Ecotoxicological effects of decommissioning offshore petroleum infrastructure: A systematic review

By

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Statement of Originality

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

(Signed)______________________________ Date: 07/01/2021
Amy MacIntosh

Declaration

This thesis is written in the form of a journal article intended for submission to Critical Reviews in Environmental Science and Technology.

I wish to acknowledge the following assistance in the research detailed in this thesis: This research is one part of a MRes + PhD bundle project made possible through funding from a collaboration between the Australian Nuclear Science and Technology Organisation (ANSTO), BHP Australia and Macquarie University (Project ID 113793469: Developing an ecological framework for closure of offshore petroleum structures). Additional funding assistance was from being a recipient of the New South Wales Industry Foundations Scholarship as part of the ANSTO Graduate Institute.

Abstract

Successful decommissioning of subsea oil and gas infrastructure requires a safe and effective approach to assess and manage waste products. These products, often present as scale on internals of pipelines, include naturally occurring radioactive materials (NORM) and trace metals. Understanding the potential biological effects of these contaminants on marine fauna is crucial to managing global decommissioning. A systematic review was conducted, and information extracted from available literature on the biological effects of contaminants on marine organisms and current environmental regulations of petroleum-associated NORM management. Studies defining the chemical and radiological effects from decommissioned structures were limited. The main source of contaminants was identified from offshore platforms, with none from subsea structures. Only three studies measured variable chemical effects of radium to organisms from scale materials in subsea oil and gas infrastructure. Current international regulations are absent for the closure of subsea pipelines with NORM being underreported and not addressed in environmental impact assessments. This review highlights research gaps from environmental monitoring and characterisation of NORM associated with decommissioned structures. Key recommendations for future research include using available techniques to monitor and characterise NORM scale and assess effects of scale to marine organisms through direct organism exposure experiments. This study provides guidance for the formation of appropriate risk assessments and decommissioning decisions incorporating ecotoxicological principles.

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COVID Impact Statement

Due to the unforeseen global COVID-19 pandemic, my original plans for this thesis had to be changed. Prior to the pandemic my study's aim was to assess whether naturally occurring radioactive material (NORM) radionuclides and trace metals associated with pipeline scale were bioavailable in Australian benthic marine organisms. COVID-19 caused the closure of ANSTO, thus I had to work from home on a desktop-based study. As there is limited literature on the ecotoxicological interactions between decommissioned structures and marine fauna, I chose to conduct a systematic review to investigate the knowns and research gaps within this field of research. In doing so, this thesis links into my future PhD studies aimed at assessing how NORMs and trace metals from pipeline scale are bioaccumulated in benthic marine organisms and any effects to organisms as a result. This thesis delivers new knowledge on the potential ecotoxicological interactions of scale residues associated with the offshore petroleum industry.

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This thesis is dedicated to my Papa who peacefully passed away in March 2020.

Firstly, I personally want to thank and acknowledge my incredible ANSTO supervisor Dr. Tom Cresswell for his time and commitment towards guiding me through the 'blackhole' of decommissioning research. Thank you for all the support and feedback this past year, especially the regular coffee hangouts to talk about this project. Thank you for your emotional support and pastoral care during the times of COVID. Here's to the coming years of incredible NORM research.

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Finally, to my loving and supportive parents back home in New Zealand, my grandparents in Tasmania and other members across Europe and the United States. Thank you for the support (and keeping safe) during COVID. I hope this thesis is something positive and exciting from this isolating pandemic. To my closest friends and extended family, I have missed you and thank you for giving me the confidence and resilience to keep going throughout the year (Special mention to Panayiotis, Michelle and Hamza).

Australian context of the broader study: Decommissioning-related environmental risk assessments

Australia is a leading energy exporter in offshore oil and gas resources (Pradella et al. 2014, Cullinane and Gourvenec 2017, Sommer et al. 2019, McKay et al. 2020). In 2015, total energy exports were approximately $59.8 billion with oil and gas accounting for 40% (Office of The Chief Economist 2017). As of 2018, the gross value of the petroleum industry added a gross value added (GVA) of approximately $31.4 billion AUD (Australian Bureau of Statistics 2020). By 2040, it is estimated over 100 offshore installations off the coast of Australia and in territorial waters will have been abandoned or will require decommissioning and likely face abandonment (McKay et al. 2020).

Even though there are defined regulatory frameworks for new exploration and development phases, a recent report published by the National Energy Resources Australia (NERA) ranked Australia at the bottom of the 30 major oil and gas producing countries for infrastructure abandonment (Cullinane and Gourvenec 2017). A 2015 Interim Report from the Offshore Petroleum Resource Management Review illustrated substantial work needs to be executed to form a standard risk framework for decommissioning oil and gas infrastructure (Chandler et al. 2017). This has been as a result of a "lack of clarity around policy and regulatory requirements for decommissioning offshore petroleum facilities in Commonwealth waters" (DISS, 2015). The current decommissioning requirement (in Australia) is for operators to completely remove their offshore oil and gas infrastructure (NOPSEMA). However, there is the opportunity for infrastructure abandonment under certain circumstances and where it is deemed to be environmentally acceptable (NOPSEMA, 2016; Department of Mines, Industry Regulation and Safety, 2017). Consequently, stakeholders need to demonstrate that minimal harm to marine biota (and human consumers) will occur from the deterioration of such infrastructure and exposure to any associated contaminants.

Environmental risk assessments are required for decommissioning infrastructure in Australia (in the form of Environmental Plans submitted publicly to the regulator, NOPSEMA) and need to show clear identification of likely risks from dissolved and sediment-associated trace metals, such as mercury and naturally occurring radioactive material (NORM) (NOPSEMA 2020). The exact impacts of pipeline decommissioning will depend on the specific marine species and their tolerance to disturbance or exposure to toxic contaminants. Yet, there is a relatively high number of infrastructure nearing end of field life with limited local decommissioning experience (REF). As a result, decommissioning may become one of the major issues facing Australia's offshore industry in the coming years, especially for the north-west shelf of Australia and Bass Strait (McKay et al. 2020). Until 2060, the predicted NORM inventory for Australia's decommissioned offshore assets is estimated to be between 223-1674 tonnes (McKay et al. 2020). Therefore, Australia urgently needs a decommissioning policy and risk assessment framework that balances economic, social and environmental perspectives (Bills, 2018; Techera et al., 2015; Cullinane et al., 2017; Chandler et al., 2017). For Australia to advance in environmental awareness and sustainable decommissioning strategies, a review of current knowledge on the risks of impact to marine biota from offshore petroleum-associated contaminants needs to be assessed.

This thesis delivers a review of the global perspective and outlook on current knowledge of contaminants associated with decommissioned offshore infrastructure and the potential toxicological interactions of NORM to marine organisms. This will assist Australia to direct research towards interdisciplinary environmental sciences to establish the appropriate decommissioning strategies for offshore oil and gas operations.

Marine ecotoxicological effects of offshore petroleum infrastructure-associated contaminants: A systematic review

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1. Introduction

1.1 Decommissioning of oil and gas infrastructure

Since the commencement of the modern offshore oil and gas industry in the Gulf of Mexico in 1947, there has been an increase in the exploitation of seafloor petroleum resources to meet the growing global demand for energy (Aagaard-Sørensen et al. 2018). Currently, it is estimated there are over 6,000 operating platforms worldwide extracting resources (Lakhal et al. 2009, Techera and Chandler 2015). Many of these facilities will reach the end of their operational life when it becomes no longer economically viable to continue production and will then be subject to closure conditions (decommissioned) (Bernstein 2015, Al-Ghuribi et al. 2016, Cullinane and Gourvenec 2017, Barrymore and Ballard 2019, Bull and Love 2019, Birchenough and Degraer 2020).

The various types of structures associated with offshore petroleum production (including installation platforms; fixed to the seabed, rigs; moveable platform, jackets; steel frame support and wells, pipelines) require different decommissioning options, that consider environmental, economic, human safety and engineering factors (Schroeder and Love 2004, Macreadie et al. 2011, Henrion et al. 2015, Day et al. 2018, Fowler et al. 2018, Macreadie et al. 2018b, Fowler et al. 2019). This can range from removing all infrastructure from the seabed or leaving *in situ*, with no intervention or with several encapsulation or burial options (Figure 1; Bull and Love 2019)**.** By the end of 2020, at least 600 structures within the major petroleum export countries are forecast to cease operation and subsequent decommissioning operations are expected to significantly increase between now and 2040 (Hem et al. 2016, Sommer et al. 2019). The costs of decommissioning is significant and is forecasted to increase as more assets are to undergo closure, creating large economic liabilities (Invernizzi et al. 2020). For example, in 2020, offshore oil and gas decommissioning in the United Kingdom's continental shelf is projected to cost £51 billion ($68 USD) and within oil and gas operations in the Asia-Pacific, total removal of 7.5 million tonnes of steel and 55,000 km of pipeline is estimated to cost over US$100 billion (Oil and Gas Authority, 2020). Although environmental risk frameworks exist for the exploratory and operational phases of offshore petroleum, the ecological and environmental risks associated with the decommissioning stage are not fully understood.

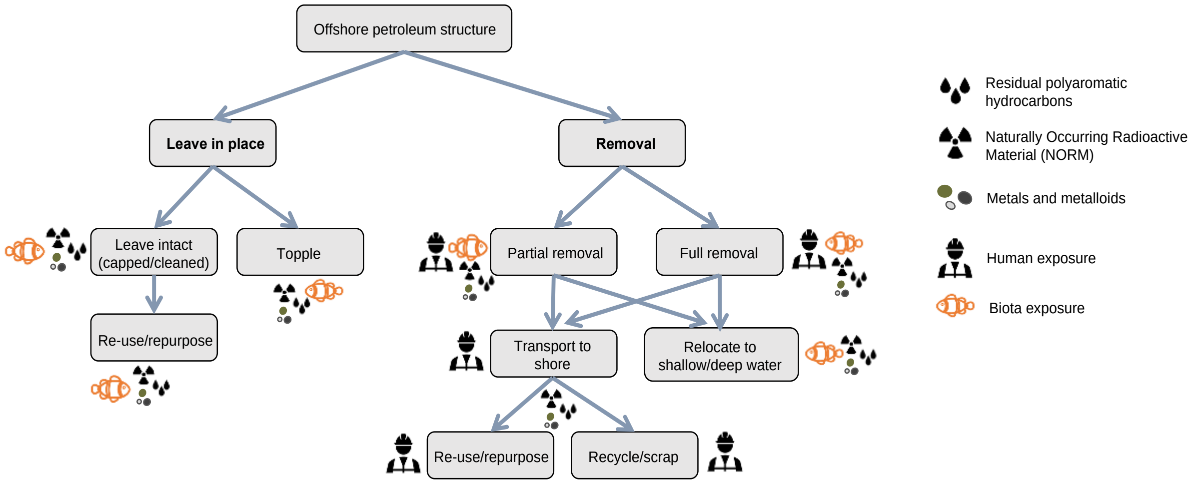

Figure 1 Decommissioning options for offshore facilities and likely associated presence of assorted contaminants at each option. Adapted from Fowler et al. (2014)

The effects and impacts of operational processes and petroleum spillages have been globally recognised. To date, the focus of the potential environmental effects in the oil and gas sector has been on carbon emissions and oil spill events, e.g. Deepwater Horizon (c. 2010) and Exxon Valdez oil spill (c. 1989) (Duffy et al. 1994, Lance et al. 2001, Page et al. 2002, Palinkas 2009, Allan et al. 2012, Eckle et al. 2012, Franci et al. 2014, Fukuyama et al. 2014, Echols et al. 2015, Liu et al. 2016, Lotufo et al. 2016, Turner and Renegar 2017, Ainsworth et al. 2018, Fernando et al. 2019, Wise et al. 2020). These have ongoing detrimental impacts on the shorelines, wildlife, marine plants and the hydrochemical profile of the ocean (Eckle et al. 2012, Amezcua et al. 2014, Soto et al. 2014, Sun et al. 2015). Even though there is a thorough understanding of the contaminants associated with operations and spillages, little is known about potential contaminants released during decommissioning. Operators are recommended to demonstrate that decommissioning activities will have minimal impact on the surrounding marine biota (Burdon et al. 2018a, NOPSEMA 2020). The decommissioning process has the potential to affect marine organisms through physical impacts and release of contaminants (Burdon et al. 2018a). Understanding these contaminant effects are important, but we also need to know what the entire suite of contaminants are associated with decommissioned structures. All structures are susceptible to contamination, including the presence of hazardous materials such as trace metals (e.g. mercury, arsenic, lead), residual hydrocarbons and naturally occurring radioactive materials (NORM; Figure 1). Such impacts may include reduced fisheries productivity, discharge of contaminants creating localised water and sediment contamination, and potential acute and chronic effects to marine biota (Cripps and Aabel 2002, Johannessen et al. 2007, Almeida et al. 2012, Almeda et al. 2014, Rouse et al. 2018, Rouse et al. 2020). Even with the projected large-scale decommissioning of infrastructure, the long-term environmental impacts from associated contaminants are often overlooked.

However, metals (e.g. mercury, lead) and NORMs are often overlooked. Many jurisdictions adopt marine environmental quality guidelines covering threshold concentrations for metals and hydrocarbons in waters and sediments to protect marine ecosystems and biota e.g. Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZG), National Oceanic and Atmospheric Administration (NOAA), Canadian Marine Sediment Quality Guidelines (Burton 2002). Guidance, advice and recommendations for the management and application of guidelines for NORM in industry are provided by the International Atomic Energy Agency (IAEA) exempt levels for low-level radioactive waste; concentration of a radionuclide that may result in doses to humans. These exclusion activity concentrations for NORMs are 1 Bq/g i.e. if levels of NORM radionuclides are below the exempt threshold, there is no regulatory concern. However, no such exemption levels for non-human biota exposure or marine ecological guidelines are available for NORM (IAEA 2004).

1.2 Naturally Occurring Radioactive Material (NORM) in offshore petroleum infrastructure

Uranium (^{238}U) and thorium (^{232}Th) naturally occur in petroleum reservoirs along with their radioisotope decay daughter products (Nelson et al. 2015, Ali et al. 2019). Uranium and thorium are relatively insoluble and often remain within the reservoir, although their decay products (e.g. radium) may be soluble within the reservoir and therefore extracted with oil and formation water (Kolb and Wojcik 1985). Once the soluble cations e.g. barium (Ba) and radium (Ra), have been exceeded within a solution such as the oil and formation water stream, precipitation and/or deposition of NORM may occur at various points along production infrastructure, along with co-occurring metal contaminants (e.g. mercury and other metalloids) in the form of scale (Figure 2). On older, uncleaned pipes, the resulting accumulation of scale can reduce the internal diameter of pipelines, thereby reducing the flow rate or increasing the pressure within the pipe. This may result in significant economic costs associated with reduced production or internal cleaning via mechanical and chemical means (Read 1958, Vetter and Phillips 1970, Vetter et al. 1982, Todd and Yuan 1992). Increased salinity of formation water results in a higher accretion rate of NORM scale within flowline infrastructure and thus can increase the economic costs of management (Shawky et al. 2001, Otumudia and Ujile 2016).

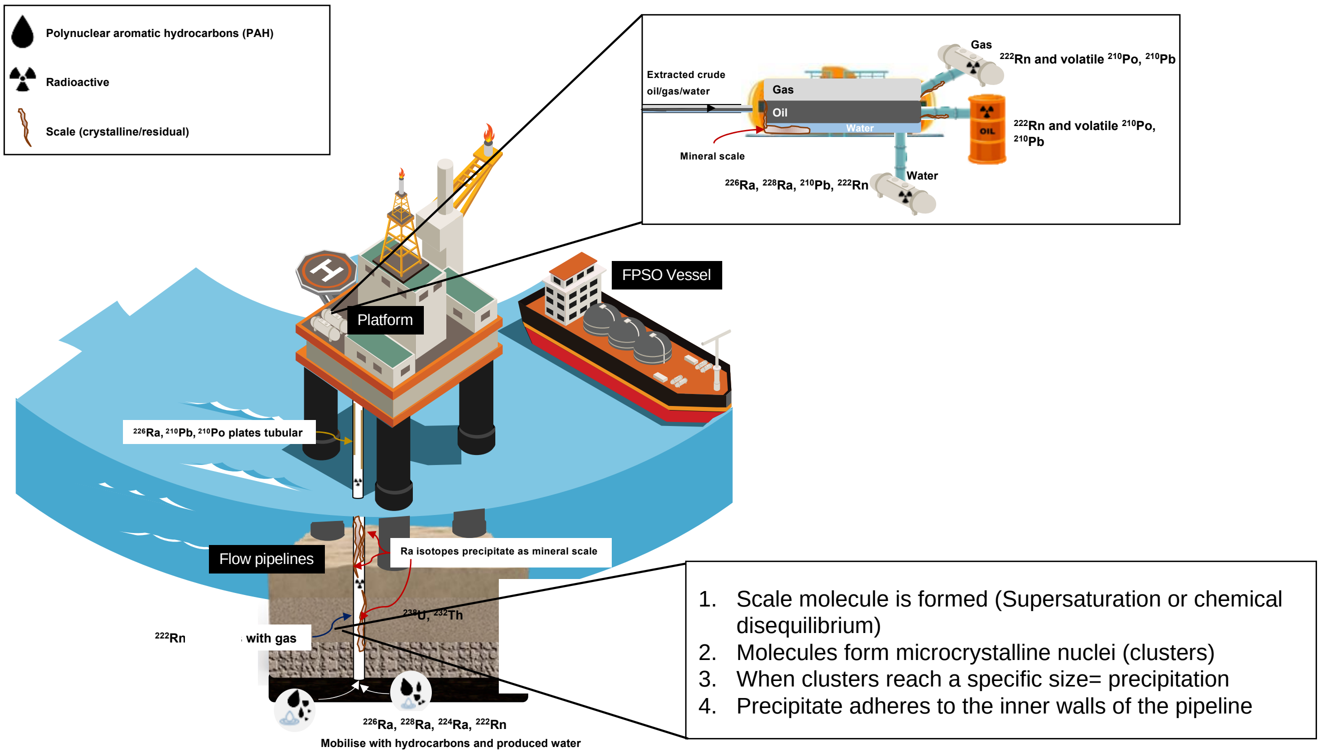

Figure 2 The origins, formation and location of NORM in the offshore hydrocarbon production process. Rn, radon; Ra, radium; Pb, lead; Po, polonium; U, uranium; Th, thorium. Adapted for offshore petroleum operation using an illustration created by International Association of Oil & Gas Producers 2008.

The degree of NORM accumulation can vary substantially from one facility to another depending on many factors including the geological formation, environmental features (e.g. depth/pressure, acidity of formation water, ambient temperature), infrastructure material and operational practices of extraction (Mitchell et al. 1980, Heaton and Lambley 1995, Godoy and Petinatti da Cruz 2003, Abo-Elmagd et al. 2010, Doyi et al. 2016, Abdelbary et al. 2019, Ali et al. 2019). For example, in Italy and Syria, scale is often composed of carbonates in contrast to Brazil, Kazakhstan and Egypt containing very few carbonates, sulphates and silicates (Testa et al. 1994, Vegueria et al. 2002, Godoy and Petinatti da Cruz 2003, Al-Masri 2006, Abdelbary et al. 2019)**.** However, ubiquitous components of scale present among countries and petroleum structures include barite ($BaSO_4$), strontium sulfate ($SrSO_4$) and calcium carbonate ($CaCO_3$) with barite receiving the most research attention thus far **(**Payne et al., 2006; Neff, 2008; Schaanning et al., 2011; Canet et al., 2014; Fang et al., 2018).

1.3 Biological exposure and interactions of marine biota with NORM

Petroleum scale can make NORM and other non-hydrocarbon constituents directly available to organisms *in situ* or through release into the surrounding benthic environment. While pipeline scale is not a sediment contaminant, once the pipe corrodes (following a "leave in place" decommissioning strategy) the scale will deposit on and mix with the surficial layer of sediment. Benthic and pelagic communities may then be exposed to associated contaminants through dietary ingestion of particulate and dissolved particles or external adsorption through the exoskeleton (Rainbow 1992). Interactions between marine organisms and scale-based contaminants depends on the dissolved and particulate concentrations, but also the organism's feeding behaviour and physiology (Eggleton and Thomas 2004, Simpson et al. 2005, Simpson and King 2005). Organisms inhabiting offshore petroleum structures in close contact with scale or other petroleum sediment-associated contaminants, may bioaccumulate contaminants and suffer subsequent ecotoxicological effects from the chemical and radiological properties of the scale material (Hosseini et al. 2012).

Biological exposure to radioactive material, both artificial radionuclides (e.g. radiocaesium; ^{137}Cs, radioiodine; ^{131}I, radiostrontium; $^{89/90}$Sr) and NORM can cause detrimental biological effects on one or more levels of biological organisations (individuals, populations, ecosystems) or up the trophic chain , including increased risk of mortality, oxidative stress, neurological and physiological disorders, genetic mutations and reduced reproductive success (Jackson et al. 2005, Bréchignac et al. 2016, Real and Garnier-Laplace 2019). Coincidentally, studies on the radiotoxic and chemotoxic effects are common for small mammals (Beresford et al. 2008), aquatic fish (Jonsson et al. 1999), plants (Kovalchuk et al. 2004, Penrose et al. 2015) and birds (Hermosell et al. 2013, Galván et al. 2014), with limited studies on NORM in the marine environment. The dose, exposure pathways, duration of exposure to contaminants, and biological responses differ between terrestrial and marine organisms. However, few studies have been conducted in the marine environment to understand how each of these factors influences the toxicology of NORM. Therefore, potentially affected marine biota may not conform to the wider understanding of multiple stressor effects from radiation and trace metals. The presence and release of radionuclides into the marine environment sourced from decommissioned infrastructure can expose marine fauna to different forms of ionising radiation (IR); internal doses from alpha (α), beta (β), gamma (γ) and external doses from beta (β) and gamma (γ) (Vives i Batlle 2012). However, knowledge is limited on the chemotoxic and radiotoxic effects from NORM, dose rates emitted from scale constituents and other petroleum-associated contaminants, the form of radiation, and the effect thresholds that signal potential benchmark toxicity.

In order to better inform *in-situ* decommissioning strategies, a review of current knowledge on the presence of contaminants associated with offshore petroleum infrastructure and potential interactions between contaminants and marine biota is required. This evidence will facilitate appropriate decommissioning decisions that will optimise outcomes, considering the impacts on the overall marine environment, inhabiting wildlife, engineering and ideal economic strategy for stakeholders.

The aims of this systematic review were to: (1) synthesise current literature on the presence of contaminants associated with decommissioning of oil and gas offshore infrastructure and (2) evaluate the possible radiological and ecotoxicological effects of NORM contaminants associated with infrastructure by assessing the biological responses to NORM exposure. Additional targeted information was extracted after the systematic review process on global and regional decommissioning guidelines, regulations and management as related to contaminants, including NORM. We identified significant research gaps that should be addressed in future studies.

This review provides recommendations for standardising decommissioning policies across jurisdictions, and proposes a framework for the collection, processing, analysis and interpretation of environmental samples around offshore infrastructure to identify contaminants of primary concern.

2. Methodology

2.1 Literature search

A systematic literature review was conducted from May to September 2020 to capture available literature to meet the following aims: 1) to identify the contaminants associated with decommissioned petroleum infrastructure; and 2) evaluate the ecotoxicological effects of NORM on marine biota. The protocol used for the systematic review was a tiered, two stage screening process following the Reporting Standards for Systematic Evidence Synthesis, (ROSES; Haddaway et al. 2018; Figure 3). To address the two aims, two separate searches (search 1 and search 2) were conducted using the ISI's Web of Science (all databases) and Scopus (Figure 3). Searches in Google Scholar were utilised to identify additional sources of peer-reviewed literature and publicly available grey literature by using the first 50 references as sorted in the relevance ranking (Haddaway et al. 2015). No access was available to commercial-in-confidence reports. All searches used English search terms and studies were limited to English language publications, with no restriction on publication date. Only peer-reviewed literature was systematically reviewed, therefore grey literature may have contained data appropriate for this review that was inaccessible.

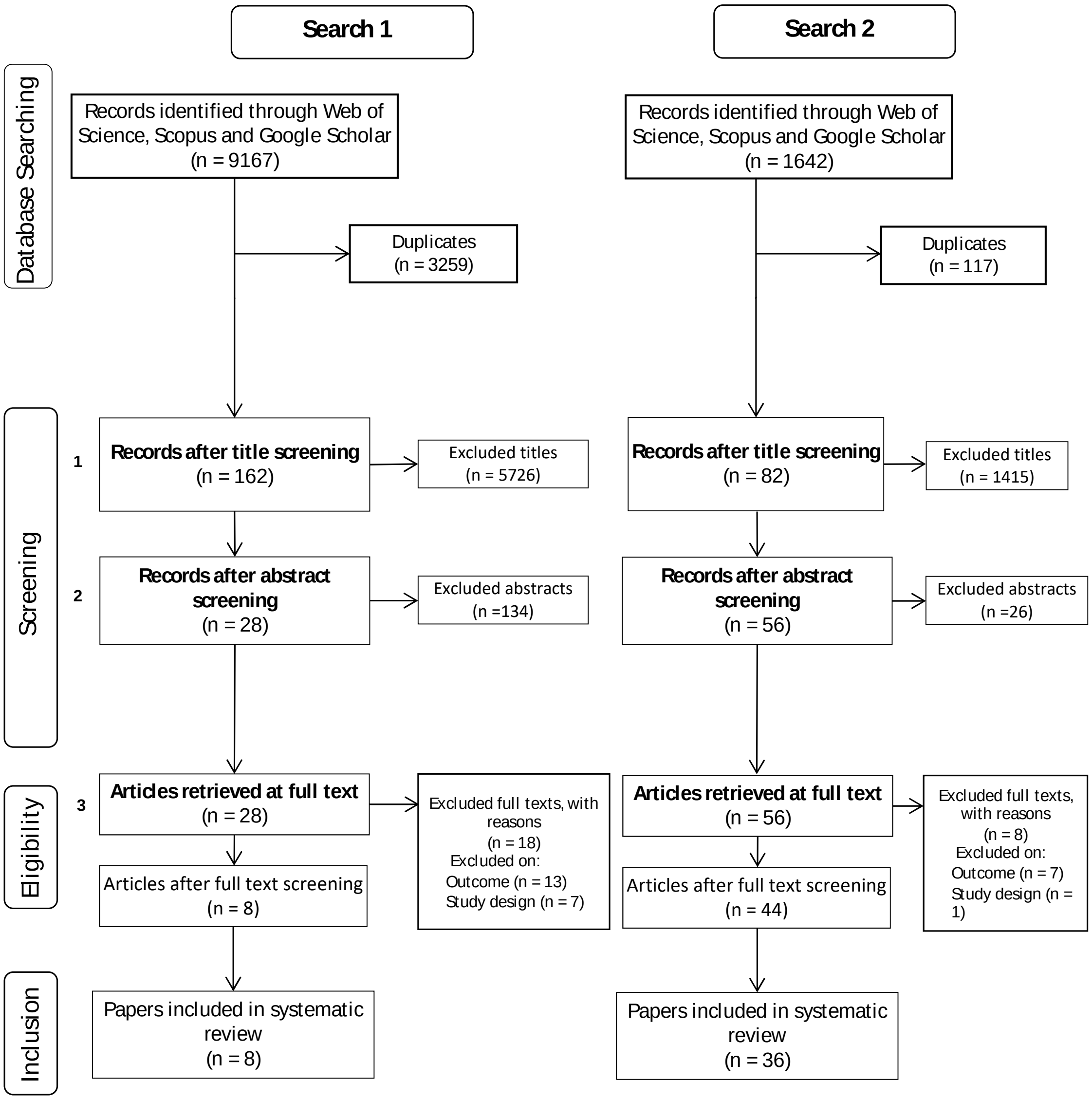

Figure 3 ROSES flow diagram illustrating the tiered procedure for the selection of studies for inclusion in this systematic review. Search 1 identified literature on contaminants associated with the decommissioning process and search 2 identified literature investigating the potential ecotoxicological effects of naturally occurring radioactive material (NORM) on marine biota. The tiered screening followed assessing the papers at the title, abstract and full-text level. Numbers and bolding represent the three stages of screening. Eligibility was measured by if papers met the respective inclusion criteria. Data were recorded from all 44 included papers.

A scoping exercise to gather appropriate search strings was conducted which included checking published reviews and consultation with experts from academia and oil and gas industry personnel. Search terms for intervention/exposure of biological organisms to offshore structures were formulated using published reviews on the topic of offshore petroleum infrastructure decommissioning and discussion with industry experts. No terms for taxa were included, as scoping indicated different taxonomic resolutions are used in different studies, which cannot be captured using taxa group names. All search terms were truncated and written with a wildcard at the end to include alternative forms of the word, alternative spelling and hyphenation of words, if relevant. Scoping revealed many articles on the unrelated topics of freshwater and terrestrial environments or studies focusing on human exposure, medicinal health, seafood, offshore wind farms, biofouling paints, agriculture, soil and land-based contaminants. Related words to these topics were included in the search with the Boolean NOT operator to exclude results when possible (Supplementary Table 1).

To evaluate the accuracy and comprehension of the search strategy and search terms, a test list of articles from a recent review on decommissioned infrastructure was used as a benchmark to compare with the search results (Love et al. 2013, Fraschetti et al. 2016, Fujii and Jamieson 2016, Aagaard-Sørensen et al. 2018, Bond et al. 2018a, Bond et al. 2018c, Bull and Love 2019, Lacey and Hayes 2019, Love 2019, McLean et al. 2019). If any articles were found to be absent from our results, the search string was amended.

The sets of search criteria contained the major terms related to offshore petroleum decommissioning, combined with terminology related to associated contaminants are included in Supplementary Table 1.

The search strings targeting studies assessing the ecotoxicological effects of different types of radionuclides from the ^{238}U and ^{228}Th decay chains were performed separately, in combination with ecotoxicological terminology (Supplementary Table 2). The following variations of search strategies were performed on the titles, keywords and abstracts used in each database:

Aim 1 Search: (oil* OR petroleum* OR gas* OR offshore*) AND (decommission* OR abandon* OR clos* OR remov* OR infrastructure* OR man-made structure* OR subsea* OR jacket* OR pipeline* OR well* OR vessel* OR platform* OR artificial reef*) AND (drilling* OR barite* OR pipeline* OR rig* OR produced*)

AND (metal* OR trace* OR radio-* OR NORM* OR persistent organic pollutants* OR waste* OR poly-* OR hydrocarbon-* OR PAH* OR BTEX* OR plastic* OR discharge* OR contamin-* OR pollut-* OR environment-* OR monitor-* OR copper* OR lead* OR mercury* OR cadmium* OR polonium* OR uranium* OR thorium* OR radium* OR arsenic*)

Aim 2 Search within the results of the naturally occurring radioactive contaminants (NORM) identified from search 1. (organism* OR animal OR biota OR vertebrate OR invertebrate AND effect* OR impact* OR exposure* OR uptake* OR toxic-* OR physiol-* OR reprod-* OR gene-* OR behaviour-* OR divers-* OR ecotox-* OR ecolog-* OR biolo-* accumulation* OR bioaccumulation* OR benthic* OR pelagic* OR fish* OR community* OR crusta-* OR fauna* OR bioacculm-* OR uptake*)

The search results for the final search strings were imported into EndNote X9.3 for further screening, with duplicates removed (additional information available in online data repository). To ensure the review captured all available literature, the imported articles were checked to confirm the results included all the test list articles. Search 1 resulted in 5888 papers and Search 2 resulted in 1497 papers.

2.2 Article screening and study inclusion criteria

Following the ROSES procedure (Haddaway et al. 2018) articles for both respective aims of the review were included if they were: 1) available in their full text (e.g. publications without an abstract, conference paper, individual case reports and official presentations were excluded); 2) original research (e.g. review papers and cumulative studies were excluded); 3) directly involved a type of offshore petroleum infrastructure-associated contaminant; 4) manipulative, experimental or observations from environmental monitoring surveys and assessments; 5) supported by appropriate controls (e.g. for observational studies, experimental controls are needed for comparisons with exposed treatments or impacted petroleum sites); and 6) about marine animals (additional information available in Supplementary Material).

For the first and second tier respectively, titles and abstracts were screened to evaluate the relevance to this study, and those deemed outside the scope of the review (did not meet the inclusion criteria) were excluded from further evaluation (Figure 3). After screening of the abstracts, 28 papers from search 1 and 56 papers from search 2 met the inclusion criteria (Supplementary Table 3).

Any article where relevance was not certain from the screening process alone remained included for full text review. The full text of articles that remained after screening were read to determine if the article met all the inclusion criteria (search 1 n=8; search 2 n=36). At each stage, a subset of 10% (n= 10) of the articles were assessed by all authors to check for consistency in inclusion decisions. In no cases did authors disagree on the eligibility of the papers for inclusion in the systematic review.

Reference and citation lists of relevant literature were also screened, following the same criteria to identify other appropriate studies not found by the initial search. Other studies conducted by the same authors were also checked for suitability, however none were suitable. All articles excluded at the full text stage (n=26) were included in a separate list with each article's reason for exclusion (Supplementary Table 4 and 5).

2.3 Quantitative and qualitative analysis

Once appropriate studies were screened (n=8 for search 1, n=36 for search 2), data were manually extracted and reported as a descriptive synthesis. For both searches, we recorded bibliographic information (year of publication, year of study, title) and geographical information (continent, country, study location, latitude/longitude). Information recorded from the eight studies identified by the first search included the type and design of the study (e.g. laboratory, field, appropriate controls, Before-After-Control-Impact (BACI), sample size), sampling point (e.g. proximate location to structure, pre/during/post operation, season of sampling, year of sampling), contaminant class (e.g. NORM, metals and metalloids, hydrocarbons), contaminant name (e.g. cadmium, polyaromatic hydrocarbon), concentrations of contaminants, type of infrastructure (e.g. jacket, pipeline, platform, vessel), decommissioning option (if applicable), source or process leading to contaminant (e.g. surface discharges and releases, seabed and water column discharges, accidental discharges and releases from vessels, produced water, drilling waste, contained within infrastructure), background levels (control/reference site, locally acquired, temporal, inferred from another study).

For the second search, information recorded included the type of study (laboratory or field experiment), duration of the experiment, source of NORM (natural, anthropogenic), number of replicates, treatment and control groups, sample size, type of NORM, exposure concentration, biological information of the study species (phylum, species, functional group, life-history stage, sex), level of ecotoxicological effect measured (individual, population, community), type of effect measured (cellular: genetic, biochemical, or individual: mortality, reproduction, behaviour, physiology, or population/community), measures of effect (mean, SE) for control and exposure groups, any underlining assumptions relating to NORM dose exposure/uptake/effects.

For the respective research question, quantitative data were recorded and coded in a Microsoft Excel spreadsheet. Data from Search 2 was originally extracted for use in a meta-analysis, but insufficient data were available. Information was therefore summarised in graphs, tables and trends interpreted qualitatively. In instances where no raw data were presented, but data were presented in figures, the GetData Graph Digitizer program version 2.25.0.32 (www.getdata-graph-digitzer.com) was used to extract means and standard deviations. If relevant data could not be extracted, the corresponding author of the article was contacted to request the information.

An additional database was created of current offshore decommissioning jurisdictions and their associated decommissioning regulations from across the world. Specifically, countries identified by the literature searches as potentially having relevant decommissioning guidelines, regulations and management for contaminants were included in targeted searches through Google Scholar to identify the associated literature. This search was complimentary of the major aims of the systematic review, to provide additional information and evaluations of the main components and potential issues of the decommissioning process on a global and regional level. Jurisdictions were assessed from countries that currently participate in offshore petroleum activities and have available documentation on decommissioning regulations and additional jurisdictions regarding environmental law and regulations. Information about trends and gaps in current environmental impact assessments (EIA), contaminants of primary concern and overall decommissioning process for all types of infrastructure was collated.

3. Results and Discussion

3.1 Offshore-associated petroleum contaminants: geographic focus, study period and methodologies

Of the initial 162 papers considered, only 8 studies assessed the presence of contaminants directly associated with offshore petroleum infrastructure. However, no studies investigated decommissioned infrastructure, instead all were focused on pre-drilling, drilling and post-drilling operations. Most studies were conducted in Europe (n=4) and North America (n=2), with single studies in Africa and South America (Figure 4a). No studies were identified from Asia, Australia and the rest of Oceania through the systematic review. The majority of research was done 10-20 years ago with each assessment focused on a particular geographical location and conducted in consecutive years (Figure 4b).

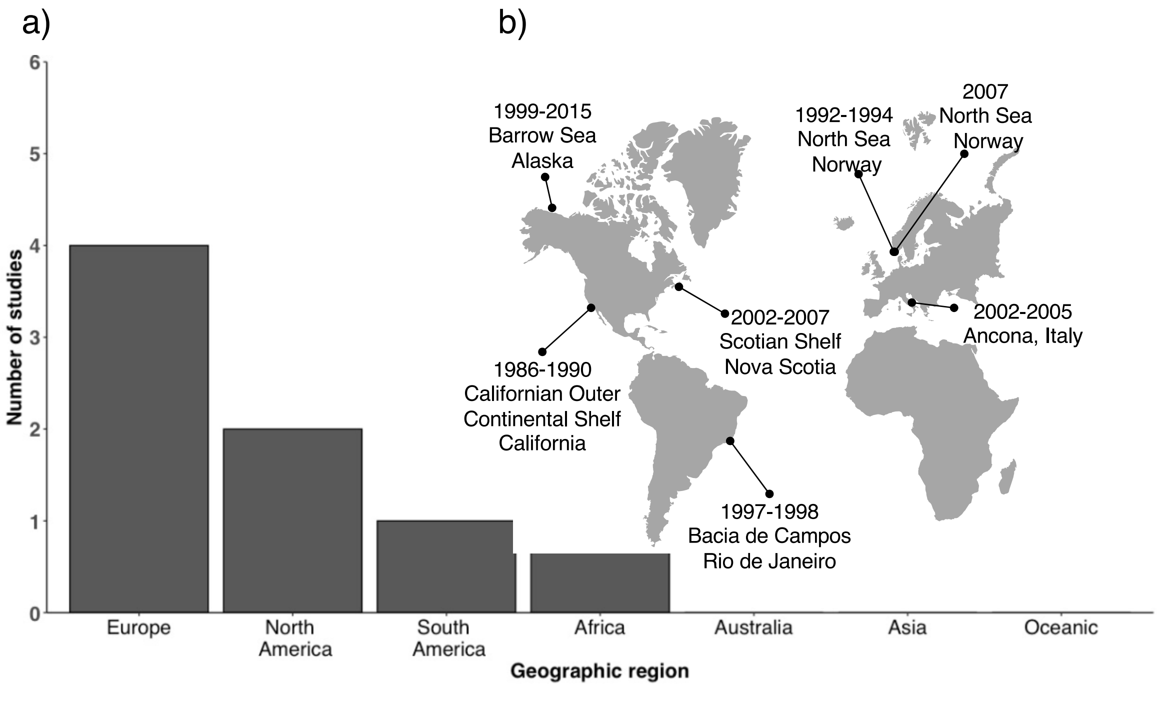

Figure 4 a) The number of studies and geographic region of each study monitoring the presence of offshore petroleum infrastructure-associated contaminants (N=8); b) The geographic region (country or coastal city) and the time scale of the eight studies.

Studies predominantly consisted of field-based surveys in the form of BACI designs (n=3), following standard environmental impact assessments techniques such as a) radial designs by allocating samples according to distances from infrastructure and b) transect designs using distance interval radial transects around infrastructure. Laboratory experiments or robust comparative *in-situ* surveys with appropriate control sites and quality assurance/control measures were rare (n=2). Only two studies had a control or reference site for comparisons with environmental background levels (Yeung et al. 2011, Okogbue et al. 2016), whilst three studies inferred background levels from other papers (Steinhauer et al. 1994, Gomiero et al. 2011a, Dowdall and Lepland 2012). Two studies examined the effect of season variability (i.e. dry and wet season, summer and winter) (Durell et al. 2006, Okogbue et al. 2016).

3.2 Contaminant classes, sources and associated infrastructure

Several studies (n=5) assessed more than one contaminant, with a combination of predominantly hydrocarbons (total polynuclear aromatic hydrocarbons, BTEX, total alkanes, phenols) and trace metals. The common alkali-earth metals, transition metals and metalloids (hereafter referred to as metals) analysed were barium, zinc, arsenic, cadmium, chromium, copper and lead (Figure 5). Only two studies investigated NORM and quantified the presence of various radionuclides (^{226}Ra, ^{228}Ra, ^{40}K), and none assessed the daughter radionuclides (e.g. ^{210}Pb, ^{210}Po, ^{228}Th).

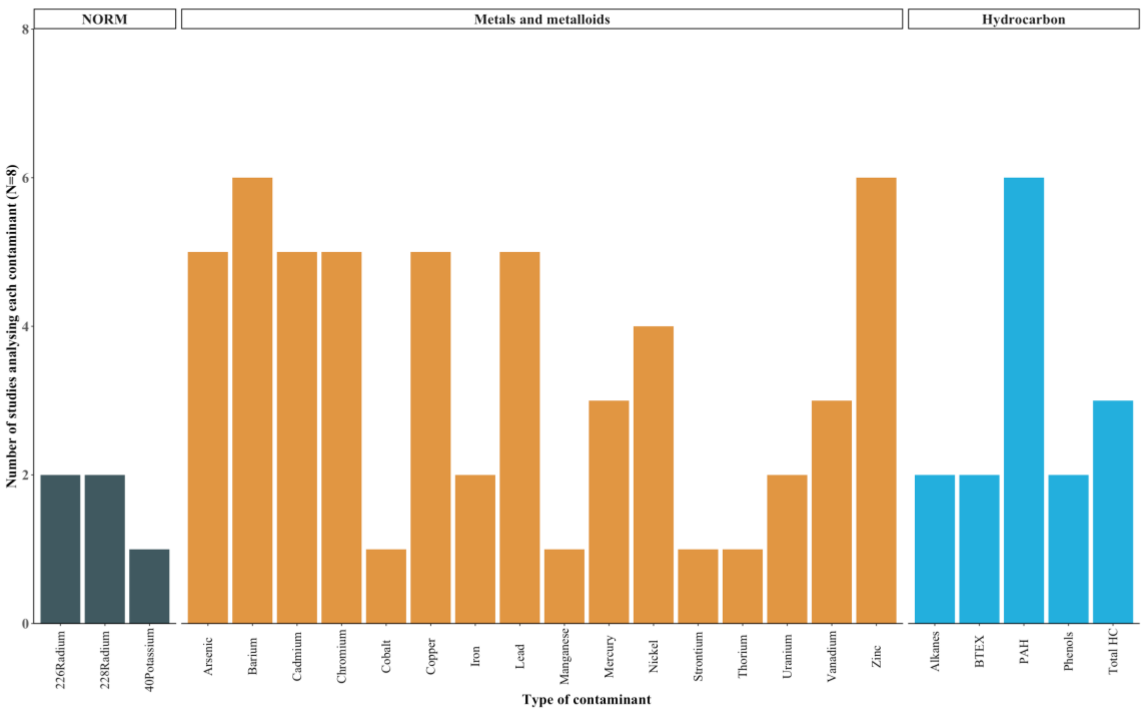

Figure 5 Contaminant classes associated with offshore petroleum processes and infrastructure identified from the literature with the number of studies assessing the presence of each contaminant class (n=8). Grey= Naturally Occurring Radioactive

Material (NORM); Orange= Trace metals; Blue= Hydrocarbons. BTEX= benzene, toulene, ethylbenzene and xylene; PAH= Polyaromatic Hydrocarbons; Total HC= Total hydrocarbons (primary data available in data repository).

Elevated concentrations of metals (Pb, Ni and Zn) and Ba (often in the form of barite; $BaSO_4$, added to drilling mud to increase the density) relative to background levels and applied sediment quality guidelines were reported in most studies (Table 1). Gomiero et al. (2011b) found elevated concentrations of Ba and Zn from one month to three years after drilling operations. Attin et al. (2008) analysed an unknown number of drilling mud samples taken from a database of trace metal concentration recordings from the vicinity of petroleum installations in Norway. No numerical means were provided, instead the range of various metal concentrations (Ba, Ni, Pb, Zn) were above the environmental Default Guideline Values for Australia and New Zealand (Table 1).

Table 1 Studies included in this review with elevated concentrations of offshore petroleum-associated contaminants above the Australian and New Zealand sediment quality guidelines; indicated in **bold** (ANZG 2018). From each study, concentrations were retrieved from pre-drilling, during operations and post-drilling sampling events. PAH- polyaromatic hydrocarbons; Ba- Barium; Pb- Lead; Ni- Nickel; Zn- Zinc. DGV- Default Guideline Value for sediment. The sediment DGVs are intended to indicate the concentrations below which there is a low risk of adverse effects occurring to benthic organisms.

Author	**Year of study**	**Contaminant analysed**	**Source or process of origins of contaminant**	**Pre-drilling mean concentration (mg/kg dw) (sampling year; sample size)**	**During operations mean concentration (mg/kg dw) (sampling year; sampling size)**	**Post-drilling mean concentration (mg/kg dw) (sample year; sampling size)**	**ANZG sediment DGV (mg/kg dw)**
Steinhauer et al.	1994	PAH	Discharges from platform to seabed (sediment)	**55** (1986)	-	**48** (1990)	10
		Ba	Discharges from platform to seabed (sediment)	752 (1986)	-	862 (1990)	NA
		Ba	Drilling mud[a]	-	107782	-	NA
		Ba	Drilling cuttings[a]	-	5200	-	NA
		Pb	Drilling cuttings[a]	-	**1926**	-	50
		Ni	Drilling mud[a]	-	**41**	-	21
		Ni	Drilling cuttings[a]	-	**67**	-	21
		Zn	Drilling mud[a]	-	**290**	-	200
		Zn	Drilling cuttings[a]	-	**1346**	-	200
Attin et al.	2008	Ba	Drilling cutting near platform	-	(720-449000)*	-	NA
		Ni	Drilling cutting near platform	-	(3.8-19.9)*	-	21
		Pb	Drilling cutting near platform	-	(0.4-**4225**)*	-	50
		Zn	Drilling cutting near platform	-	(0.06-**12300**)*	-	200
Gomiero et al.	2011	Ba[b]	Sediment near platform	-	224 ± 9.4 (2003)		NA
		Ba[c]	Sediment near platform	-	323 ± 30.8 (2005)		NA

[a]- Sampled at five weeks of operations from the platform
[b]- Sediment samples were taken one month after drilling
[c]- Sediment samples were taken three years after drilling
*- Only the range concentrations were reported. No means or standard errors were provided in the study

Ba and Zn are regularly found in produced water at higher concentrations than seawater, with the corrosion of offshore structures also identified as a source of Pb and Zn (Neff 2002a, Neff 2008b, Okogbue et al. 2016, Al-Ghouti et al. 2019). The accumulation of drill cuttings on the sea floor can also increase the concentrations of Ba and other metals in the sediments near the discharge point (Neff 2002b, Neff 2002a, Neff 2008a). Concentrations of Ba in drilling mud has been found to exceed 1000 mg/g near offshore drilling discharges (Steinhauer et al. 1994, Altin et al. 2008).

Steinhauer et al. (1994) sampled discharged sediment from a platform and found elevated Ba between pre-drilling (1989; treated as background levels) and post-drilling (1990) operations. When compared to current environmental quality guidelines, only the post-drilling concentrations of PAHs (48 mg/kg dw; n=31) were above the sediment quality value (SQV) of 10 mg/kg dw. The drilling mud and drill cuttings contained elevated levels of Ni (41 mg/g dw; 67 mg/g dw) and Zn (290 mg/g dw; 1346 mg/g dw) above the SQV. Okogbue et al. (2016) and Yeung et al. (2011) quantified contaminant concentrations from produced water and sediment, and all were below environmentally relevant guidelines (see raw data in online). Other metals quantified from all eight studies did not exceed the Australian and New Zealand sediment or marine water quality guidelines (raw data repository).

Dowdall and Lepland (2012) and Jerez et al. (2002) investigated the presence of radionuclides in archived sediments and produced water, respectively. Dowdall and Lepland (2012) found high levels of ^{226}Ra (19.9 ± 0.7 – 730 ± 56.7 Bq kg/dw) and ^{40}K (641 ± 116.9 – 730.7 ± 56.7 Bq kg/dw) from sediment cores surrounding eight offshore platforms. Jerez et al. (2002) analysed produced water from two platforms across two years of offshore operation, and found concentrations of ^{226}Ra and ^{228}Ra ranging from <0.01 to 6 Bq/L with a mean of 1.9 ± 0.17 Bq/L and <0.05 to 12 Bq/L with a mean of 2.9 ± 0.39 Bq/L, respectively. These studies illustrate the possibility that sediments and waters surrounding offshore infrastructure may contain petroleum-associated NORMs.

NORMs and Ba do not have associated environmental quality guidelines; therefore, no comparisons could be made to the studies reviewed here to deem if the operational and post-drilling concentrations were environmentally safe and posed low risks to biological organisms. Often offshore oil and gas companies and operators are unaware of the presence of radioactive material in environmental media such as sediment and water (Carvalho 2017). As Ba and Ra behave in a similar manner in the marine environment, the fate of Ba in drill cuttings or mud during operational activities could provide key information of the expected long-term fate and behaviour of Ra and the daughter radioisotopes during decommissioning (Carroll et al. 1993, Legeleux and Reyss 1996).

The main sources of contaminants identified from offshore petroleum activities were produced water, accidental discharges from vessels, drilling mud and surface sediment (cuttings discharged at seabed and drilling piles; Figure 6). Seven studies were associated with offshore platforms, whilst one focused on discharges from a FPSO (floating production storage and offloading) vessel (Okogbue et al. 2016). No studies assessed the presence of contaminants associated with other major structures, for example subsea pipelines, wells, jackets or rigs.

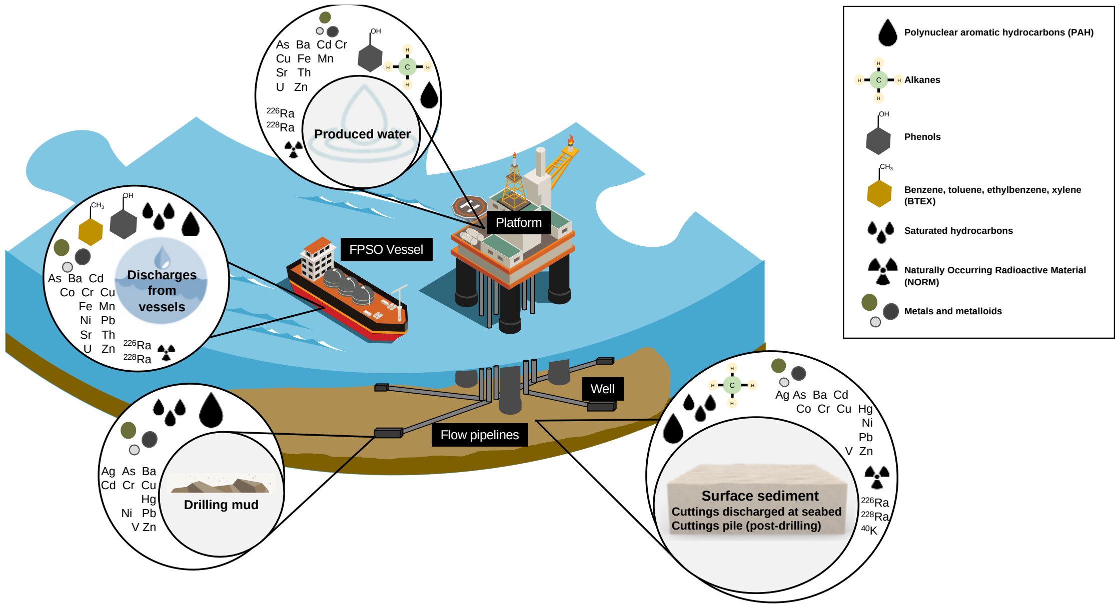

Figure 6. Key sources and activities related to the release and/or accumulation of offshore petroleum infrastructure-associated contaminants as reported from the literature (n=8). Original illustration was created by the primary author A.MacIntosh (2020)

3.2.1 Data limitations from available literature

Contaminant concentrations varied between studies due to differing sample collection and analytical methods and therefore direct data comparisons could not be performed. The variability of natural background concentrations and methodologies from industry-impacted studies (closed access to datasets and geoenvironmental surveys) limited the ability of this review to assess if non-hydrocarbon associated contaminants were elevated due to offshore petroleum infrastructure. The scope of this review may have also been limited by the lack of open access data on the topic. All of the papers screened were peer-reviewed public literature and none were grey literature i.e., industry reports. Given our knowledge of the extensive environmental monitoring in the oil and gas industry during operations, the small number of papers retrieved from the systematic search was likely influenced by the search terms, which limited results to studies specifically about decommissioning, rather than operations. This would have restricted the search outputs along with the inclusion and exclusion criteria of the systematic process. There are few long-term studies that collate insights into the potential long-term effects of offshore contaminants (Henry et al. 2017). As only peer-reviewed literature was systematically reviewed, the grey literature may contain data appropriate for this review that was inaccessible. Commercial-in-confidence industry reports, consultancy reports and environmental plans have the tendency to not be released to the public, therefore limiting the extent of accessible data from grey literature. Environmental contaminant data is often held as commercial-in-confidence by the issuing operator (consultation with industry expert). This creates challenges for industry, external research institutions and academic stakeholders. Here we have incorporated all the available literature to assess the likely presence of contaminants during decommissioning and highlight that future data transparency and consistent methodologies would further improve this assessment.

3.3 Ecotoxicological effects of petroleum associated NORM on marine biota

Numerous studies have been published on the accumulation of radionuclides by a range of marine organisms (n=36; Supplementary Figure 1). The studies comprised a total of 154 marine species that were mostly ray-finned fish (Chordata; 31%), molluscs (Mollusca; 28%) and crustaceans (Crustacea; 24%) (Supplementary Figure 1). Very few publications addressed the bioavailability of radionuclides associated with petroleum processes to marine biota. The majority of the literature only measured direct exposure and concentrations of NORM from natural sources to marine biota (78%; Figure 7). However, studies assessing direct biological effects of NORM in marine organisms are limited. From the 36 studies examined, only three measured NORM effects on marine biota (Figure 7). All three studies measured variable effects (genetic, mortality, reproduction and biochemical functions) from experimental exposure to ^{226}Ra in solid and solution. No studies measuring the effects of ^{226}Ra at the individual level were able to infer community or population effects with validated statistical evidence or confidence.

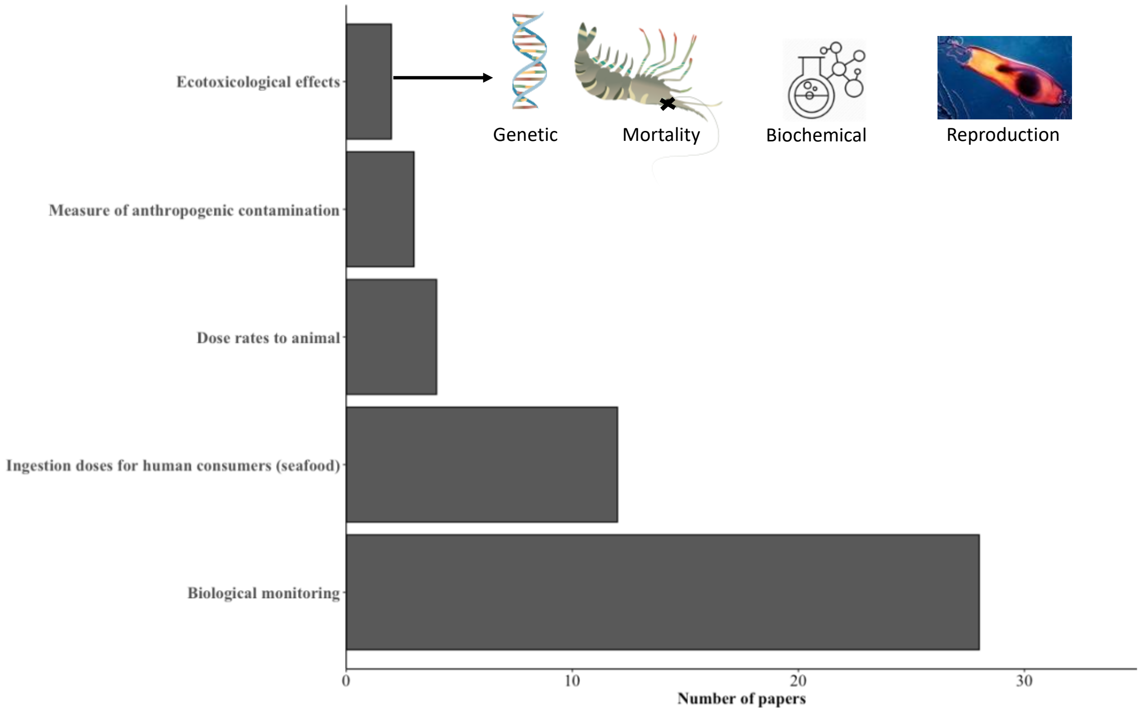

Figure 7. Main aim and objective of the studies measuring either exposure, uptake, human consumption or effects of NORM contaminants on marine biota (n=36). Biological monitoring includes a) natural activity concentrations in marine biota for environmental surveys and b) monitoring radionuclide concentrations in seafood for risk assessment to human consumers. Measure of anthropogenic contamination are studies assessing biota in contaminated areas from NORM related events (e.g. wastewater, power plant discharge)

Two of the effect studies were dietary exposure experiments designed to assess the influence of scale inhibitor, ^{226}Ra with/without barite on marine organisms (Grung et al. 2009, Olsvik et al. 2010). Olsvik et al. (2010) studied the genetic effect of adding a scale inhibitor (compound not mentioned) to dietary exposures of ^{226}Ra, barite or radium sulfate on the resulting doses for developing Atlantic cod blastula cells (*Gadus morhua*). The experimental concentration of 2 Bq/L of ^{226}Ra had limited effects on the transcription of marker genes for embryonic development suggesting that effects on fish eggs would only occur if exposed to higher doses of radiation (above 117 Bq/L) (Supplementary Table 6). However, the researchers also found that organic compounds scale inhibitor may increase the bioavailability of ^{226}Ra. Similarly, Grung et al. (2009) spiked sediment with Ra and a scale inhibitor (SI 4470; MI Production Chemicals, Norway) to measure oxidative stress in sediment-dwelling ragworms (*Herdise diversicolor*). Exposure significantly increased concentrations in the pore water and uptake within the ragworms (Control=11.1 Bq/kg; Treatment= 145 Bq/kg). Research has used simulations to model the adsorption of ^{226}Ra to organic particles in seawater and the interactions with $Ba(Ra)SO_4$ following sediment deposition (Rye et al. 2009). As ^{226}Ra is known to co-precipitate with barite (highly insoluble), scale inhibitor has the potential to impact the mobility of ^{226}Ra in the marine environment. Unlike some essential metals (calcium, magnesium, iron), radionuclides provide no biological function, hence organisms do not actively incorporate them (Williams et al. 1981, Simkiss 1984). Grung et al. (2009) illustrated that endocytosis in sediment dwelling organisms contributes to NORM exposure and act as an active pathway for NORM uptake and potential bioaccumulation. Yet neither papers illustrated any statistically significant effects on the measured endpoints for the animals exposed to ^{226}Ra or considered the co-contaminants and the solid-phase speciation of the scale (i.e. ^{210}Po, ^{210}Pb, Hg; Supplementary Table 6).

Jensen et al. (2016) assessed the influence of produced water components on the mortality and reproductivity of copepod eggs, with molecular and individual-level endpoints. Water exposure to soluble ^{226}Ra did not produce any detectable effects on individual level performance, however exposure to artificial produced water reduced egg production in the female copepods. Studies suggest exposure and the effects from produced water on marine organisms are localised and the impact from operational discharges are fairly low (Grung et al. 2009). However, a stress response at the molecular level was evidenced by transcriptional changes to genes associated with the reactive oxygen species (ROS). In marine organisms, the primary mode of action of radiation is the ionisation of water into reactive oxygen species (ROS). However, if the presence of ROS exceeds the scavenging capacity of cellular antioxidants then the cells undergo oxidative stress and can further exert damage to cellular structures and biomolecules (i.e. DNA), inducing toxic effects (Blaylock and Trabalka 1978). Even if organisms have the innate ability to repair induced damage from naturally occurring radiation, enhanced doses from industrial activities such as the petroleum decommissioning process could potentially interfere with the sensitivity levels of marine fauna.

^{210}Pb and ^{210}Po are present as cations in seawater and bind to surfaces, including barite and exterior skeletons of biological organisms (Cook et al. 2018). Therefore, the isotopes are likely to be bound to sediment particles on the benthos and in particulate forms on organic matter floating around in the water column (Fisher et al. 1989, Stewart and Fisher 2003). The bioavailability of radionuclides in seawater is determined by their physico-chemical forms. Once released into the marine environment, radionuclides present as particles and colloids, could be more biologically available and associate with surrounding particles and sediments for adsorption. Though this illustrates the potential for ^{226}Ra and other radionuclides associated with $BaSO_4$ to suspend in the water column and become bioavailable for pelagic and benthic organisms (plankton, fish, crustaceans), the processes that lead to these pathways and level of measurable effects are still unknown. There has been a strong link identified across studies between the distributions of ^{210}Pb and ^{210}Po and that of parent ^{226}Ra, so the occurrence of ^{226}Ra may predict the behaviour of the daughters (Cook et al. 2018). As ^{210}Pb and ^{210}Po are daughter products of ^{226}Ra, it is likely the daughters are strongly integrated within the scale $BaSO_4$ matrix and therefore also exhibit low solubility potential and minimal bioavailability.

Despite the three studies on the likely effects of petroleum associated radionuclides in the marine environment, the biological and geochemical mechanisms underlying the potential bioavailability of these radionuclides to organisms remains unclear (Fowler and Fisher 2004, Stewart et al. 2005, Alam and Mohamed 2011). There are too few data to draw conclusions on ecotoxicological effects of acute and chronic irradiation on marine organisms exposed to NORM associated with the offshore petroleum industry. As there is no published accessible data on the effects of drilling waste on sediment fauna populations or communities, we need to rely on risk modelling to assess contaminant effects on these functional groups (Bakke et al. 2013). A limitation is restricted access to data on the potential effects that exposure to alpha and gamma emitters via respiration or ingestion can have on organism mortality, morbidity, reproductive capacity or physiology.

The bioavailability of radionuclides from scale-based contaminants in a marine environment is largely dependent on the partitioning behaviour (i.e. between the solid and liquid phases) and the binding strength of the contaminant to sediments (Vives i Batlle 2012). This is impacted by hydrological processes and physico-chemical conditions, which affect the solubility and sedimentation of these elements. Therefore, information on radionuclide speciation specific to NORM scales and the mobility of different radionuclides species is important to estimate the bioavailability to marine organisms. Furthermore, there have been no studies that have investigated the combined effects relationship between NORM and other metals (e.g. multiple stressors) (Hingston et al. 2005, Wood et al. 2005).

3.4 Global and regional jurisdictions for offshore decommissioning

3.4.1 Regulation of subsea pipelines decommissioning

The closure of pipelines is a process regulated on an international, regional or national level. Evidence shows most offshore petroleum participating countries do not have documented guidelines and conventions for decommissioning requirements of subsea pipelines (Table 2). Progress in developing decommissioning regulations for subsea pipelines has been hindered by the absence of international protocols or foundations. In particular, the International Maritime Organisation (IMO) when developing the decommissioning legislation provided no guidance in relation to pipelines (Robert 2013).

Current regulations at the national level support complete pipeline removal at the end life (Table 2), yet *in-situ* decommissioning is not prohibited. Countries have their own decision-making approach to form national or regional protocols for pipeline regulations (Robert 2013). At the country's national level, the common decision in decommissioning pipelines are on a case by case basis, usually through a cost-benefit analysis or a comparative approach (additional information in online data repository). For example, Norway, the United Kingdom and the Netherlands have well defined conditions and protocols applicable to pipelines (Table 2). These countries are mature regarding decommissioning activities and are more experienced in effective collaboration and exchange of knowledge and expertise in this field (Coste 1989, Fowler et al. 2014, Bull and Love 2019). Additionally, the OSPAR (Convention for the Protection of the Marine Environment of the North-East Atlantic; 1992) Decision 98/3 seems to uphold an ecosystem approach with consideration of ideal environmental practices for pipelines (OSPAR 2018).

Table 2 Offshore petroleum exploration countries with defined guidelines or regulations for decommissioning subsea pipelines and the conditions for each decommissioning option. '**NA**' in **bold** represents countries that do not have recognised decommissioning guidelines or regulations

Country	Law/Act	Options for decommissioning pipelines	Conditions
United States	30 CFR 250, Subpart Q Decommissioning Activities, 2012	Left *in situ*	Does not pose hazards to commercial fishing and navigation. Pipelines need to be flushed and cleaned, filled with seawater, cut and plugged with the end ends buried at least 3 feet below the mudline
Canada		**NA**	
Argentina		**NA**	
Brazil		**NA**	
Venezuela		**NA**	
Trinidad and Tobago		**NA**	
Netherlands	Dutch Mining Act (2003)	Complete removal	Obligation of the pipeline operator. Not forced by law
		Left *in situ*	Cost-benefit assessment from a decision-based framework (Benefits to society > Costs to society) Regular monitoring and cleaning
Denmark		**NA**	
Italy		**NA**	
Germany		**NA**	
Norway	Norwegian Petroleum Act & Parliament White Paper- Report No. 47	Left *in situ* Burial/trenching Rock dumping Complete removal	Do not pose a safety risk/obstruction for bottom-trawling fisheries Must be cleaned and an assessment from the operator addressing the likely impacts of past and future burial/exposure of the pipeline (potential effects on the marine environment)
Ireland		**NA**	
United Kingdom	OSPAR Decision 98/3 & Pipeline Safety Regulations 1996	Complete removal Partial removal	Does not cause adverse effects on the marine environment
		Left *in situ*	Operators need to demonstrate removing the pipeline will achieve a clear seabed (water quality, geological characteristics, potential for pollution/contamination, deterioration of pipeline upon removal) a) appropriately buried to a minimum depth of 0.6 metres above the top of the pipeline b) pipelines not buried are expected to self-bury within a reasonable time and remain buried c) burial of the exposed sections is to a sufficient depth and is expected to be permanent d) not trenched or buried (if comparative assessment indicates it is the preferable option) e) unforeseen events due to structural damage or deterioration making removal unsafe
Algeria Egypt Italy	Barcelona Convention- Article 20	Complete removal	Prevent pollution to the marine environment
Angola		**NA**	
Equatorial Guinea		**NA**	
Gabon		**NA**	
Nigeria		**NA**	
Republic of Guinea		**NA**	

Azerbaijan Kazakhstan Russian Federation Iran Turkmenistan	Tehran Convention (2006)	Complete removal	Continual monitoring of the continental shelf/oceanic region
Oman Qatar United Arab Emirates	Regional Organisation for the Protection of the Marine Environment (ROPME) 1979	Partial removal Burial/trenching	Flush and removal all residual pollutants
Australia	Commonwealth Offshore Petroleum and Greenhouse Gas Storage Act 2006	Complete removal Partial removal Left *in situ*	Environmental impacts need be as low as reasonably practical and of an acceptable level
New Zealand	Crown Minerals Act, 1991	Case by case	Removal or abandonment can be left *in situ* dependent on location and in accordance with what is deemed good industry practice
Indonesia		**NA**	
Malaysia	Guidelines for Decommissioning of Upstream Installations, 2014	Case by case assessment of removal operations	Flushed and cleaned, filled with seawater, cut and plugged with the ends buried below the mudline
Thailand	The Petroleum Act (No. 6) B.E. 2550, 2007, Section 80/1 and 80/2	Left *in situ* or removal and disposal onshore	Appropriate monitoring programme must be determined
Brunei	Petroleum Mining Act 2002	Complete removal	If pipelines are in less than 30m water depth or within 3 nautical miles of the border with another country or in shipping lanes of sensitive coastal areas

While the IMO Guidelines provide minimal strict measures to reduce risks to local fisheries and maritime navigation during decommissioning, international law is ambiguous, outdated and centred around human-focused objectives and reasoning (Ounanian et al. 2020). This places pressure on national governments to formulate policies and frameworks for pipelines. To include more eco-centric motives into global regulations on offshore decommissioning, marine ecosystem restoration practices need to be incorporated (Ounanian et al. 2020).

Research demonstrates there are several key conditions with the current decommissioning policies from countries who are bound by the IMO Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone (Coste 1989, Beckman 2013, Fowler et al. 2014, Henrion et al. 2015, Chandler et al. 2017, Cullinane and Gourvenec 2017, Fam et al. 2018, Boza and Gutierrez Rico 2019, Bull and Love 2019, Birchenough and Degraer 2020); online data repository). The writing of the IMO guidelines had a direct focus on anthropocentric risks (e.g., economy, human health, marine traffic) from obsolete abandonment of offshore structures. It was not until 1996 when the London Dumping Convention (LDC) became the first global convention to regulate the protection of the marine environment regarding the disposal of waste at sea (IMO 2006). However, the LDC does not prohibit decommissioning human-made structures *in situ* (Techera and Chandler 2015). The definition of '*dumping*' is vague as it does not include pipelines as a category of abandoned structures. The LDC does not specify oil rigs and other determinable abandoned structures can be dumped, yet the definition of an '*abandoned or disused installation or structure*' is unclear. The lack of clarification within the LDC results in ambiguity around the definition of pipelines as human-made structures or waste and therefore waste governance processes are unclear.

The uncertainty of dealing with pipelines amongst all participating countries is complicated by the absence of uniformly accepted rules in international governance and decision-making. The United Nations Convention on the Law of the Sea (1989) has no clarity regarding the fate of subsea pipelines (OSPAR 2007, ASCOPE 2012, Fam et al. 2018). This raise concerns on what might constitute an environmentally responsible approach to decommissioning pipelines within international law. The variable geographic regions and environments between participating countries shows a lack of international clarity on decommissioning frameworks for pipelines, which will not create a one-size-fits-all approach. The marine environment varies widely between countries and is influenced by local and regional factors (e.g. oceanography, biogeography, native biota), with the decommissioning frameworks founded from the local ecosystem (e.g. tropical coral reef, cold-water deep-sea) (Fowler et al. 2014). Given the geographical discrepancies and ecological factors framing regulations, standardising an overarching global framework that supports local frameworks would allow for a direct and global perspective for directing pipeline decommissioning plans.

3.3.2 Environmental plans and management of NORM

Most countries require environmental impact assessments (EIA) or reviews to support their decommissioning plans (Table 3). These are used to predict likely effects on the environment, ensure the practices are safe and pose low risks and are required to by operators to outline the extent of decommissioning e.g., structures to be decommissioned, characteristics of the substances and an inventory of contaminants, chosen method of disposal based on a risk assessment. Whilst it is a standard international requirement, our review shows the majority of countries (90%) often do not quantify the presence of metal and NORM in environmental impact assessments (Table 3). As there is no comprehensive international treaty dealing with the management of NORM from decommissioned structures, seemingly only the Russian Federation includes NORM into the decommissioning EIA requirements. In all countries, even though operators are required to outline contaminants likely to be dispersed and cause potential exposure of biota, only hydrocarbons and petroleum components are assessed (Table 3).

Table 3 Evaluation of the offshore petroleum operating countries and the inclusion of an environmental impact assessment in the decommissioning process of offshore infrastructure and if any petroleum-associated contaminants are compulsory in the assessment. PAHs: polyaromatic hydrocarbons; metals and metalloids; NORM: Naturally Occurring Radioactive Material

Country	**Environmental Impact Assessment**	**Contaminants**		
		PAHs	**Metals**	**NORM**
North America				
United States	✓			
Canada	✓	✓		
Central America				
Trinidad and Tobago	✓Certificate of Environmental Clearance			
South America				
Venezuela	✓			
Brazil	✓	✓		
Argentina				
Europe				
Denmark	✓			
Netherlands	✓			
Norway	✓	✓		
United Kingdom	✓ Environmental Safety Case	✓	✓	
Italy	✓			
Central Asia				
Russian Federation	✓	✓		✓
Azerbaijan	✓			
Kazakhstan	✓			
India				
Middle East				
United Arab Emirates	✓	✓		
Qatar	✓ Discretion of operator			
South-East Asia				
Brunei	✓			
Indonesia				
Malaysia	✓			
Myanmar	✓			
Africa				
Angola	✓ Site Abandonment and Rehabilitation Plan			
Equatorial Guinea	✓ Additional Abandonment Plan	✓		
Algeria	✓	✓		
Egypt	✓			
Gabon	✓			
Nigeria	✓			
Republic of Guinea	✓			
South Pacific				
Australia	✓	✓		
New Zealand				

The main drivers of environmental risk are considered to be the spillage of oil and petroleum components, due to the large volumes contained within structures and the hazards they pose to the marine environment and human health (Blackman and Law 1980, Amoroso and Keenan 1994, Andrade et al. 2004, Allan et al. 2012, Adams et al. 2014, Amezcua et al. 2014, Alexander et al. 2017, Bender et al. 2018). Additionally, the technology for removal and effective cleaning of hydrocarbons is extensively researched and has well defined waste disposal management protocols (Mascolo et al. 2008, Shokrollahzadeh et al. 2012, Akinpelu et al. 2019, Naeem and Qazi 2020). As a result, there appears to be little visibility of the extent of NORM expected during decommissioning especially within subsea infrastructure (pipelines, flow lines and well equipment) (McKay et al. 2020). The presence of NORM is rarely mentioned in environmental plans and the inclusion of potential non-hydrocarbon contaminants and their likely biological effects are rarely investigated (Table 3).

A major issue is operators across the globe have insufficient data to accurately quantify and predict the extent or effects of NORM and metal contaminants in infrastructure, in advance of decommissioning and cleaning procedures. Furthermore, few countries acknowledge the presence of ionising radiation or radioactive waste as a by-product of decommissioning processes. Waste or depository facilities for NORM and hazardous metals are few in all countries, with many non-existent in developing countries (Ferronato and Torretta 2019). It is likely the sources and diversity of contaminants released into the marine environment will increase, given the current and projected scale of decommissioning (Fowler et al. 2018, Fowler et al. 2019). Hence, an assessment of the ecological and toxicological risks of these contaminants of concern is urgently required and should be considered in future EIA to ensure mitigation efforts include those contaminants.

Leaving oil and gas structures *in situ* can support establishment of an ecosystem and provide potential benefits to the local faunal community (REF). Despite this, recognising the ecological value of decommissioned infrastructure to classify if they are or can provide a suitable ecosystem often excludes the consideration of associated contaminants. This is highlighted in an expert opinion article, where more than 60 % of representatives from the benthic ecology field did not consider contaminants as a major negative impact from decommissioning (Fowler et al. 2018, Fowler et al. 2019). This emphasises that effective global decommissioning practices for offshore structures is often hindered by a lack of information on relevant contaminant stressors. Due to the paucity of data, ecologists and policy makers cannot make decisions because the extent of contaminants from assessments and monitoring of the marine environment after leaving a structure *in situ* or partial disposal in the deep-sea and the ecotoxicological effects with biological organisms, are still largely unknown. As to whether *in situ* decommissioning will benefit or harm the marine environment, research and worldwide policies need to incorporate comprehensive environmental assessments of decommissioning options for structures (Techera and Chandler 2015). The limited information and ambiguity within global decommissioning frameworks, in terms of acknowledging the presence of contaminants is vitally important in the governance process of national decision-making in the oil and gas sector.

3.3.3 Decommissioned infrastructure as artificial reefs

A large proportion of artificial reefs from offshore petroleum structures are created for increasing potential habitat for marine fauna, fisheries, prevention of trawling and ecological restoration devices. This review highlighted that only the United States permits artificial reef creation from offshore installations and structures left in marine environments. Half of the US coastal states' guidelines and criteria are based on guidance from the National Artificial Reef plan (amended in 2007), yet there is no federal coordination or oversight regulating the Rigs-to-Reef (RtR) program in US waters (Paxton et al. 2020). However, in 2010 California passed a bill to mandate the conditional partial removal of offshore platforms; California Marine Resources Legacy Act, with the inactivation of the RtR legalisation (Meyer-Gutbrod et al. 2020). Australia mentions the application of the RtR program, yet it is still not an option due to the absence of reliable research and evaluation. Under the OSPAR convention, all North Sea participating countries are not permitted to abandon structures to be converted to artificial reefs. As there is no clear constitution on what classifies as a net benefit to the ecological community from the RtR program (further to excluding joint pipelines), it is difficult to come to a consensus.

Decision analyses should apply the novel ecosystems concept, predominantly based on the ecology identified from *in situ* offshore platforms (Gates and Jones 2012, Gates et al. 2017a, Bond et al. 2018b, Macreadie et al. 2018a, Gates et al. 2019, McLean et al. 2019, Sommer et al. 2019, van Elden et al. 2019, McLean et al. 2020a). Current literature of global decommissioning processes and regulations called for incorporating an ecosystems-based approach (Sommer et al. 2019, van Elden et al. 2019). Bull and Love (2019) also briefly mentions this, however the review is focused on the United States and the RtR program. The creation of artificial ecosystems from converted oil platforms have shown to support reef habitat for diverse marine biota with examples of increased fish production in California and increased biodiversity of reef communities in West Africa (Friedlander et al. 2014, Claisse et al. 2015). There is substantial unpredictability and uncertainty regarding the effectiveness of artificial reefs, considering the variability and complexity of global marine ecosystems (Ounanian et al. 2020). Furthermore, the effective use of decommissioned platforms and rigs as artificial reefs requires a multi-disciplinary approach to monitor and confirm that the health of the local marine ecosystem has been improved following abandonment of the infrastructure.

The ecological uncertainty and involvement of environmental politics have been shown to influence decision-making for existing decommissioning policies. The RtR program ceased in the North Sea after the Brent Spar incident when an offshore oil storage buoy was arranged to be buried in a deep-water trench, but would have resulted in marine contamination (Gage and Gordon 1995, Pulsipher and Daniel Iv 2000, Osmundsen and Tveterås 2003, Jørgensen 2012). Greenpeace and the public boycotted gas stations across Europe in protest of the dumping of the Brent Spar, with public pressure preventing the disposal of the offshore platform (Ounanian et al. 2020)**.** This illustrates that social and political values are influential on decommissioning guidelines, with the potential to disrupt or stabilise current policies.

The long-term marine ecological implications from leaving a pipeline *in situ* or via partial disposal on the seabed is unknown. Available information on the extent to which decommissioned pipelines support marine fauna communities or a new ecosystem has only emerged in the last five years (Bond et al. 2018a, McLean et al. 2019, McLean et al. 2020b)**.** These rely on current and historical remote-operated vehicle (ROV) data to understand the impacts of *in situ* structures (including jackets, pipelines, wells) on the local marine ecology (Gates et al. 2017b, Bond et al. 2018b, Macreadie et al. 2018b, McLean et al. 2018)**.** As to whether *in situ* decommissioning will benefit or harm the marine environment long-term, multiple experts including marine biologists engineers, lawyers, social scientists and health professionals, are needed to communicate the likely risks (Techera and Chandler 2015)**.** This brings into focus the need for research and worldwide policies to be directed to incorporating a combined environmental and ecological-based approach of decommissioning options for pipelines.

4. Research gaps

4.1 Environmental monitoring pre- and post- decommissioning

Quantifying environmental concentrations of petroleum-associated contaminants during operation is difficult as produced water and cutting piles can dilute in seawater. None of the eight studies in this review analysed the environmental media at the decommissioning stage, most likely due to a lack of adequate chemical analysis of environmental media at the decommissioning stage and post-operation environmental monitoring. Additionally, the ability to detect radionuclides in offshore structures with appropriate tools is limited, and therefore radioactive contamination may go unnoticed during the planning and execution of decommissioning. Using estimates of organism effects and contaminant concentrations based on risk modelling and outdated data is not likely to be accurate and reliable. Baseline or background level data are still lacking in the public domain for the vicinity of offshore installations that can not be easily monitored for decommissioning conditions (Joye et al. 2011, Joye et al. 2016).

Long-term monitoring in the deep sea associated with oil and gas developments is extremely limited (Harman et al. 2011). Temporal monitoring and surveying of contaminants is important because metals and NORMS have the potential to accumulate past the post-drilling stage, as illustrated by the studies in this review. This has implications for the decommissioning process and structures to have residual contaminants (Kennicutt II et al. 1996). The changing environmental conditions and the slow recovery of ecosystems over time is also important to account for during the continual monitoring of contaminants at decommissioned structures (Barreyre et al. 2012).

Olsgard and Gary (1995) suggested trace metals in old cutting piles will become the main source of environmental impacts, thus following decommissioning, cuttings piles are likely to become a future source of episodic contamination (Bakke et al. 2013). Even though toxicity is still assessed from a determination of hydrocarbon concentrations under many regulatory guidelines, biodegradation of drilling mud and the presence of barite scale with metals and NORM constituents is likely to occur years beyond cessation of operations. Cuttings piles are vulnerable to physical disturbances that cause dispersion of contaminated material; thus, erosion and uncovered pipelines may uncover layers and enhance leakage and dispersion of contaminants into the benthic environment and water column. For example, the determination of barium is important considering its low solubility and precipitation in the presence of sulfates and carbonates (Church and Wolgemuth 1972, Monnin and Galinier 1988, Crecelius et al. 2007, RIVM 2020). Therefore, for metals and NORM, the dissolved fractions (i.e. soluble products upon contact of the scale with surrounding seawater) should be considered as highly relevant for ecotoxicological assessments in decommissioning.

4.2 Characterisation of petroleum scale and NORM components

Successful decommissioning of subsea oil and gas infrastructure requires an effective and safe approach to assessing and managing chemical and radiological residues. Little work has been done to define the characteristics and properties of scale, considering the variability of matrixes, environmental features such as the local geology and operational methods employed (i.e. pigging of the pipelines, residuals in trunk lines and wells, injection of produced water).

4.3 ERICA radiological dose assessments

Research investigating radiological impacts to marine biota often employ the ERICA screening tool and minimal laboratory experiments (Figure 7). The applicability of the ERICA tool and other radiological dose models to subsea infrastructure is limited, due to the lack of suitable homolog organisms in the ERICA database that are likely to inhabit or grow on the infrastructure. This creates uncertainties in assessing realistic estimations of exposure to marine biota. Limited data available on acute and chronic irradiation from NORM indicates there is inconsistent evidence and a lack of data for any effects at dose rates below the 4 μGyh^{-1} benchmarks (Fuller et al. 2015). The heterogeneity in the endpoints assayed, together with different types of radiation emitted from the radionuclides and the variety of species exposed, makes it difficult to compare the results obtained in these studies to reference organisms. In this review, the studies measuring dose rates in exposed organisms to radiation lower than the benchmark value of 10 μGyh^{-1} did not examine or indicate detrimental effects including mortality, reproductive capacity or morbidity (Andersson et al. 2008).

Furthermore, extrapolation to populations is difficult due to the multitude of physicochemical interactions. The availability of only two International Commission on Radiological Protection (ICRP) Reference Animals; crab and flatfish, to radiological dose assessments presents challenges to a more general understanding of how NORM impacts all marine phyla. For decommissioned subsea structures, the benthic and pelagic communities comprising of species from molluscs to marine mammals do not have an appropriate reference organism for radiological dose assessments. For example, little is known about what constitutes a lethal acute or chronic radiological dose to cartilaginous fish, marine mammals or aquatic reptiles. This implies there is uncertainty of applying the ERICA screening tool or similar dose assessment tools towards absent species of animals often not considered when it comes to research on the effects of IR. From the few studies on acute exposure of ^{210}Po in tissues of marine organisms from diverse taxa confirms the large variability in concentrations of the dose received between tissues and as a whole-body. For example, effective dose-equivalent rates for benthic crustaceans were calculated to range from 0.30 to 3.0 mSv y^{-1} in muscle and 130–750 mSv y^{-1} in hepatopancreas (Cherry and Heyraud 1982, Heyraud et al. 1987, Heyraud et al. 1994, Fowler and Fisher 2005, Fowler 2011). Thus, determining radiation doses received by exposed individuals in the population of a species and then relating absorbed dose to biological effects needs to be carefully interpreted because of the high inter-species and tissue variability. A meta-analysis of research measuring the effect of chronic low dose radiation on indicators of oxidative stress (markers of oxidative damage, enzymatic and non-enzymatic antioxidants) found significant heterogeneity in effect size across species and tissues (Costantini and Borremans 2019). This suggests selection for organisms able to cope with ionising radiation (e.g. upregulation of DNA repair mechanisms, antioxidants). This knowledge gap needs to be filled through more comprehensive research or inclusion of a diverse range of marine organisms to accurately predict organism responses and low-dose stressor exposure.

Despite the environmental relevance of marine fauna and their ongoing exposure to radionuclides through contaminants, fewer than 100 publications exist on the effects of IR on marine invertebrates and none measure effects from petroleum-associated scale. Internal and external doses arise from the relatively low activity concentrations of the NORM in scale, but also from natural environmental background levels of the radionuclides (Hosseini et al. 2012). Carvalho et al. (2010) described an assessment of absorbed radiation doses from low-level radioactive waste dumpsites in pelagic planktivorous sardine and the blue marlin in the Northeast Atlantic Ocean, which indicated most of the radiation dose was from NORM. However, there is still less information available about radioactivity in the continental shelf surrounding petroleum reservoirs and the resulting radiation exposure of inhabiting biota to the naturally occurring radionuclides (Carvalho et al. 2010). Dose rate calculations from exposure to NORM in scale from the petroleum industry is often difficult to discern from the variability in dose rates observed in natural marine systems (Hosseini et al. 2012). This is because the total radiological doses acquired by marine fauna are from natural background sources, thus the relative contribution of IR from scale-based NORM can be hard to monitor (Fowler 2011). Therefore, it is crucial to have a thorough understanding of separating exposure from natural background levels of NORM from scale in pipelines and other decommissioned infrastructure to environmental background levels. In terms of petroleum scale contaminants and exposure of marine biota to IR, existing knowledge is currently unknown on the dose rates emitted from scale, the form of radiation (α, β, γ) and the effect thresholds that signals potential benchmark toxicity.

5. Future directions

5.1 Framework for standardised environmental monitoring pre- and post-decommissioning

A lack of standardised methods and toxicity tests designed for NORM from offshore oil and gas operations makes assessing the effects of decommissioning methods difficult. Thus, the BACI approach can be integrated into environmental assessments as a technique to indicate if contaminants are elevated post-operations, to see if ecotoxicological effects are likely to occur in marine organisms. Environmental quality guidelines specifically for contaminated environmental media (produced water, cutting piles, scale) associated from offshore oil and gas structures and by-products would benefit the risk assessment for contaminants of primary concern. However, such guidelines would focus on mitigation and risks during operations of onshore or offshore human activities and rely on assessments considered beforehand. This is a crucial step in terms of whether they are applicable for decommissioned offshore structures.

As there are currently no globally prescribed guidelines or protocols to assess subsea infrastructure associated contaminants or scale, a tiered assessment framework for the assessment of contaminated sediments and water is needed (Supplementary Figure 2). The ideal framework would be applied to monitor the contaminants entering the marine environment through decommissioning procedures and submerged infrastructure scale. Frameworks need to be generalised, but then applied to site-specific conditions accounting for the type of infrastructure-associated contaminants and concentrations, along with depth, pH, temperature and local ecology (Reynoldson et al. 2002, Apitz et al. 2005, Simpson et al. 2005, Brack et al. 2017, ANZG 2018).

5.2 Elemental and radiometric analyses of petroleum scale and NORM components

Our recommendation is for industry to use available elemental and radiometric techniques to perform analyses to identify and classify the chemical composition and radioactivity levels of scale. This can include, but not be limited to using inductively coupled mass-spectrometry/optical emission spectrometry and x-ray fluorescence to quantify inorganic elements and major ions in the scale. Gamma-ray spectrometry is the ideal technique for quantifying the activity concentration of radionuclides (Cresswell and Sanderson 2012, Cresswell et al. 2017, Joel et al. 2017, Cresswell et al. 2020). Care must be taken to understand the reading of radioactivity relative to where the gamma measurement is conducted on the piece of infrastructure e.g. if on the external surfaces of pipes, attenuation of the signal by the steel is important to consider. However, gamma spectrometry will not detect alpha-emitting radionuclides such as ^{210}Po. This analytical technique will require samples of the scale to be collected and brought on shore as analysis of alpha-emitting radionuclides cannot be conducted in-situ. High-purity detectors have been developed and are extensively utilised in environmental studies to detect radioisotopes of contaminated waste (Scholten et al., 2013; Siegel, 2013; Van Beek et al., 2010). Therefore, gamma and alpha spectrometry can be used to measure the uranium and thorium radioisotopes and their decay products. Due to environmental and operational differences between petroleum operators, collection, analyses and characterisation need to be conducted on several different sources of pipe scale. It is therefore recommended that scale samples are recovered from subsea infrastructure for analysis, either by cutting and lifting pipelines and then recovery of scale mechanically or by analysis of pigging dust/solids. For the latter, it is important to note that pigging solids represent a homogenous sample of scale from the entirety of the pipeline pigged and will not provide information on potential hotspots of contaminants along the pipe. Early detection will enable petroleum regulators to develop and utilise thresholds at which issues may occur in marine biota (Cordes et al. 2016). This will eventually lead to new possibilities for management and repair of contaminated past or historical decommissioning processes.

5.3 Direct organism exposure assessment scenarios

This review has identified new directions for ecotoxicological research in the offshore decommissioning field to improve understanding about the biological effects of NORM. Performing laboratory studies by exposing a variety of marine species to infrastructure-associated NORM contaminants will create refined estimates of contaminant bioavailability, radiation dose and subsequent assessments of effects from NORM and ionising radiation (IR), combined with metals. Radiotracing techniques can provide new perspectives on the pathways and rates of uptake (e.g., bioaccumulation) and biomagnification processes of radioactive and non-radioactive contaminants (Lanctôt et al. 2017, Cresswell et al. 2020). Laboratory studies are needed to investigate the acute and chronic radiation-induced effects from NORM contaminants associated with petroleum scale. Furthermore, understanding the actual bioavailability of inorganic contaminants and radionuclides within scale will increase certainty around the potential for biological impacts to occur. Direct dietary and water exposures of scale material and their dissolution products respectively to a series of benthic and pelagic marine organisms under different environmental scenarios would allow for a better understanding of the potential for organism bioaccumulation, potential effects and food chain transfer. Organisms should be selected to represent active sediment feeding behaviours (i.e. worst-case scenario of ingestion of scale mixed with sediment) and ideally should include organisms targeted for fisheries (e.g. prawns and commercial fish) to better understand the potential for human consumption and subsequent implications.

5.4 Radiological dose modelling assessments

With inferences stating significant activity concentrations of NORM for benthic organisms colonising exterior of structures, it is recommended simplified radiological dose modelling using the ERICA assessment tool and seawater leachate tests are conducted to estimate the potential radiological doses and effects to model marine organisms inhabiting subsea tubular infrastructure. As ERICA does not have the ability to characterise the external dose and interior dimensions of a pipeline, a range of scenarios of pipeline degradation (from non-degraded operational use to fully degraded pipeline mixing with surficial sediments) need to be adapted to account for the circular source and shielding from pipes.

5.5 Collaboration with industrial stakeholders, government officials and environmental policies

From this review, it is clear there is a lack of data transparency relating to the presence and concentration of contaminants associated with decommissioned infrastructure and potential biological interactions with marine biota. To improve data transparency, multi-stakeholder collaboration can provide the opportunity to create open source datasets (Jones 2009, Gates et al. 2017b, Macreadie et al. 2018b, Murray et al. 2018b). Even though data collection is part of routine operations and provides important information about the ecology of offshore structures, external parties and scientists still have the challenge of inaccessibility (Burdon et al. 2018a, Birchenough and Degraer 2020). Acquisition of environmental data is recommended for decommissioning decisions, as access to industry datasets can expand understanding of the legacy impacts of the offshore industry (Levin et al. 2019). Decisions need to incorporate sufficient scientific knowledge to predict environmental as well as economic and social impacts, with an acceptable degree of uncertainty. Trust between participating stakeholders is a current barrier to data sharing. Maintaining long-term communication through collaborations can help to build trust and develop working relationships (Murray et al. 2018a). This will lead to the development of reliable and invaluable data sharing agreements. Partnerships between the oil and gas industry and scientists are encouraged to gain access to inaccessible data, through effective communication (Todd et al. 2018, Sward et al. 2019, McLean et al. 2020a, Todd et al. 2020).

Efforts should be made to increase collaboration with national/international regulators, operators (industry) and academic stakeholders (regional and multi-national) to expand decommissioning policy frameworks (Fowler et al. 2019, Lacey and Hayes 2019). Such collaborations should seek to develop multi-criteria decision analysis, incorporating likely impacts on the overall marine environment and associated wildlife, engineering and ideal economic strategy for operators (Fowler et al. 2014). Providing segments of pipelines or recovered scale for analyses will enable an understanding of the potential ecological and environmental impacts associated with the planned decommissioning scenarios. This will communicate the presence of NORM and interactions with marine organisms during decommissioning of offshore seabed infrastructure to stakeholders. Collaboration between science and industry will strengthen the relationship, to demonstrate the importance of environmental protection and formation of risk assessments (Burdon et al. 2018b). Communicating simple environmental science and its importance to expand the limited global knowledge on the potential effects of NORM contaminants associated with decommissioning will ensure a more robust and transparent decommissioning process.

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Supplementary Material

Methodology

Article screening and study inclusion criteria for the second aim

For the second aim, we limited our searches to marine organisms in the kingdom Animalia. Studies on marine plants, algae, bacteria, terrestrial and freshwater animals were excluded as they are not the focal organisms of this review. Ecotoxicological studies had to explicitly report changes to any measurable biological trait (compared to a control) a) at the cellular level (genomic, biochemical), b) individual level (behaviour, physiology, reproduction, mortality), or c) at the population of community level (abundance, richness, diversity etc.). Changes to community structure examined with multivariate analyses were excluded. Also excluded were terrestrial studies, modelling risk assessments and studies regarding coastal and onshore infrastructure, petroleum treatments and scale inhibitors, human health and maritime transport (see Supplementary Table 3).

Supplementary Tables

Search terms for database search, inclusion and exclusion criteria and excluded studies

Supplementary Table 1 Search terms used to identify studies reporting contaminants associated with decommissioned petroleum infrastructure and the ecotoxicological effects on marine vertebrates and invertebrates

	Title, abstract or keyword
Petroleum decommissioning terms	oil, petroleum, gas, offshore, decommissioning, abandonment, closure, removal, infrastructure, structure, subsea, jacket, pipeline, well, vessel, platform, artificial reef, discharges, waste, release, spill, scale
Contaminant terms	metal, radionuclide, radioisotope, radioactive, naturally occurring radioactive material, NORM, persistent organic pollutant, waste, poly-, hydrocarbon, PAH, BTEX, plastic, discharge, contaminant, pollutant
Naturally Occurring Radioactive Material terms	radionuclide, radioisotope, naturally occurring radioactive material, NORM, polonium, radium, uranium, thorium, lead
Ecotoxicological terms	organism, animal, biota, vertebrate, invertebrate, physiology, mortality, reproduction, genetic, behaviour, diversity, abundance, ecotox, ecology, biology, impact, effect
Additional terms for search strings for search 2	benthic, pelagic, fish, community, crustacean, fauna, bioaccumulation, uptake
Excluded terms (NOT Boolean operator)	freshwater, seafood, terrestrial, human health, onshore, land, soil, wind, biofouling, nuclear, public

Supplementary Table 2 Search strings used to target studies assessing the ecotoxicological effects of different types of radionuclides from the 238U and 228Th decay chains, in combination with the ecotoxicological search terms (see above)

Polonium	(polonium-* OR "210Po"* OR "Po-210"*)
Lead	(lead-* OR "210Pb"* OR "Pb-210"*)
Radium	(radium* OR "228Ra"* OR "226Ra"* OR "Ra-226"* OR "Ra-228"* OR radionuclide* OR radioisotope*)
Thorium	(thorium* OR "228-Th"* OR "Th-228" OR radionuclide* OR radioisotope*)
Uranium	(uranium* OR "228-U"* OR "U-228"* OR radionuclide* OR radioisotope*)
Combined each search string associated with key terms for search 2 related to ecotoxicological effects with each of the following search terms associated with a different radionuclide (shown above)	

Supplementary Table 3 Inclusion and exclusion criteria for ongoing screening of the publications from both searches. Search 1: studies on the presence of contaminants associated with offshore infrastructure; Search 2: studies on the radiological and ecotoxicological effects of naturally occurring radioactive contaminants associated with infrastructure

<table>
<tr><th>Selection Criteria</th><th colspan="2">Inclusion criteria</th><th>Exclusion Criteria</th></tr>
<tr><th></th><th>Search 1</th><th>Search 2</th><th></th></tr>
<tr><td>Subject</td><td>Any assessment or monitoring of various contaminants associated with offshore petroleum infrastructure</td><td>Any measurable exposure, uptake or effect of the following radionuclides on marine invertebrates or vertebrates: radium-226, polonium-210, lead-210, radium-228, thorium-228, uranium-228</td><td rowspan="5">Any of the following types of studies:
No mentioning of contaminants
Terrestrial studies
Oil spill focus
Literature reviews
Coastal and onshore infrastructure
Risk assessments (modelling)
Geological exploration/oil field exploration assessment
Not related to petroleum industry
Corrosion of infrastructure
Modelling and simulations
Bioremediation
Potential of treatments and scale inhibitor
Studies on freshwater species/freshwater monitoring
Artificial reefs (ecology)
Maritime transport
Human exposure and public health studies
Offshore windfarms</td></tr>
<tr><td rowspan="5">Comparator</td><td>Any measurable concentrations of contaminants (compared to a control or background levels) associated with decommissioned infrastructure or post-drilling operations</td><td>Any measurable ecotoxicological effect in response to the NORM contaminants (compared to a control) associated with decommissioned/post-drilling operating petroleum infrastructure</td></tr>
<tr><td>Studies could be before/after operations, or measurements across radial or temporal gradients in the field</td><td>Studies could be before/after and control impact (BACI) laboratory of filed-based experiments, or measurements across exposure gradients in the laboratory or field</td></tr>
<tr><td>Field studies measuring other contributing variables (e.g. effect of season, radial distance around infrastructure) were included, if a control or reference site was included</td><td>Correlative field studies measuring effects across a gradient will be included if a control site is reported</td></tr>
<tr><td></td><td>Only primary data sources were considered</td></tr>
<tr><td></td><td>Only studies using marine organism in kingdom Animalia. Keystone seafood species were included, if all other inclusion criteria were met</td><td>Marine plants, algae, bacteria, terrestrial and freshwater organisms</td></tr>
<tr><td rowspan="2">Outcomes</td><td>Changes to the concentrations of the different contaminants from pre-drilling operations compared to post-drilling operations</td><td>Changes to any measurable trait (compared to a control) a) at the cellular level (genomic, biochemical), b) individual level (behaviour, physiology, reproduction, mortality), or c) at the population or community level (abundance, richness, diversity etc).</td><td>Changes to community structure examined with multivariate analyses</td></tr>
<tr><td>Identification of the associated structures and process(es) contributing to the presence of offshore-petroleum contaminants to the marine environment</td><td>Mentioning of dose rates to marine organisms were considered for possible inclusion for qualitative analysis</td><td></td></tr>
</table>

Supplementary Table 4 Studies from the first database search (search 1) reporting contaminants associated with decommissioned offshore petroleum infrastructure that were excluded at the full text screening stage of the systematic review process

Author(s) & Year	**Reason for exclusion**
Adami et al. 2007	Onshore study near Niger Delta
Agbalagba et al. 2013	Study focuses on dose rates alone
Balaam et al.	Study did not provide average concentrations and no standard errors
Brasil do Amaral Sobrinho et al. 2018	Onshore focus
Eiceman et al. 1984	Coastal lagoon not offshore
Habib et al. 2010	Onshore oil field
Hylland et al. 2008	Study does not mention the water column concentrations
Jibiri and Amakom 2011	Onshore oil field in Nigeria
Khodashenas et al. 2012	Onshore oil field in Iran
Maguire-Boyle and Barron 2014	Onshore oil field near the Gulf of Mexico
Narres et al. 1984	Study focuses on analysing types of crude oil. Not associated with infrastructure
Olajire et al. 2005	Onshore oil field near the Gulf of Mexico
Olawoyin et al. 2014	Study focuses on PCA analysis of soil pollution on land
Orecchio et al. 2010	Study focuses on excavation operations, dredging and laying
Peralba et al. 2010	Onshore oil field
Ponce-Vélez et al. 2012	Coastal lagoon not offshore
Zhao et al. 2008	Risk assessment through modelling
Zhou et al. 2015	Impact of Ni and Cr on corrosion of pipeline

Supplementary Table 5 Studies from the second database search (search 2) to identify papers evaluating the ecotoxicological effects of naturally occurring radioactive material on marine biota excluded at the full text screening stage

Author(s) & Year	Reason for exclusion
Baena et al. 2012	Not appropriate study design
Bustamante et al. 2006	Accidental duplicate of the same article in the reference management tool
Durand et al. 2012	Study only measured fractions bound to metallothionines
Sures et al. 2003	Accumulation of lead-210 in parasites
Jeffree et al. 1997	Not appropriate study design
Song et al. 2016	Freshwater fish
Mothersill et al. 2014	Freshwater fish
Zuykov et al. 2012	Descriptive article on adsorption- no numerical concentrations
Stewart and Fisher 2003	Not appropriate study design
de Moura et al. 2015	No numerical concentrations for polonium
Stewart et al. 2005	No numerical concentrations for polonium
Khan et al. 2014	Duplicate of same article in reference management tool

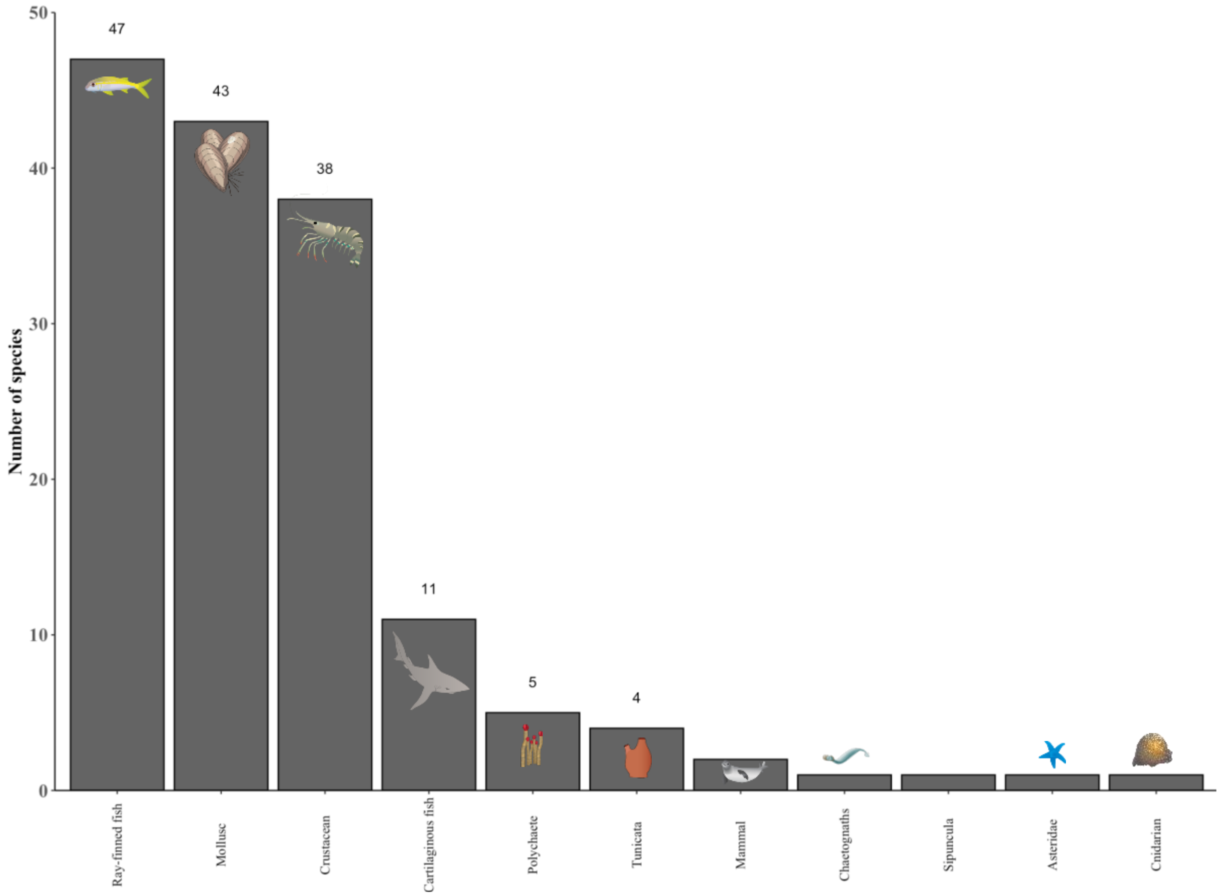
Additional information from the three studies measuring ecotoxicological effects to marine biota

Supplementary Table 6 Summary of findings from the three studies that measured the ecotoxicological effects of petroleum associated naturally occurring radioactive material on marine biota

Ecotoxicological effect	**Species of animal**	**Sample size**	**Highest experimental exposure concentration**	**Concentration of radionuclide in animal (mean +/- standard error)**	**Significant effect (compared with the control group to a P < 0.05)**	**Key finding**	**Reference**
Total oxyradical scavenging capacity (TOSC); Peroxyl radicals [Biochemical/Physiology]	Ragworm (*Herdise diversicolor*)	5	226Ra (48 240 Bq) + 565 mg scale inhibitor	144 ± 22 Bq kg^{-1} dw	X	Activity in the sediment for the exposed group contained more than 2 orders of magnitude higher radiation from ^{226}Ra than the background levels	Grung et al. 2009
Total oxyradical scavenging capacity (TOSC); Hydroxyl radicals [Biochemical/Physiology]					X	No significant increases of ^{226}Ra in pore water or the polychaete treated in the exposure group after 4 weeks of exposure	
Genetic (Physiology)	Atlantic cod (*Gadu morhua*)	Unknown	117 Bq/l of 226Ra	Not measured	X	Radiation did not affect the morphology of Atlantic cod EC with a high degree	Olsvik et al. 2012
Mortality	Copepod (*Calanus finmarchicus*)	10	Scale inhibitor	Not measured	X	No marked differences were found when comparing ^{226}Ra and scale inhibitor treated specimens to the controls	Jensen et al. 2012
			Artificial produced water	Not measured	✓	Only APW treatment resulted in a significantly higher mortality rate compared to control	
Cumulative number of eggs per female[Reproduction]		10	Scale inhibitor	Not measured	X	Exposure to ^{226}Ra did not produce any apparent detectable effects on individual level performance	
			Artificial produced water	Not measured	✓	Egg production of females exposed to APW seemed to be reduced compared to control	

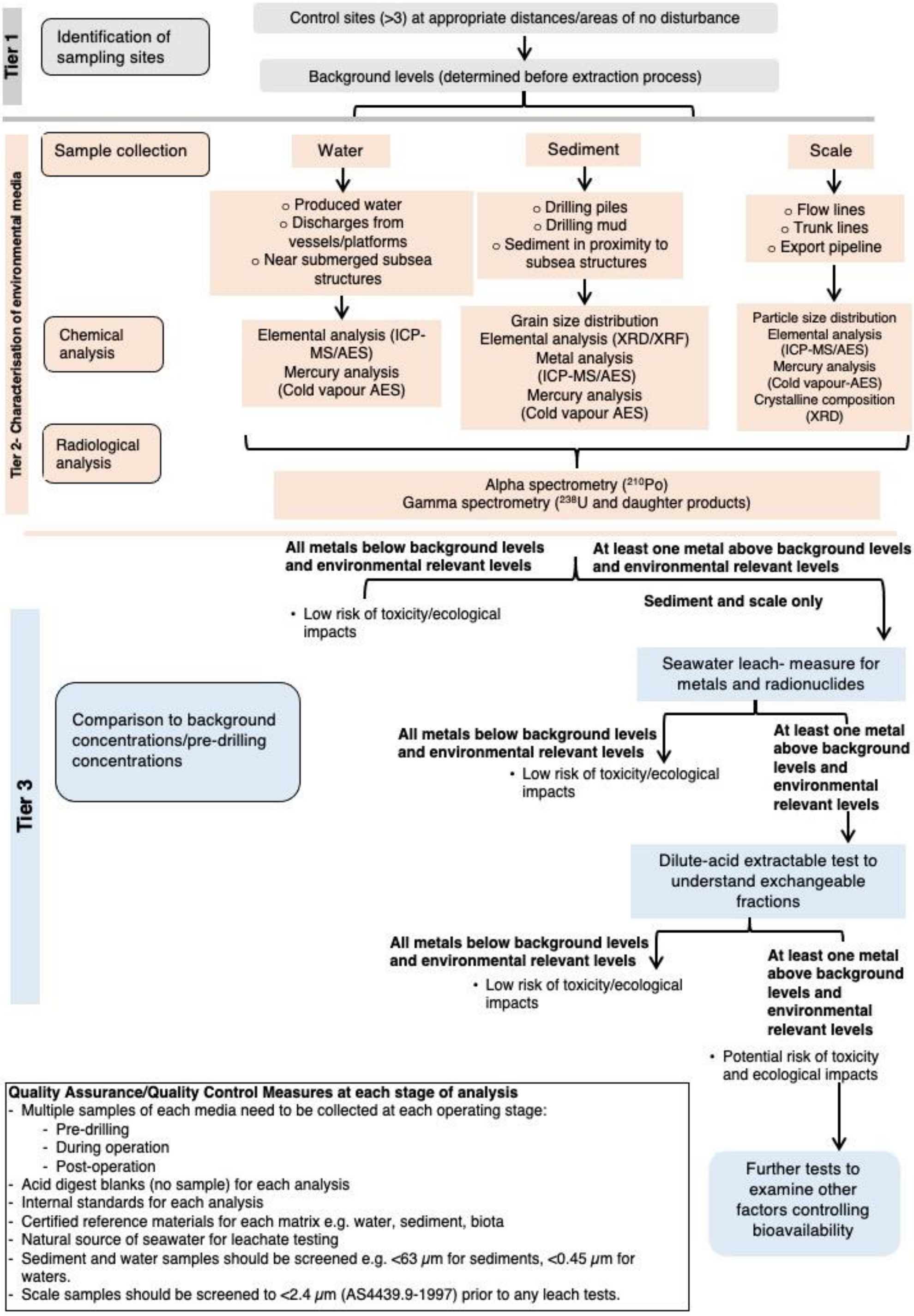
Supplementary Figures

Marine species studied in the papers associated with exposure to naturally occurring radioactive material



Supplementary Figure 1 Number of marine biota species studied for measuring exposure, uptake or effects of naturally occurring radioactive materials (NORMs) from the literature (N=42)

Tiered framework for the assessment of contaminated environmental media from offshore petroleum operations and decommissioning



Supplementary Figure 2 A generalised three-tiered framework for the continual assessment of contaminated water, sediment and scale from offshore petroleum structures and processes. Framework is recommended for the ongoing monitoring of contaminants entering the marine environment through decommissioning procedures and submerged infrastructure scale. Assessment should be followed before, during and after offshore operations in preparation for the decommissioning process. Quality assurance and control measure for sampling and analyses procedures are provided in the textbox. Adapted from Simpson et al. (2005)