installations showed strong or significant impacts of drilling persisting more than one year.

Table 1: Selected UK Benthos industry surveys, including the maximum sampled distance away from structure, and accompanying total oil content, aromatic hydrocarbon, trace metal and sedimentological data following categories defined in the UK Benthos v6 database ('X' indicates these data were available) with benthos sampling method (Van Veen or Day grab).

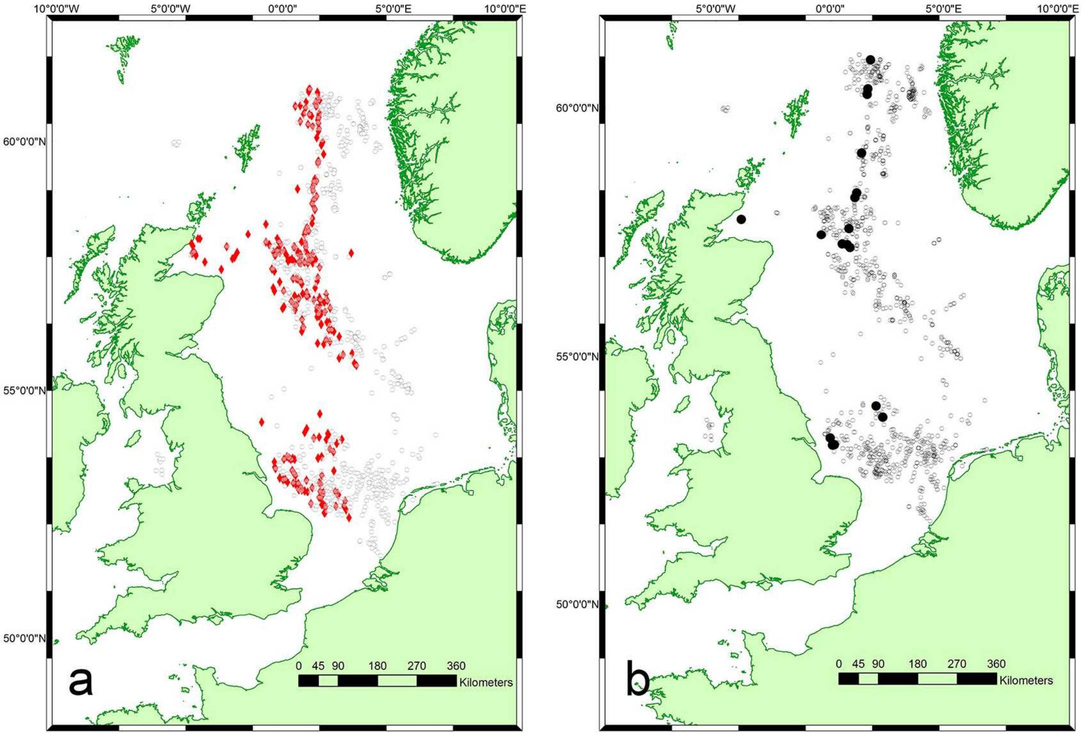
Structure	**Region**	**Latitude, longitude (GPS co-ordinates)**	**Water depth (m)**	**Survey year**	**Pre- or post-drilling (yrs)**	**# of stations**	**Macrofaunal size (mm) and grab sampling method**	**Total oil content**	**Aromatic hydrocarbons**	**Trace metals**	**Sediment properties**
Strathspey Manifold	North	60 55.65N, 01 42.41E	130	1991	Pre-	14	0.5mm, Van Veen	X	X	X	X
				1994	1	10	0.5mm, Van Veen	X	X	X	X
Well 44_12	North	54 33.07N, 02 16.37E	20	1988	Pre-	24	1mm, Day	X	X	X	
				1989	1	12	1mm, Day	X	X	X	
Maureen A	North	58 07.87N, 01 42.11E	98	1979	Pre-	23	1mm, Day	X	X	X	X
				1981	Pre-	24	1mm, Day	X	X	X	X
				1988	5	35	1mm, Day	X	X	X	X
Murchison	North	61 23.77N, 01 44.43E	156	1978	Pre-	20	0.5mm, Van Veen	X	X		X
				1985	5	10	0.5mm, Van Veen	X	X	X	X
				1987	7	10	0.5mm, Van Veen	X	X	X	X
				1990	10	9	0.5mm, Van Veen	X	X	X	X
				1993	13	23	0.5mm, Van Veen	X	X	X	X
				2006	26	6	0.5mm, Van Veen	X	X	X	X
Alba	North	58 03.53N, 01 04.86E	140	1991	Pre-	15	1mm, Van Veen	X	X	X	X
				2000	7	19	1mm, Van Veen	X	X	X	X
				2005	11	6	1mm, Van Veen	X	X	X	X
Beatrice A	North	58 06.90N, 03 05.20W	46	1981	Pre-	83	1mm, Day	X	X	X	X
				1983	2	20	1mm, Day	X	X	X	X
				1985	4	20	1mm, Day	X	X	X	X
				1987	6	22	1mm, Day	X	X	X	X
Beryl B	North	59 36.62N, 01 30.78E	120	1983	Pre-	20	1mm, Day	X	X	X	X
				1985	1	20	1mm, Day	X			X
				1988	4	20	1mm, Day	X	X		X

Platform or well	**Region**	**Latitude, longitude (GPS co-ordinates)**	**Water depth (m)**	**Survey year**	**Pre- or post-drilling (yrs)**	**# of stations**	**Macrofaunal size (mm) and grab sampling method**	**Total oil content**	**Aromatic hydrocarbons**	**Trace metals**	**Sediment properties**
Beryl B (cont'd)	North	59 36.62N, 01 30.78E	120	1991	7	6	1mm, Day	X	X	X	X
Brae A	North	58 41.57N, 01 16.81E	116	1981	Pre-	10	0.5mm, Van Veen	X	X	X	X
				1983	1	10	0.5mm, Van Veen	X	X	X	X
				1985	3	10	0.5mm, Van Veen	X	X	X	X
	North			1989	6	10	0.5mm, Van Veen	X	X	X	X
				2006	17	6	0.5mm, Van Veen	X	X	X	X
Brae B	North	58 47.54N, 01 20.85E	116	1985	Pre-	20	0.5mm, Van Veen	X	X	X	X
				1989	1	11	0.5mm, Van Veen	X	X	X	X
North Alwyn	North	60 48.58N, 01 44.16E	126	1984	Pre-	23	1mm, Van Veen	X	X	X	X
				1989	3	12	1mm, Van Veen	X	X	X	X
				1992	6	15	1mm, Van Veen	X	X	X	X
Buchan A	Central	57 54.22N, 00 01.93E	118	1980	Pre-	27	1mm, Day	X	X		X
				1982	1	20	1mm, Day	X	X	X	X
				1988	8	23	1mm, Day	X	X	X	X
Forties C	Central	57 43.63N, 00 50.83E	127	1975	Pre-	11	1mm, Day	X	X	X	X
				1984	9	16	1mm, Day	X	X	X	X
Forties E	Central	57 42.97N, 01 01.93E	95	1983	Pre-	20	1mm, Day	X	X	X	X
				1984	Pre-	16	1mm, Day	X	X	X	X
				1988	5	19	1mm, Day	X	X	X	X
Nelson	Central	57 39.77N, 01 08.73E	84	1991	Pre-	31	0.5mm, Day	X	X	X	X
				1993	1	31	0.5mm, Day	X	X	X	X
				1995	3	20	0.5mm, Day	X	X	X	X
				1999	5	24	0.5mm, Day	X	X	X	X

Platform or well	**Region**	**Latitude, longitude (GPS co-ordinates)**	**Water depth (m)**	**Survey year**	**Pre- or post-drilling (yrs)**	**# of stations**	**Macrofaunal size (mm) and grab sampling method**	**Total oil content**	**Aromatic hydrocarbons**	**Trace metals**	**Sediment properties**
Nelson (cont'd)	Central	57 39.77N, 01 08.73E	84	2006	15	6	0.5mm, Day	X	X	X	X
Amethyst A1	South	53 36.67N, 00 43.49E	29	1989	Pre-	4	1mm, Day	X	X	X	X
				1992	1	6	1mm, Day	X	X	X	X
Amethyst B	South	53 33.96N, 00 52.45E	29	1991	Pre-	8	1mm, Day	X	X	X	X
				1992	1	6	1mm, Day	X	X	X	X
Amethyst C	South	53 38.82N, 00 36.09E	25	1991	Pre-	8	1mm, Day	X	X	X	X
				1992	1	6	1mm, Day	X	X	X	X
Audrey A	South	53 32.43N, 02 00.95E	27	1986	Pre-	19	1mm, Day	X	X	X	X
				1988	1	19	1mm, Day	X	X	X	X
Caister	South	54 12.31N, 02 26.96E	31	1991	Pre-	15	0.5mm, Van Veen	X	X	X	X
				1993	1	17	0.5mm, Van Veen	X	X	X	X

Table 2: Overview of environmental variables that controlled North Sea benthic community composition around oil and gas installations. If a contaminant gradient decayed with distance from the platform or well, any disturbance and pollution-tolerant indicator species was listed (NA means not applicable). Also reported is the maximum footprint, or distance away from the well or platform over which effects on benthos were detected (NA means no contaminant gradient detected).

Platform or well	**Key environmental variables**	**Contaminant gradient detected**	**Indicator species**	**Maximum footprint (m)**
Alba	normal alkanes, lead	Yes	*Capitella capitata*, *Ophryothrocha* spp.	500
Amethyst A1	organics	No	NA	NA
Amethyst B	organics, oil content	No	NA	NA
Amethyst C	organics, oil content	No	NA	NA
Audrey A	silt/clay fraction, grain size, nickel	No	NA	NA
Beatrice A	organics, silt/clay fraction, grain size, oil content	Yes	*Cirratulus* spp., *Poecilochaetus serpens, Thelepus cincinnatus*	750
Beryl B	organics, silt/clay fraction, zinc	Yes	*Polydora* spp., *Pholoe inornata, Balanus crenatus*, Autolytinae spp., *Ophryotrocha* spp., *Rhaphidrilus nemasoma*	1000
Brae A	grain size, bioavailable barium	Yes	*Praxillella affinis*	1000
Brae B	normal alkanes, zinc	Yes	*Parougia caeca*, *Glycera alba*, *Capitella* spp.	750
Buchan A	organics, silt/clay fractions, grain size, normal alkanes, oil content	No	NA	NA
Caister	6-ringed polyaromatic hydrocarbons, mercury	Yes	few species found at stations with high mercury concentrations	895
Forties C	organics, oil content	Yes	*Chaetozone* spp., *Eudorella truncatula*, *Chaetoderma nitidulum*	500
Forties E	oil content, normal alkanes, lead, total barium	Yes	*Ophryotrocha* spp., *Capitella capitata, Glycera alba*, *Paramphinome jeffreysii*	1200
Maureen A	grain size, organics, silt/clay fraction, normal alkanes, bioavailable barium	Yes	*Pholoe inornata*	750
Murchison	normal alkanes	Yes	*Eteone longa*, *Typosyllis hyalina*, *Ophiodromus flexuosus*, *Ophryotrocha* spp., *Thyasira* spp., *Nereimyra punctata*	1200
Nelson	4-ringed polyaromatic hydrocarbons	Yes	*Thyasira* spp., *Capitella capitata*	500
North Alwyn	organics,silt/clay fractions, oil content, bioavailable barium, chromium	Yes	*Caulleriella alata*, *Apporhais* spp., *Lunatia montagui*, *Thyasira sarsi*	800
Strathspey Manifold	base oil content, carbon preference index	No	NA	NA
Well 44_12	4-ringed polyaromatic hydrocarbons, bioavailable barium	Yes	*Capitella* spp., *Ophryotrocha* spp., *Anaitides maculata*, *Nereimyra punctata*	200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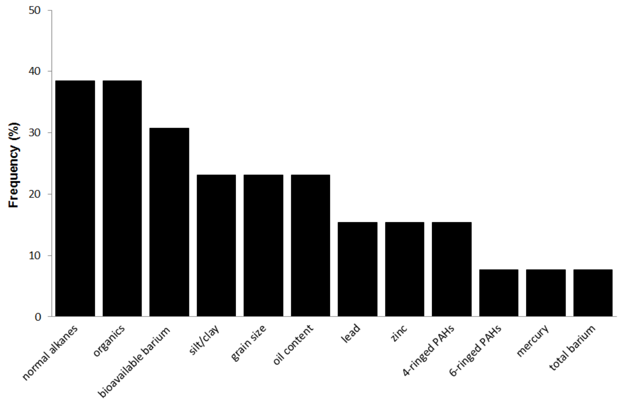
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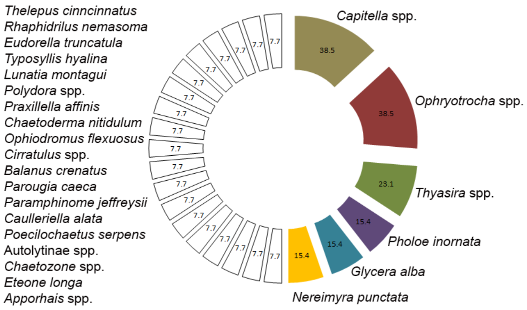
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Eudorella truncatula
Typosyllis hyalina
Lunatia montagui
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Praxillella affinis
Chaetoderma nitidulum
Ophiodromus flexuosus
Cirratulus spp.
Balanus crenatus
Parougia caeca
Paramphinome jeffreysii
Caulleriella alata
Poecilochaetus serpens
Autolytinae spp.
Chaetozone spp.
Eteone longa
Apporhais spp.
Capitella spp.
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Ophryotrocha spp.
38.5
Thyasira spp.
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Pholoe inornata
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Glycera alba
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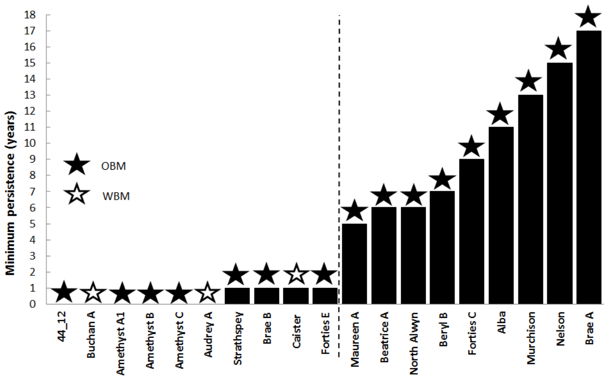
Minimum persistence (years)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
OBM
WBM
44_12
Buchan A
Amethyst A1
Amethyst B
Amethyst C
Audrey A
Strathspey
Brae B
Caister
Forties E
Maureen A
Beatrice A
North Alwyn
Beryl B
Forties C
Alba
Murchison
Nelson
Brae A

Highlights

- industry environmental data from 19 North Sea installations were analysed
- ecological impacts of drill cuttings reached 1.2 km away and lasted over 8 years
- new evidence-based recommendations for drill cuttings monitoring are provided
- OSPAR is urged to re-consider Decision 98/3 and widen the scope for derogation