Autonomous marine environmental monitoring: application in decommissioned oil fields

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Abstract

Hundreds of Oil & Gas Industry structures in the marine environment are approaching decommissioning. In most areas, decommissioning operations will need to be supported by environmental assessment and monitoring, potentially over the life of any structures left in place. This requirement will have a considerable cost for industry and the public. Here we review approaches for the assessment of the primary operating environments associated with decommissioning — namely structures, pipelines, cuttings piles, the general seabed environment and the water column — and show that already available marine autonomous systems (MAS) offer a wide range of solutions for this major monitoring challenge. Data of direct relevance to decommissioning can be collected using acoustic, visual, and oceanographic sensors deployed on MAS. We suggest that there is considerable potential for both cost savings and a substantial improvement in the temporal and spatial resolution of environmental monitoring. We summarise the trade-offs between MAS and current conventional approaches to marine environmental monitoring. MAS have the potential to successfully carry out much of the monitoring associated with decommissioning and to offer viable alternatives where a direct match for the conventional approach is not possible.

Keywords

Survey; oil and gas; infrastructure; observatories; marine autonomous systems; AUV; glider; rigs to reefs

Highlights

- Decommissioning will impact the marine environment at a global scale
- Environmental monitoring of decommissioning activities helps mitigate impacts
- Marine autonomous systems could automate much environmental monitoring
- Autonomy provides cost savings and improved spatial and temporal resolution
- Trade-offs exist between efficiency and comparison to conventional approaches

1. Introduction

There are 475 oil & gas (O&G) installations in UK seas that will have to be decommissioned as a result of OSPAR Decision 98/3 (Oil and Gas UK, 2014). By 2018, over 50 of these will be approaching or entering decommissioning. The OSPAR Convention prohibits the dumping, and leaving wholly or partly in place, of most offshore installations, although some large structures are exempt (derogation cases; OSPAR decision 98/3). The technical approaches for decommissioning are becoming better understood, but are still being developed on a case-by-case basis. The environmental consequences of decommissioning decisions are relatively poorly known, can cause great controversy, and appear to have the potential for cumulative impacts over a broad scale (Owen and Rice, 2003; Jørgensen 2012).

Pollutants, including oil, other chemicals, and radioactive residues, that can be associated with O&G industry infrastructure were of primary concern during the controversy that surrounded the decommissioning of the Brent Spar in the mid-1990s (Owen & Rice, 1999). Furthermore, significant accumulations of drilling-related sediments, or cuttings piles, lie underneath many oil and gas installations, and may be contaminated with oil and other chemicals (Henry et al. 2017). These cuttings piles represent a disturbance of the natural seabed system, alter faunal communities, and lead to changes in the functioning of seabed ecosystems (Trannum et al. 2010). They also represent a potential hazard for the future as currently stable piles containing harmful chemicals could be re-mobilised and redistributed. Structures in the marine environment, including O&G installations, can also have potentially positive impacts on marine ecology, providing habitat for animals that require hard surfaces (Forteath 1982), focusing local production and / or biomass of fish and seafloor animals (Claisse et al. 2014), and by acting as stepping stones to connect dispersed populations of some species (Thorpe 2012). For example, many North Sea structures are rapidly colonised and typically develop a high biomass ecosystem that may include conservation priority species, such as the cold-water coral *Lophelia pertusa* (Gass and Roberts 2006), recently synonymised with *Desmophyllum pertusum* (Horton et al, 2019). It has also been suggested that the network of structures could also facilitate biological invasions (Glasby et al. 2007).

Decommissioning of obsolete O&G infrastructure is identified as an increasing source of chemical contaminants entering the marine environment from marine sources (Tornero &

Hanke, 2016). Removal of structures has the potential for impacts in the water column through resuspension of contaminated sediment (Schroeder & Love, 2004), including toxic oil-based drilling mud (Ekins et al., 2006), or through leaching of contaminants such as PCBs, residual oil, heavy metals, and other toxic substances as structures corrode (Tornero & Hanke, 2016). The underwater noise (including explosions) likely to be associated with decommissioning has potential impacts on cetaceans, fish (Schroeder & Love, 2004), and seabed invertebrates (Solan et al., 2016).

To understand and manage the environmental impacts of decommissioning, regulations make specific requirements on operating companies for environmental monitoring and assessment. The UK Guidance Notes (DGN: BEIS 2018) issued by the Department for Business, Energy and Industrial Strategy (BEIS) state that decommissioning programmes will need to be supported by an Environmental Appraisal or Environmental Impact Assessment (EIA). In addition, OSPAR Derogation cases will need to be surveyed and monitored for environmental and structural conditions for their entire lifespan, which could be hundreds of years (Sandberg, 1996; Quigel & Thornton, 1989). The European Marine Board (2017) highlights the need for scientific input to “provide a greater evidence base in assessing potential impacts and determining good practice for the decommissioning of offshore installations”. Given the large number of impending decommissioning cases, there is a clear need for a highly efficient survey and monitoring procedure that limits potential costs but also fits the regulators' needs. The traditional methods of marine monitoring, used during the development of the UK O&G industry, are now being supplemented by new, often automated monitoring techniques (Bean et al., 2017). Advances in marine autonomy offer the prospect of enhanced data collection and substantial efficiency gains over current practice, but now require the development of effective and efficient approaches for decommissioning monitoring.

Effective evaluation of impacts is aided by clear guidance on the most relevant environmental factors to consider. The Global Ocean Observing System (GOOS) sets out essential ocean variables (EOVs), parameters that are feasible to measure across platforms and provide relevant information for conservation and management (Miloslavich et al., 2018). In Europe, the Marine Strategy Framework Directive sets out 11 descriptors of Good Environmental Status (GES) for European marine waters (MSFD, 2008). These may be useful to consider in evaluating the optimal approach for monitoring associated with decommissioning (Table 1). Decommissioning has particular potential to impact on several of the GES descriptors. For example: seabed integrity will be disrupted, which may change the functioning of the ecosystem (descriptor 6); underwater noise (descriptor 11) will increase in decommissioning cases; removal of long-term structures from the seafloor and water column will impact the water flow patterns (Cripps & Aabel, 2002) (descriptor 7); and changing three dimensional structure that has been acknowledged to support fish assemblages (Claisse et al., 2014, Fowler & Booth 2014) may have implications for maintenance of biodiversity (descriptor 1) and commercial fish populations (descriptor 3).

Unmanned, self-contained systems (which we refer to as being “autonomous”) have been used to monitor the marine environment for over a century (e.g. Ekman recording current meter; Sverdrup et al., 1942). The greatest revolution in marine autonomous systems (MAS), to date, started with the Swallow float (Swallow, 1955) and led to the global ocean autonomous monitoring network “Argo”, an array of c. 4000 autonomous sensor systems now surveying the upper 2000 m of the world’s ocean (e.g. Medhaug et al., 2017). These ‘simple’ floats have further evolved to sophisticated particle sensing and capturing instruments (Lampitt et al., 2008), and to highly successful underwater gliders (e.g. Rudnick et al., 2004). The last two decades have seen a dramatic rise in the numbers and types of autonomous systems operating in the marine environment, and in the types of sensors these systems now carry (Wynn et al., 2014). Autonomy lends itself well to cost-effective long-term and large-scale monitoring programmes, and is important in a variety of contexts (Danovaro et al. 2016). The basin-wide decommissioning of North Sea O&G infrastructure may be an important case in point. The environmental monitoring of these activities presents a challenge with the standard approaches used that can be solved for the future using MAS.

Here we suggest possible approaches to integrating cost-effective autonomous monitoring of the safety and environmental status of decommissioned structures and their environs into industry practice. The monitoring requirement for decommissioning is potentially huge, with standard time-series monitoring programmes and monitoring “in perpetuity” of many structures and contaminated sites requiring very considerable ship time. Autonomous systems provide a potentially low-cost high-quality solution for repeat assessment (e.g. Wynn et al., 2014). This paper will assess monitoring of decommissioned structures (platforms, wellheads and pipelines), the surrounding seabed (including cuttings piles), and the water column, through the use of autonomous systems. The paper reviews the potential autonomous systems and sensors used, the data they provide for environmental monitoring and discusses trade-offs between MAS and traditional approaches.

2. Areas of interest for environmental monitoring

Oil and gas operations introduce artificial structures into the environment (Figure 1), such as complex three-dimensional structures and pipelines, which regularly extend for tens of kilometres (de Groot, 1982). These structures have the potential to influence both the seabed and water column in the vicinity of operations and beyond. In this section, we briefly introduce the main types of oil field infrastructure; provide an overview of the operating environment, focusing on the North Sea; summarise decommissioning activities; and provide some context for the relevant environmental monitoring requirements (which are presented in Table 2).

2.1. Structures

North Sea O&G structures have been in place since the 1960s to serve drilling and production operations. They are of two basic types: gravity based structures (GBS; e.g. Shell Brent B) and steel jackets (e.g. BP Miller). GBS can be extremely large (e.g. Statoil Troll A is 472 m tall, weighing 683,600 t), however, steel jackets are the most common, at >200 compared to 8 GBS platforms (UK Oil and Gas Authority data 2016). Deep-water fields typically do not use platforms, instead using subsea infrastructure connected via a riser pipe to surface vessels or connected to other facilities via seafloor pipelines (Cordes et al., 2016). In the North Sea, structures are rapidly colonised (Bell & Smith 1999) and typically develop a highly productive ecosystem, e.g. ~2700 tons of marine life have been estimated to live on the Shell Brent Alpha platform (Shell UK, 2017), including conservation priority species such as *Lophelia pertusa*. These structures also likely increase, or at least focus, fish production (Claisse et al. 2014), surrounding benthic biomass, diversity, and connectivity (Macreadie et al. 2011).

A range of options exist for the decommissioning of O&G structures, each of which have different financial, environmental, legal, and technological consequences (Schroeder and Love, 2004). Typical options include (a) leaving the structure unaltered in its current location; (b) toppling the platform; (c) partially dismantling the structure in its current location (for platforms this is usually through “topping” – the removal of only the upper portion of the platform); (d) relocating the structure either to another marine location or to shore for recycling/disposal (Macreadie et al. 2011; Fowler et al., 2018). In the OSPAR area, the assumption is that structures will be removed unless there are specific technical barriers to this (OSPAR decision 98/3), which are listed in annex 1 of the OSPAR decision document (derogation cases). Two UK installations have already received government approval for decommissioning programmes with derogation from OSPAR 98/3, these are NW Hutton, operated by BP, and Frigg MCP01, operated by Total. Several other installations (8 GBS, 31 large steel jackets) and pipelines (>5000 km) are likely to apply for OSPAR derogation owing to their size and / or the difficulty of safe removal (FLTC, 2018). The legal regime for decommissioning is highly variable across jurisdictions globally, leading to major differences in regional practice. For example, in the US Gulf of Mexico, some 200+ structures were left in place (usually unaltered, toppled or moved to a dedicated location) between 1987 and 2006 under the “rigs-to-reefs” programme (Kaiser & Pulsipher, 2005), while in the OSPAR area almost all of the 129 installations decommissioned by 2012 were removed (Jørgensen, 2012).

There will be a need for an environmental assessment of plans for decommissioning of structures, which will need to evaluate the results of recent (within 5 years) environmental baseline / monitoring surveys around the installations to be decommissioned (DECC, 2011). Consideration of the long-term impacts of the decommissioning will be required as will specific plans for emergencies (e.g. oil release). The monitoring requirements for decommissioning are generally not stipulated in detail and need to be developed in consultation with the relevant authority (BEIS Offshore Decommissioning Unit in the UK). In the UK, there is a minimum requirement for debris surveys and post-decommissioning environmental seabed sampling to monitor levels of hydrocarbons, heavy metals and other contaminants in sediments and biota (DECC, 2011). Across Europe, there is also a requirement to consider whether the decommissioning will have a significant effect on species covered by the EC Habitats Directive, for example the cold-water coral *Lophelia pertusa*, and the reef-forming worm *Sabellaria*, which commonly grow on or near North Sea structures. There may be a requirement to conduct surveys to establish whether such species or habitats are present and to what extent (DECC, 2011).

2.2 Pipelines

There are >45,000 km of pipeline in the North Sea, ranging from 1.1 m diameter, surface laid trunk-lines, to umbilicals and power cables (5-20 cm diameter; Oil and Gas UK, 2013). The narrower diameter pipelines are commonly trenched and buried, with an estimated 35-40 thousand subsea protective mattresses, grout bags and rock baskets protecting sections of pipeline in the North Sea (Oil and Gas UK, 2013). Pipelines provide habitat for a range of marine species. Local fish abundance can be significantly higher on pipelines than surrounding seabed (Love & York, 2005), with the increased habitat heterogeneity potentially supporting particular species and enhancing biodiversity (Mclean et al., 2017). Tracking studies show that pipeline routes are targeted by marine mammals for foraging

(Russell et al., 2014) and by commercial fishing operations (Rouse et al., 2018). Pipeline rupture has obvious environmental impacts, however, their routine presence can lead to ongoing environmental concerns, particularly related to contaminants introduced from corrosion of the pipeline or its covering materials.

Various options for pipeline decommissioning have been suggested, from leaving *in situ* with minimal intervention, to total removal (Oil and Gas UK, 2013). Protective structures are to be considered for removal with the aim to achieve a clear seabed. If this is not the optimal solution, alternative options should not interfere with other users of the sea. In the UK, DECC guidance (2011) and the BEIS guidance (2018) indicates that post-decommissioning surveys should extend 100 m either side of the pipeline, with a follow-up survey a year later. As with any decommissioned infrastructure, liability rests with the owner in perpetuity (UK Petroleum Act 1998).

2.3 Near-field seabed

The seabed in the proximity of O&G platforms has typically been exposed to a variety of impacts over the decades of life of the platform. Characteristically, drill cuttings piles are present, formed by the deposition of rock cuttings and drilling mud (clays, barite suspended in fluid such as oil, brine or water) onto or near the seabed (Gerrard et al., 1999). Drilling muds were variously water-based, oil based (typical prior to 1992), or synthetic, and contained a range of other chemical constituents, such as emulsifiers, lubricants, viscosifiers and corrosion inhibitors (Neff, 2005). The sedimentary environment of cuttings piles is therefore typically contaminated with hydrocarbons and metals (Breuer et al., 2004). The initial ‘smothering’ of the seabed by cuttings deposition and subsequent contaminant-related effects generally resulted in reduced abundance and diversity of the local benthic community (meiofauna, Netto et al., 2009; macrofauna, Currie & Isaacs, 2005; megafauna, Jones et al., 2006). In the northern and central North Sea, cuttings pile effects extended to c. 1 km from the wells and persisted for at least 6-8 years, potentially longer if the pile was disturbed (Henry et al. 2017). In deeper waters, the effects may be detectable for years to decades (Jones et al 2012, Gates & Jones 2012, Cordes et al. 2016). In contrast, in shallower waters (e.g. Southern North Sea), where distinct cuttings piles may not form because of stronger currents (Breuer et al., 2004), impacts on the fauna may be essentially undetectable (Henry at al., 2017).

The options for decommissioning of cuttings piles include (i) leaving them *in situ*; (ii)treating them *in situ*, for example through dispersal, dredging, burial or capping; or (iii) removal, and then reinjection into existing wells or shipping ashore for treatment (Gerrard et al., 1999). Most comparative assessments done to date, favour leaving cuttings piles *in situ* and minimising disturbance during decommissioning operations (e.g. Shell UK Ltd, 2016; CNR International, 2017). This option is likely to require the most intensive post-decommissioning survey, especially as potentially harmful levels of hydrocarbons could be released through leaching or if these cuttings piles are disturbed by natural (e.g. storms) or anthropogenic events (e.g. fishing). Coordinated monitoring across many sites may be necessary periodically over many years.

2.4. Far-field seabed

The seabed distant from O&G operations is likely a key environmental monitoring target, serving as a ‘control’ with which to compare both local impacts and temporal change post-decommissioning. The seafloor environment of the North Sea is heterogeneous, encompassing several major gradients: water depth, sedimentology, water column mixing, and organic matter supply (Basford & Eleftheriou, 1988; Dyer et al., 1983; Bricheno et al., 2015). Nevertheless, coherent benthic assemblages can be identified (Basford et al. 1990), as can broadscale biogeographic variations (Heip & Craeymeersch, 1995). It is a dynamic system subject to seasonal change (Hiddink et al., 2015), where the benthos are also known to respond to longer-term climate cycles (Dippner et al., 2014; Birchenough et al., 2015; see section 2.5). The North Sea benthos are subject to numerous other impacts, not least demersal fishing (Kaiser 1998). Monitoring should follow the same approach as for near-field operations. However, distinguishing impacts and recovery post-decommissioning will be complex and likely require a broadscale and long-term approach that acknowledges other impacts, biogeographic variation, and climate-related change.

2.5. Water column

The water column immediately surrounding O&G installations may have locally enhanced biomass (Claisse et al., 2014), including commercially important species (Fujii, 2015). Evidence suggests that marine mammals may utilise these localised stocks as a food resource (Todd et al., 2009). Consequently, removal of O&G infrastructure will diffuse these local aggregations to the background populations or to other comparable physical habitats. Post-decommissioning, other impacts might include seabed (cuttings pile; section 2.3), and near-seabed (any remaining physical infrastructure; section 2.1) impacts, release of contaminants, e.g. metals, hydrocarbons, and other organic chemicals (Shimmield et al., 2000). It is conceivable that there may be some residual reefing effects, where some infrastructure is left in place, but this is expected to be minor.

Any release of contaminants at or near-seabed in the near-field environment (section 2.3) will be likely rapidly diffused to the background / far-field water column. Conventional approaches for oceanographic assessment, such as Niskin bottle sampling or sensor-based water column assessment (e.g. CTD), can be used to monitor changes in a wide range of parameters, including physical, chemical and biological. Water column monitoring was often considered lower priority than benthic assessment in typical industry surveys, but is now receiving increased attention (Nilssen & Bakke, 2011) and may be important in decommissioning applications. Water column monitoring is typically split into environmental effects monitoring, which examines effects on caged organisms, and environmental condition monitoring, which relates to temporal and spatial measurement of water column conditions (Nilssen & Bakke, 2011). As noted in the far-field seabed case (section 2.4), biological effects monitoring is likely to be complicated by the known impact of long-term climate cycles, e.g. North Atlantic Oscillation and Atlantic Multidecadal Oscillation, on the North Sea pelagic system and fish stocks (Gröger et al., 2010; Auber et al., 2015); again suggesting the need for a broadscale and long-term monitoring approach.

3. Autonomous systems for decommissioning monitoring

The capability and use of marine autonomous systems (MAS) has increased rapidly in recent years, enabling oceanographic observations at spatial and temporal scales impossible from traditional ships (Rudnick et al., 2004; Hartman et al., 2012). MAS are increasingly applied in marine geoscience (Wynn et al., 2014), habitat mapping (Robert et al., 2014), and benthic ecology (Morris et al., 2016). MAS can be divided between static, fixed-point observatories (FPO; Cristini et al., 2016), and a variety of mobile platforms. The latter can be broadly split into underwater gliders, autonomous underwater vehicles (AUV), unmanned surface vehicles (USV), and seabed landing and crawling vehicles.

3.1. Underwater gliders

Gliders are driven by a buoyancy engine, and capable of long deployments (months) covering large areas or time-series observations at particular locations (Liblik et al., 2016). Gliders are slow moving (0.3 ms^{-1}) and their payload is limited to low-power sensors (<1 W). They travel forward in a “saw-tooth” or “yo-yo” dive profile, providing repeated water column profile data. When surfaced, GPS positioning, data transmission, and mission refinement messages can be sent via satellite (Rudnick, 2016). Gliders carry an increasingly diverse sensor payload, including depth, temperature, conductivity, depth average current, turbidity, fluorescence and acoustic energy. Underwater navigation is from dead reckoning relative to the water column and is often poor, so it is not possible to attribute sensor readings to precise locations. Given their low speed, gliders may be difficult to operate in strong currents. In decommissioning, gliders may have a role in demonstrating ‘evidence of absence’ or identifying local anomalies, e.g. increases in turbidity or fluorescence. Networks of vehicles could be used for tracking specific release events, such as hydrocarbons mobilised by cuttings pile disturbance during decommissioning (Reed & Hover, 2014). Gliders may also be a suitable platform for active (Guihen et al., 2014) or passive acoustic monitoring (Baumgartner et al., 2013; Mellinger et al., 2007) of the post-decommissioning environment.

3.2 Autonomous underwater vehicles

AUVs can be broadly classified as either ‘survey-class’ or ‘hover-class’ vehicles. The former are typically large (>1.5 m) torpedo-shaped vehicles driven by a single propeller (Huvenne et al., 2018), that require constant forward motion to maintain stability and manoeuvrability, and can reach speeds up to 2 ms^{-1} (Wynn et al., 2014). They are well suited to geographically precise survey work that requires long distances to be covered at constant speed (e.g. geoacoustic surveys). Hover-class vehicles have several propellers or thrusters to provide low speed full 3D manoeuvrability and may be operated in proximity to both natural (Monk et al., 2016) and artificial structures (Bingham et al., 2010) or over complex seabed terrain (Ferrari et al., 2016).

Underwater vehicles cannot navigate with direct reference to satellite positions, which can cause problems for accurate positioning (Paull et al., 2014). Dead-reckoning is usually used for navigation, based on an inertial navigation system and a doppler velocity log (DVL; Paull et al., 2014). This requires an initial position fix estimate and is subject to cumulative error, or drift over the dive track (Huvenne et al., 2018). The growth of this error can be limited by: (a) acoustically linking the AUV to a ship or USV to improve navigational accuracy (Phillips et al., 2018); (b) operating the AUV within an acoustic long baseline (LBL) system of fixed acoustic nodes (Paull et al., 2014); (c) utilising terrain aided navigation (TAN) where observed bathymetric features are compared to an *a priori* map (Salavasidis et al. 2018); or (d) simultaneous localisation and mapping (SLAM) where a map is built and used for localisation in real time from observed bathymetric features (Barkby et al. 2009). The moderate range of survey or hover-class vehicles mean they would typically be launched from a ship. Long range survey class AUVs, such as Autosub Long Range (Furlong et al, 2012;

Roper et al. 2017), offer shore launch capabilities and multi-month endurance but have lower navigational accuracy and more limited power than typical survey- or hover-class AUVs.

Depending on payload and energy capacity, AUVs can be equipped with a wide range of sensors: acoustic systems (e.g. acoustic Doppler current profilers, multibeam echosounders, sidescan sonars, interferometric sonars, sub-bottom profilers, passive acoustic monitoring), geophysical tools (magnetometers, gravimeters), oceanographic sensors (conductivity, temperature, depth, oxygen, turbidity, fluorescence, pH, REDOX, etc.) and optical systems (conventional cameras, stereo cameras, laser scanners) (e.g. Caress et al., 2008, Connelly et al., 2012; Morris et al., 2014; Sumner et al., 2013; Williams et al., 2010; Yoerger et al., 1998). At present, AUVs have a very limited capacity for the collection of physical samples, largely restricted to relatively small volume water samples (Harvey et al., 2012; Pennington et al., 2016), though note that other samplers are in development and field testing is ongoing, for example for a zooplankton sampler equivalent in performance to a high-specification towed net system (Billings et al., 2017).

In decommissioning-related environmental monitoring, AUVs have capability for detailed acoustic mapping and visual inspection of structures (Robert et al., 2017) and cuttings piles (Gerrard et al. 1999), sensor-based assessment of chemical contaminant and suspended solid concentrations (Camilli et al., 2010), photographic assessments of benthic and pelagic marine life (Morris et al., 2016; Pedersen et al., 2010), and acoustic determination of fish and marine mammal densities (see 3.1). AUVs may have particular application for monitoring in O&G activity areas impacted by ice (Dowdeswell et al., 2008) including oil spills (Kukulya et al., 2016). Long range vehicles may be well suited to regular monitoring of many decommissioned sites spread over a wide geographic area.

3.3. Unmanned surface vehicles

This category includes both powerful boat-like vessels with diesel engines, and environmentally-powered platforms that may use solar, wind, or wave energy. Diesel-powered vehicles are generally used for short-term operations (hours, days) and may be operated remotely or autonomously, usually within sight of the operator. Environmentally powered vehicles can have considerable endurance, even crossing ocean basins (Goebel et al., 2014), and can be controlled via satellite. Both classes may carry a range of sensors to assess surface ocean conditions. Diesel-powered vehicles have application in seabed mapping (Wilson & Williams, 2017). They have been used in the Gulf of Mexico to increase the efficiency of metocean data collection, communicate with underwater vehicles (Leonard and Bahr, 2016), detect hydrocarbons, and carry out passive acoustic monitoring (e.g. Pai, 2015). There may be potential for coupling of surface vehicles with aerial drones, for example to carry out aerial photography (e.g. of seabirds, cetaceans, infrastructure) or make atmospheric measurements.

3.4 Fixed-point observatories

Having developed from simple anchored, self-recording instruments, today's fixed-point ocean observatories (FPOs) can provide multidisciplinary water column and / or seabed environmental time-series data in real- or near-real time (Cristini et al., 2016). These observatories variously apply acoustic, short-range radio, satellite link, and cabled data transmission to shore stations (Ruhl et al., 2011). Sensors are frequently self-powered, requiring routine servicing, though may be augmented by solar power, and in some cases are supplied with cabled power (Martin Taylor, 2009). They are typically equipped with a range of oceanographic sensors, including passive acoustic monitoring (Lin et al., 2015), and optical systems, that may be arranged through the water column, and at the seafloor (Ruhl et al., 2011). FPOs are increasingly used to provide long-term data on environmental variability and have already been employed in O&G-related studies (Vardaro et al., 2013; Osterloff et al., 2016). FPOs would allow high-temporal resolution data to be obtained before, during and after decommissioning operations, tracking a range of parameters including suspended solids, chemical contaminants, noise, light and faunal behaviour. They may also offer an approach for long-term monitoring, although they usually require regular maintenance (e.g. Juniper et al., 2013; Vardaro et al., 2013).

3.5. Seabed landing and crawling autonomous vehicles

Vehicles operating in contact with the seabed are currently the least common class of MAS, with the best known systems operated in association with deep-water FPOs. The "Benthic Rover" is a tracked vehicle that operates at the Station M long-term observatory site in the NE Pacific (Smith et al., 2009). It is primarily equipped with seabed observing cameras and a pair of flux chambers that can be inserted into the seafloor to measure sediment community oxygen consumption (McGill et al., 2009). TRAMPER is also a tracked crawling MAS and typically operates at the HAUSGARTEN observatory in the Fram Strait (Soltwedel et al., 2016). It too is equipped with seabed observing cameras, and is primarily designed to carry out sediment oxygen profiling using fibre optic-based optodes inserted into the seafloor (Wenzhöfer et al., 2016). Both of these deep-water crawling vehicles are designed for long-term studies of 6-12 months. A variety of seabed landing / interacting AUVs are in development or concept (Wang et al., 2009; Matsuda et al., 2017) as is a hybrid crawl-hover-class AUV (Pyo & Yu, 2016). Seabed landing and crawling vehicles may provide a useful role in decommissioning monitoring, particularly in the monitoring of cuttings piles. Here, the flux chamber or profiling electrode approach could be used to assess spatial and temporal change in contaminant release and seabed ecosystem function.

4. MAS sensors for monitoring decommissioning

Autonomous operations are typically very limited in terms of physical sample collection, and are consequently reliant on sensor-based data. Sensor research and development for MAS applications is currently very active, with microfluidic technology at the forefront of recent advances (Nightingale et al., 2015). MAS offer the potential for increasing the spatial and temporal resolution of sensor-based measurements. In the following, we consider established technologies that are at a high state of readiness, which can be relied upon today for monitoring of decommissioning (summarised in Table 3).

4.1. Geoacoustic sensors

Survey-class AUVs provide very attractive platforms from which to conduct geophysical surveys (multibeam echosounders, MBES; sidescan sonars; synthetic aperture sonars; sub-bottom profilers) by being decoupled from sea surface motion and holding a steady altitude above seabed. As a result, this application is already very well developed in commercially available vehicles. For example, O&G AUV-based MBES surveys are used to characterise new exploration and exploitation areas (e.g. Jones et al. 2014), providing better quality (by minimising pitch, roll and yaw variation) and higher resolution bathymetry data (m-scale pixels) than can be achieved from surface vessels (10 to 100m pixels).

AUVs are generally well-proven in geological and geomorphological investigations (e.g. Wynn et al., 2014; Huvenne et al., 2018). For the monitoring of finer-scale patterns of seafloor composition or disturbance (e.g. debris <1 m, trawl marks, cuttings piles), high-resolution sidescan or synthetic aperture sonars (>200 kHz) are commonly integrated in AUVs. They have also been employed to monitor change in conservation priority habitats such as cold-water corals and *Sabellaria* reefs (Huvenne et al., 2016a; Pearce et al, 2014). Similarly, obtaining high-resolution profiles of the shallow subsurface can be achieved using sub-bottom profilers or chirp systems (Tubau et al., 2015), with application in monitoring seafloor integrity, cuttings piles, buried pipelines, and the presence of gas or fluids in the shallow sub-seafloor. In addition to these conventional applications, the same sensor systems can be reorientated, on appropriate vehicles, to map vertical and overhanging surfaces and structures (Guerneve & Petillot, 2015). Such approaches have been successfully applied to joint geological and ecological assessments of complex seafloor terrain (Huvenne et al., 2016b; Robert et al., 2017) and the AUV-based mapping of the underside of sea ice and ice shelves (Jenkins et al., 2010). These techniques would be directly applicable to the monitoring of any structures remaining after decommissioning operations.

4.2. Visual sensors

Conventional imaging (photography) in the marine environment has a long and successful history in the assessment and monitoring of many aspects of marine biology and ecology

(Solan et al., 2003; Durden et al., 2016). An option for seabed photography is already available in a number of commercially available AUVs, having been employed from research vehicles for some time (Jones et al., 2005; Morris et al., 2014). Similarly, time-lapse photography is well-established in FPO operations (Bett, 2003; Bett et al., 2001), with O&G-related examples including both long-term deep-water seabed observations (Vardaro et al., 2013), and water column observations of infrastructure-associated fish populations (Fujii & Jamieson, 2016). Water column imaging systems for the assessment of particle concentration and plankton populations are well developed (Benfield et al., 2007), with many suited to integration with MAS operations. Laser-based particle imaging has been implemented on survey-class AUVs for the study of zooplankton (Pedersen et al., 2010) and suspended sediment particles (Thompson et al., 2013). A development of these approaches allows the monitoring of oil droplets, gas bubbles, and oil-coated gas bubbles, and has been trialled in a submarine mining tailing placement study that may have particular relevance to cuttings pile disturbance (Davies & Nepstad, 2017).

Laser-based imaging systems have also been employed to provide 3D reconstruction of the viewed scene, using a variety of techniques (laser line scanning, laser striping, range-gated imaging, structured lighting), that have been implemented in towed systems, Remotely Operated Vehicles (ROVs), and AUVs (Massot-Campos & Oliver-Codina, 2015). Such approaches have been further developed to combine conventional imaging (colour photography) with 3D scene capture (Bodenmann et al., 2017), and have been successfully deployed on a hover-class AUV (Nishida et al., 2016). These various imaging systems have clear applications to post-decommissioning environmental monitoring, whether censusing pelagic or benthic communities, quantifying particles in the water column, or examining the 3D structure of the seafloor or any remaining O&G infrastructure.

4.3. Oceanographic sensors

Many commercially available Argo floats, gliders and AUVs can be, or are routinely, equipped with a basic set of oceanographic instruments comprising conductivity, temperature, depth, oxygen, turbidity, and fluorescence sensors. Similar, and often more extensive, sensor suites are typically fitted to FPOs (Hartman et al., 2012; Vardaro et al., 2013). In addition to their typical use in assessing phytoplankton (chlorophyll), fluorescence sensors have also been employed to monitor oil in water. Coloured (or chromophoric) dissolved organic matter (CDOM) fluorescence can be used to detect crude oil, including use on a survey class AUV in the mapping of the deep-water oil plume following the Macondo blowout (Ryan et al., 2013). CDOM sensors are not specific to oil or particular oils, greater specificity can be achieved by membrane inlet mass spectrometry (MIMS) and these instruments have been developed for *in situ* operations (Schlüter & Gentz, 2008). Carried by a hover-class AUV, this type of system was also used to map the Macondo deep-water oil plume (Camilli et al., 2010; White et al., 2016). *In situ* chemical sensors are in a phase of development, with some potentially suitable for MAS applications, for example dissolved manganese sensors (Meyer et al., 2016), that have been carried by a hover-class AUV (Doi et al., 2008). Sensors for *in situ* microbiological sensing are generally large and expensive at present but innovations in technology and biochemistry are leading to potential for use in offshore monitoring of water quality (McQuillian & Robidart, 2017).

4.4. Water column acoustics

Many MAS operations (gliders, AUVs, USVs, FPOs) include acoustic Doppler current profiling instruments that enable assessments of water movements (Randeni et al., 2017), and have the potential to estimate suspended sediment concentrations and movements as may result from trawling or dredging activities (Van Lancker & Baeye, 2015). Larger MAS systems have been used to obtain water column acoustic data for some time, and have now been successfully incorporated in gliders (Guihen et al., 2014). The ability of acoustic systems to detect particles in the water column is also exploited in hydro- / bioacoustic MAS applications through the use of multifrequency or broadband fisheries echosounders (Trenkel et al., 2009; Brierley et al., 2003). The geoacoustic sensors (section 4.1) commonly deployed on AUVs can also be employed to assess fish stocks, using both MBES (Innangi et al., 2016) and sidescan sonar instruments (Grothues et al., 2017). Similarly, gas escapes from the seafloor can also be mapped using these techniques (MBES: Urban et al., 2017), including survey-class AUV-mounted interferometric sidescan sonar (Blomberg et al., 2017). MAS systems may be favoured over other methods because they can carry these range-limited instruments closer to the targets of interest (e.g. Benoit-Bird et al., 2017), and being generally quiet, may minimise observer bias (Griffiths et al., 2001). Despite this, some mobile midwater organisms do exhibit escape responses to moving MAS (Dunlop et al., 2018).

Active acoustic methods can be used to characterise a range of parameters of direct relevance to decommissioning operations. Water column MBES measurements are also used to characterise the full extent of large objects on the seabed (e.g. Hughes Clarke et al., 2006). Gas escapes from the seafloor or pipelines can also be assessed by passive acoustic monitoring (PAM) (Leighton and White, 2012), where MAS deployment may be the preferred option (Blackford et al., 2015). The PAM approach can also be employed to detect, and potentially localise, a wide range of natural and anthropogenic sounds in the marine environment (Baumgartner et al., 2018). MAS applications, often targeting marine mammals, have been successfully undertaken from simple FPOs (Merchant et al., 2014; Hildebrand et al., 2015), cabled-FPOs (Lin et al., 2015; Caruso et al., 2017), an O&G-related deep-water FPO (Vardaro et al., 2013), gliders (Suberg et al., 2014), and USVs (Bingham et al., 2012).

5. MAS data for monitoring decommissioning

Here we briefly review some key properties of the data generated by autonomous platforms and how they can be analysed. We focus on the challenges presented by data from autonomous platforms that are likely to be used to support environmental monitoring of decommissioned areas.

5.1 Geoacoustic data

Geoacoustic data acquired by MAS are very similar in nature to that acquired by ship-board operations and are often of higher resolution. Processing of data from autonomous platforms follows similar routines to conventional surveys, except for additional complications owing to higher positional uncertainty (see below) and the vertical position of the vessel changing considerably throughout the survey (Calder and Mayer, 2003). General

AUV mapping approaches are well developed (e.g. Grasmueck et al., 2006; Dupré et al., 2008) and have now also been adapted to the mapping of complex structures (e.g. Robert et al., 2017). Navigational errors may pose challenges for acoustic mapping, particularly if data for one survey are obtained over different dives or different parts of the dive. Solving this is best done at the time of acquisition, but it is possible to correct the navigation based on manual or automatic feature matching across overlapping sections of data (Barkby et al., 2009). For most decommissioning applications spatial accuracy and precision requirements will be very high, likely beyond that which can be achieved through dead reckoning alone. The most robust solution to bound navigation errors is via regular acoustic position updates throughout the dive, either via a network of seabed transponders or by acoustic communication with a surface vessel (ship or USV).

5.2 Visual data

Autonomous platforms can generate large volumes of high-quality visual data, such as seafloor photographs (Morris et al., 2014). For many applications, manual image annotation has been the primary way of extracting data from images, which can be slow and laborious for large datasets (Durden et al., 2016). New tools for pre-processing (Lu et al., 2017) and annotation speed up workflows (Langenkämper et al., 2017). However, advances in artificial intelligence are likely to be important in more routine use of autonomous vehicles for monitoring. These will aid the workflows by identifying features of interest for human annotators and by automatically identifying objects visible in images. Semi-automated approaches, with expert training of identification algorithms, have been successfully applied to underwater image sets, with reasonable accuracy (Schoening et al., 2012). Automated approaches have been successfully applied to the assessment of both geological (Schoening et al., 2016) and biological features (Gormley et al., 2018; Lüdtke et al., 2012; Kannappan et al., 2014).

AUV photography can be used to make high-resolution photo-mosaics (Singh et al., 2004) over relatively large areas of seafloor (e.g. ~0.1 km^2; Kwasnitschka et al., 2016). Mosaics construction can be automated (Pizarro et al., 2017) and can be achieved with lower-quality navigation (Barreyre et al., 2012). The resulting mosaics have many applications (Martin et al., 2007), including accurate spatial and temporal assessment of changing environmental conditions (Barreyre et al., 2012), which would be directly relevant for monitoring of changes in decommissioned sites. Stereo photography (Johnson-Roberson et al., 2010) or structure-from-motion techniques (Robert et al., 2017) can also be used to automatically generate accurate bathymetry maps or morphometric assessments of structures. Laser-based approaches from AUVs offer the potential for higher resolution automated 3-dimensional reconstruction and metrology (Massot-Campos and Oliver-Codina, 2015; Thornton et al., 2016), which could be used to assess centimetre-scale changes in decommissioned structures over time.

5.3 Oceanographic data

Underwater gliders collect water column profile data similar to a ship-deployed CTD instruments. Increasingly complex sensor payloads collect high quality water column data over relatively long time periods, including during weather conditions that may prevent ship-borne operations (Peterson and Fer 2014). Internally stored position and engineering data for the glider and its sensors are transmitted by Iridium or ARGOS satellite when the glider is at the surface. At these times, return control communication is available to enable adaptive mission planning. Low power and slow speed, particularly in coastal waters, and dead-reckoning navigation between surfacing means that spatial precision can be low, but temporal resolution of oceanographic processes is high.

Glider survey design relies on a balance between survey duration, data quantity and quality, sampling frequency and battery life (Willcox et al., 2001). The maximum depth for the saw-tooth dive profile of submarine gliders can be regulated by an altimeter or pressure sensor. Use of an altimeter can provide greater coverage of the water column in shallower water, i.e. by diving to a specified altitude above the seabed rather than a specified depth in the water column (Suberg et al., 2014). Glider attitude may influence sensor data relevance and reliability, e.g. irradiance sensors are sensitive to orientation of the glider (Ross et al., 2017). Information from high data rate / volume sensors, such as active and passive acoustic systems, may be too extensive for satellite transmission such that full data processing is only possible after the glider is recovered.

Fixed-point observatories may be cabled or standalone, collecting a broad range of oceanographic parameters at depths from the surface to the seabed (Cristini et al., 2016). Standalone FPOs provide similar data to the temporary metocean moorings often used by industry to inform engineering design of surface and subsurface infrastructure. They may provide near real-time data via satellite communications with the surface buoy (e.g. Hartman et al., 2012). Cabled observatories can offer direct communications to control the instrumentation, collect real-time data, and can potentially interact with autonomous mobile platforms such as AUVs (Howe et al., 2015). The different arrays of instruments and sensors on FPOs require varying workflows but there are some common requirements, in particular around quality assurance; these include automated and manual procedures (e.g. Abeysirigunawardena et al. 2016). Algorithm-based event detection is also a very desirable capability for long-term environmental monitoring. For example, autonomous geohazard observatory systems may respond to particular pressure or seismicity changes by increasing sampling rates and issuing an alert communication (Monna et al., 2014).

Common challenges for long-term instrument deployments include sensor calibration, sensor drift, and biofouling. In the case of gliders, ship-bourne CTD deployments can be carried out at the launch and recovery points to account for sensor drift (Suberg et al., 2014), and / or data can be cross-referenced between simultaneous glider deployments (Ross et al., 2017). Ships of opportunity, and observatory servicing vessels, can play a similar role in the calibration of FPO instruments (Beggs et al., 2012). Sensors deployed in the deep ocean typically experience only modest biofouling, however, instruments deployed in the surface ocean or coastal seas can be subject to extreme biofouling. The intended operating environment and the nature of the sensor system will determine the need for anti-fouling measures (Delauney et al., 2010; Rolin et al. 2011; Laurent et al., 2017).

5.4 Sound and Noise data

Passive acoustic monitoring (PAM) uses hydrophones to detect sound in the marine environment and can be applied to ambient or anthropogenic sources (Merchant et al. 2014). Hydrophones have been deployed on fixed-point observatories (Caruso et al. 2017), autonomous underwater vehicles (Mellinger et al. 2017) and unmanned surface vehicles (Bingham et al. 2012). EU MSFD descriptor 11 sets out monitoring requirements for noise pollution, including measuring the 10 Hz to 10 kHz frequency band for sound sources likely to impact marine animals, and the annual average of continuous ambient sound (60 Hz -125 Hz; van der Schaar et al., 2017). Monitoring of bioacoustics is less prescriptive and may fall within the MSFD biodiversity indicator suite. Cabled FPOs offer a flexible approach to acoustic data flow and data processing. In contrast, stand-alone observatories or moorings may have communication limitations and require on-board data storage (with compression) and transmission of pre-processed data. Other considerations include acoustic interference such as intentional noise (modems, ADCPs), mechanical noise (e.g. movement of the platform) or electrical noise, which may be mitigated by decoupling the hydrophone from other systems and / or data processing methods. Similar challenges exist for mobile platforms, though submerged gliders may be well suited because of the lack of continuous motor noise and sea surface noise (Mellinger et al. 2017).

Passive acoustic monitoring often produces high volume datasets. Van de Schaar et al (2017) propose that for environmental impact assessment, a noise level and cetacean presence report should be presented, including the levels over time and the distribution of cetacean detection. For comparisons in space and time, standardised metadata protocols for PAM datasets have been developed (Roch et al. 2016). PAM data is often classified manually, aurally or visually from the spectrogram parameters (e.g. Klinck et al., 2012), although advances are being made in automated classification (e.g. Frasier et al., 2017). Automated systems have been demonstrated with varying levels of classification success depending audio quantity, quality and number of species present (Gillespie et al. 2013), but are becoming increasingly comparable with manual assessments (Korneliussen et al. 2016). In the case of odontocete echolocation clicks, compressed acoustic data stored onboard gliders have been screened autonomously using a detection algorithm (Klinck & Mellinger., 2011) and successfully reported specific detection events back to shore during glider surfacing (Klinck et al., 2012).

5.5 Active acoustic water column data

The mid-water acoustic datasets obtained by MAS are comparable to those obtained by other means, although equivalent data are considerably slower to obtain with gliders than with other MAS systems and ships (Guihen et al., 2014). To date the application of these data has been to measure the abundance and distribution of midwater organisms, including zooplankton, fish and marine mammals (Baumgartner et al., 2013; Dunlop et al., 2018; Guihen et al., 2014; Klinck et al., 2012; Melvin et al., 2003). Depending on the platform, careful processing of data may be necessary, as they are sensitive to vehicle attitude (Guihen et al., 2014). Calibration of the sensor and the resultant data is important, but can be complex for mid-water MBES as it relies on precise vehicle navigation (Dunlop et al., 2018). Although additional steps may be required for processing, these are readily automated and are unlikely to pose a significant challenge for monitoring operations. Mid-water acoustic data, particularly that obtained by MBES are voluminous, which may present some problems with storage and processing (Dunlop et al., 2018).

5.6 Data quality and management

The quality control of large data streams generated by MAS is important, particularly for monitoring applications where datasets are compared that are collected on multiple occasions potentially with multiple vehicles and different operators. The production of good quality and representative data is dependent on good field and laboratory practices (Ibe and Kullenberg, 1995). Such practices may include sensor calibration prior to deployment and validation of sensor calibrations at deployment and recovery. Intercalibration of approaches may be required (Birk et al., 2013). Post-collection quality control of data is often important and may be accomplished via automated approaches, such as those used for large-scale integrations of ocean data — for example the European Commission Copernicus Marine Service (CMEMS; von Schuckmann et al., 2018). Documentation of the approach (in metadata) is essential to allow both the assessment of data quality and to provide the necessary information to afford a reasoned interpretation of data. Parts of this documentation may be inherent to MAS system operation (e.g. in mission programmes), but needs to be recorded alongside datasets with the appropriate range of other metadata.

The effectiveness of MAS operations for monitoring of decommissioning is dependent not only on the data collection but also on the implementation and maintenance of procedures to ensure access to high-quality data, data documentation, and derived products (Porter et al., 2004). Management of monitoring data requires robust systems for assembly, storage, registration, dissemination, and permanent archiving of data collections. Management of high-quality data is not a unique challenge for use of MAS in monitoring, although the volume and possible complexity of MAS data may mean that effective data management is particularly important. The approaches for data management are not reviewed here, but significant international (e.g. Global Ocean Observing System (GOOS)) efforts have been made to promote standardised management practices for ocean data including integrating those obtained by MAS (Meredith et al., 2013).

6. Trade-offs between MAS and other approaches

In many cases, MAS simply provides a new platform for well-established sensors that have a historic track record in O&G industry-related monitoring programmes. As such, where they offer gains in efficiency, increased spatial and temporal coverage, and / or reduced cost, there is little need to question their adoption. However, the currently rather limited capability for MAS to acquire physical samples warrants further consideration.

Physical samples have been important in past and current environmental assessment and monitoring for decommissioning, providing material for laboratory analyses that yield widely understood results. Some resistance to change may stem from an assumption that physical samples are necessary. Yet, if the parameter of interest can be measured at an appropriate accuracy and precision with a MAS sensor, then the temporal, spatial, and statistical distribution of that monitoring target will be better established via MAS. A range of such approaches already exist and have been deployed on MAS. Some sophisticated approaches are already possible, for example, autonomous mass spectrometers have been demonstrated for water column chemical characterisation (Camilli et al., 2010), micro-sensors and other techniques (such as eddy correlation) are used routinely in scientific applications to measure a range of parameters in sediments, including from autonomous landers (Glud, 2008), but require expert interpretation that does not yet exist in commercial service providers (White et al., 2016). Translating these techniques to MAS and remotely operated systems is already in progress, for example through developments with seabed crawlers (Purser et al., 2013, Smith et al., 2014). In contrast, some other analyses /

parameters may be very difficult (if not impossible) to achieve via MAS, e.g. macrofaunal abundance and diversity. It is conceivable that proxy solutions could be implemented, for example through *in situ* molecular techniques (e.g. Harvey et al., 2012); however, the selection of alternative indicators may be the most tractable option. In the case of the key variables of ecosystem health that often lie at the centre of environmental monitoring, e.g. the essential biodiversity variables (EBVs) of the global biodiversity observing system (GEO BON; Kissling et al. 2018), there are certainly numerous alternatives. The potential uplift in temporal and spatial monitoring resolution that would be possible with MAS should be carefully weighed against maintaining historical precedent.

As a relatively novel tool for the monitoring of decommissioning, MAS data may not always be directly comparable with the available legacy data (Table 2). Some parameters, which cannot be assessed autonomously - those currently requiring physical samples, may nevertheless be essential to understand specific environmental impacts. This linkage to legacy data may be an important consideration, they have a clear role in understanding long-term trends, particularly those associated with historic field development and those at distant locations (control sites) beyond the immediate influence of O&G operations. However, those data collected for baseline assessments and monitoring of O&G projects are highly variable in quality and quantity, and many sites have insufficient data for any robust time-series assessments to be made (Henry et al., 2017). Consequently, the true value of such large existing industry databases (e.g. the UK Benthos Database; Henry et al., 2017) to post-decommissioning monitoring is not clear. In the North Sea case, past-present-future comparisons are further complicated by both: (a) the presence of a major demersal fishing industry, with its concomitant impacts on the seafloor environment; and (b) major climate-related systematic seasonal and inter-annual variations in the fauna (see Section 2.4, 2.5). These factors again suggest the timely need to weigh the potentially major benefits of MAS against maintaining the status quo in marine monitoring generally.

There are some risks associated with MAS operations, particularly in the vicinity of oil and gas operations (Brito and Griffiths, 2016). These include risks of loss of the MAS themselves, but also potential scenarios where other operations or even safety are compromised. These more serious risks primarily relate to the potential for entanglement or collision between MAS and vessels or infrastructure. Simultaneous operation of MAS and other vessels may represent challenges, particularly if rapid response operations are necessary. These issues are wider than decommissioning monitoring and present an area of active legal and operational practice development (Showalter, 2004). MAS may also act to reduce risks of monitoring, particularly when compared to vessel-based operations.

7. Prospectus - basin-scale integrated monitoring

MAS offer many solutions for the future of marine environmental monitoring for decommissioning. MAS operations are often most effective when multiple systems (e.g. satellites, floats, moorings, AUVs, etc.) are integrated as an observation network to develop a more synoptic view of the environment (Ohman et al. 2013, Meyer et al. 2016). At present, completely autonomous operations are unlikely and will require combination with, and support from, ship-based efforts. In the case of decommissioned oil fields, a range of autonomous platforms would be incorporated in an idealised monitoring scheme. Here we consider the near-term possibilities of an integrated MAS approach that would potentially be scalable to multiple fields or a complete basin.

Regular monitoring of decommissioned sites and their environs is assumed to be a key regulatory requirement. At the broadest scale, remote sensing by satellite imaging of ocean colour has a role to play in localising and monitoring phytoplankton blooms (Blondeau-Patissier et al. 2014), and in the identification and tracking of major changes such as accidental releases of hydrocarbons (Brekke and Solberg 2005). FPOs located strategically in industrially exploited basins, such as the North Sea, would support the ground-truthing of satellite data and potentially provide the background data necessary to distinguish changes relating to decommissioning from those driven by environmental variability (natural or other anthropogenic impacts). It may be possible to utilise some existing seafloor infrastructure to introduce cabled FPOs, allowing good two-way communication with the deployed MAS network (Howe et al., 2015).

Detailed monitoring of water column (oceanographic) conditions in the vicinity of decommissioned fields is likely best achieved with underwater gliders. With month to year durations, gliders could be tasked with repeat surveys around points of interest, assessing water column parameters, potentially including release of contaminants. Such operations would likely require conventional surface vessel support, including the collection of calibration data and follow-up sampling of any persistent features detected in the telemetered glider data. Suitable support vessels would require relatively modest capabilities and could support multiple deployed vehicles and FPOs. Some of the necessary support functions could be achieved using ‘ships of opportunity’.

MAS operations may also be valuable prior to decommissioning, not least in establishing baseline conditions, with early adoption of autonomous techniques providing a smooth transition to the future monitoring scenario. Satellites and aerial drones deployed from operational rigs could provide remote sensing of ocean colour, temperature, wave climate and marine mammals (Torres et al., 2018). Small USVs could be deployed safely around existing infrastructure gathering data on a range of surface ocean characteristics (e.g. physical, chemical and noise). Similarly, gliders could be flown in tight circuits of the near-field environment to better constrain local temporal and spatial variability in water column profiles. Greater detail on key near-field baseline characteristics of the water column and seafloor might be obtained via FPOs. With the latter potentially installed and maintained using existing ROVs and their support vessels (Gates et al., 2016; Macreadie et al., 2018; Petersen, 2014). During decommissioning operations a balance would need to be achieved whereby any environmental data necessary or valuable for subsequent monitoring was collected without impacting the decommissioning operation itself. FPOs may be particularly well suited in that case; installed prior to operations beginning and providing monitoring during the decommissioning and the immediate post-decommissioning phases.

It is likely that a major data acquisition effort will be focussed on describing environmental conditions immediately post-decommissioning, with follow-up monitoring at intervals subsequently. The first step in the post-decommissioning phase may be high-resolution acoustic mapping of the area to establish baseline seafloor morphology, including any remaining structures or other features of interest - a mission that survey class AUVs are particularly well-suited to, and where they have an existing O&G industry track record (Jones et al., 2014). The same or similar AUVs could also carry out visual imaging and / or mapping of the seafloor, providing direct evidence of seafloor physical condition and benthic biodiversity data. Other AUV sensor-based monitoring could include water column temperature, turbidity, and contaminant levels (with common sensors also deployed via FPOs and gliders). Within-sediment environment conditions could potentially be assessed using FPOs and crawler class AUVs. Acoustic observations of the near-field water column by USV, gliders, FPOs or AUVs could be used to quantify the presence and abundance of fish and cetaceans in the water column. Remaining and / or buried or infrastructure could also be specifically targeted using hover class AUVs, some of which have already been specifically designed for such operations (Cormell, 2012; Liljebäck and Mills. 2017; Sverdrup-Thygeson et al., 2016). Snake-like AUVs (e.g. the Eelume vehicle; Liljebäck and Mills, 2017; Sverdrup-Thygeson et al., 2016) could be used to enter confined spaces to gather data, for example from storage cells.

At present, several MAS systems can be launched from shore, aerial vehicles, small vessels or vessels of opportunity (Phillips et al., 2017). In the near future, purpose-designed long-range AUVs are likely to be able to make long (>100 km) transits to get to or move between work sites (Roper et al., 2017; Kukulya et al., 2016). Such capabilities for self transiting will greatly facilitate and reduce the cost of operations. Force multiplication by multiple vehicles or multiple types of vehicles (e.g. AUVs coupled with USVs) offer opportunities for improvements to surveys (e.g. by improving positional accuracy) or further efficiency gains (Jung et al., 2009). It may also be possible to use any remaining (or nearby) infrastructure to improve the performance of MAS, for example using power or data transfer capacities by direct docking of AUVs and / or acoustic communication systems (Galletti di Cadilhac and Brighenti, 2003; Qiao et al., 2017). Strategic operations shared between operators within a region may further reduce costs, with MAS systems moving between multiple sites and gathering directly comparable data. Such broad-scale operations might encompass decommissioned sites, active O&G operations, and reference ‘unimpacted’ areas. A regionally-consistent monitoring programme of this type would address the specific needs of post-decommissioning monitoring, and would represent a very substantial contribution to various international commitments concerning environmental protection - not least the vision of the UN Decade of Ocean Science for Sustainable Development, that has as a strategic objective the development of enhanced ocean observing networks, data systems, infrastructure, and supporting cooperation and partnerships to service the demands of all nations by 2030 (IOC 2018).

8. Conclusions

The specific requirements for environmental monitoring post-decommissioning are likely to vary between environments, perceived threats, and jurisdictions. Nevertheless, long-term monitoring is likely to be necessary to meet regulatory requirements and provide assurance to other stakeholders. Current standard practise does permit effective monitoring, however, the temporal and spatial resolution of that effort is typically limited by the high cost of ship time. MAS does offer significant potential to reduce that financial and carbon-footprint cost and reduce human risk of seagoing operations; however, its ability to offer a major uplift in the temporal and spatial resolution of environmental monitoring data should also be given serious consideration.

Here, we have shown that autonomous solutions now exist for many of the relevant monitoring challenges, and that they already offer the potential to streamline some operations. The major perceived limitation of autonomy in post-decommissioning monitoring is the general inability to collect physical samples, particularly in the case of the seabed sediments. This necessarily limits the use of particular current standard practices. It is our view that these issues may well be surmountable through careful re-evaluation of appropriate indicators and / or by rapid technological advances. We hope that we have indicated that a number of the potential solutions already exist, though have yet to become commercially available. Industry demand and regulatory support could help to increase the pace of that technology transfer. There seems little doubt that MAS will be a transformative technology for environmental monitoring, only the rate of change is uncertain. From Eckman's mechanical current in the first years of the 20th century to the extraordinary success of today's global network of Argo floats, autonomy has revolutionised oceanographic sciences, it is now set to move marine environmental monitoring and conservation substantially forwards.

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Table 1: Marine Strategy Framework Directive (MSFD) descriptors of good environmental status, possible outcomes after decommissioning, and potential for monitoring with autonomous systems.

MSFD	Descriptor	Decommissioning	Autonomous monitoring[1]
1	Biodiversity is maintained	Removal of structures leads to local loss of epigrowth species; local infaunal returns to natural	Monitor visible benthos by AUV (spatial) and FPO (temporal)
2	Non-indigenous species do not adversely alter the ecosystem	Return to natural; loss of non-indigenous epigrowth species	AUV visual monitoring of remaining artificial hard substratum habitats and presence of non-indigenous species
3	The population of commercial fish species is healthy	Loss of local aggregations, return to natural; loss of refugia for commercially important species	Visual monitoring of demersal (AUV, FPO) and pelagic (FPO) species; acoustic assessment of pelagic species (AUV, glider, USV, FPO)
4	Elements of food webs ensure long-term abundance and reproduction	Loss of local aggregations / biomass, return to natural; local change in trophic interactions	As MSFD 1 and 3
5	Eutrophication is minimised	Reduced local eutrophication by removal of epigrowth community; potential local eutrophication increase by cuttings pile disturbance	As MSFD 1 and water column biogeochemisty (AUV, glider, FPO)
6	The sea floor integrity ensures functioning of the ecosystem	Physical disturbance of the seafloor	As MSFD 1 and 5, and geophysical mapping (AUV, USV)

7	Permanent alteration of hydrographical conditions does not adversely affect the ecosystem	Return to natural	As MSFD 5 and 6
8	Concentrations of contaminants give no effects	Mobilisation / remobilisation of contaminants; accidental discharges	Overwatch by satellite, and USV, glider, AUV, FPO standard sensors (as MSFD 5); alert physical sampling need where persistent anomaly detected
9	Contaminants in seafood are below safe levels	Risk of food chain transfer from mobilisation / remobilisation of contaminants	No autonomous measurement. Risk awareness via MSFD 5 and 8
10	Marine litter does not cause harm	Return to natural	As MSFD 1
11	Introduction of energy (including underwater noise) does not adversely affect the ecosystem	Return to natural (short-term impact only)	Passive acoustics monitoring (FPO) during decommissioning operations; continued monitoring via additional means (USV, glider) readily achieved.

[1] AUV, autonomous underwater vehicle; FPO, fixed-point observatory; USV, unmanned surface vehicle

Table 2. Summary and comparison of established methods, and potential autonomous methods, for decommissioning monitoring. For simplicity, some cases are presented as near-field (visually impacted with potential presence of structures) and far-field (distant from operations with no history of infrastructure in place). AUV: autonomous underwater vehicle; FPO: fixed-point observatory; FW UAV: fixed-wing unmanned aerial vehicle; NDT: non-destructive testing (evaluating the condition of subsea equipment); USV: unmanned surface vehicle; ROV: remotely operated vehicle.

Area of interest	**Characteristic**	**Purpose**	**Established method**	**Established indicator**	**Autonomous method**	**Most similar indicator from autonomous approach**	**Comparability of indicators**
Structures	Physical location & morphology	Safety of operations; monitoring of derogation cases	Acoustic and visual survey, diver / ROV	Bathymetry and imagery	Visual & acoustic survey by (hover) AUV; acoustic survey by USV	Bathymetry and imagery	Common instrumentation
	Physical integrity	Safety of operations; monitoring of derogation cases	Visual / NDT surveys by diver / ROV	Observable / detectable deterioration or damage	Visual / NDT survey by (hover) AUV	Observable / detectable deterioration or damage	Common instrumentation
	Biological epigrowth	Structural integrity; biological effects	Visual survey by diver / ROV	Areal (%) cover/ estimated biomass	Visual survey by (hover) AUV	Areal (%) cover/ estimated biomass	Common instrumentation
	Aggregation of mobile species	Biological effects	Acoustic / visual survey from surface vessel (diver / ROV)	Abundance and composition of mobile species (fish / mammals)	Acoustic / visual survey from USV, (hover) AUV, FPO	Abundance and composition of mobile species (fish / mammals)	(Largely) common instrumentation
Pipelines (rock dumps and mattresses)	Physical location & morphology	Safety of operations; monitoring of derogation cases	Visual, acoustic & magnetic survey from surface vessel (tow-body / ROV)	Bathymetry, magnetometry and imagery	Visual, acoustic & magnetic survey by (cruise / hover) AUV, USV option in shallow water	Bathymetry, magnetometry and imagery	Common instrumentation
	Physical integrity	Safety of operations; monitoring of derogation cases	Visual, acoustic & NDT survey from surface vessel (diver / ROV)	Observable / detectable deterioration or damage	Visual, acoustic & NDT survey by (hover) AUV; acoustic survey by USV (shallow)	Observable / detectable deterioration or damage	Common instrumentation
	Chemical composition of sediments	Monitoring sediment contaminants	Physical sampling from surface vessel	Laboratory assessment (e.g. hydrocarbons, metals)	Sediment penetrating sensor survey by (crawling) AUV, or possibly FPO	Not established	Sensor data may be limited to water column / pore water only

	Sediment characteristics	Monitoring physical changes to the sediment	Visual and acoustic survey from surface vessel (tow-body / diver / ROV); physical sampling	Visual / acoustic description; particle size data from samples	Visual and acoustic survey by AUV; acoustic survey by USV	Visual / acoustic description	Common instrumentation for visual and acoustic data; sampling not possible
	Sediment fauna	Biological effects	Primarily physical sampling from surface vessel; some visual assessment (ROV)	Typically macrofaunal abundance and composition; some visual surveys of epibenthos	Visual survey by (cruise / hover) AUV; visual monitoring from FPO	Epibenthos abundance and composition	Biodiversity metrics, but not for macrofauna
	Biological epigrowth	Biological effects	Visual survey by diver / ROV from surface vessel	Areal (%) cover/ estimated biomass	Visual survey by (hover) AUV	Areal (%) cover/ estimated biomass	Common instrumentation
	Aggregation of mobile species	Biological effects	Visual / acoustic survey from surface vessel (tow-body / ROV)	Abundance and composition of mobile species (e.g. large invertebrates / fish)	Visual / acoustic survey by (cruise / hover) AUV, acoustic surveys from USV or AUV	Abundance and composition of mobile species (e.g. large invertebrates / fish)	Common instrumentation
Near-field seabed (cuttings piles)	Physical location & morphology	Monitoring seabed / cuttings pile condition and extent	Acoustic survey from surface vessel	Bathymetry and backscatter amplitude (sidescan)	Acoustic survey by (cruise / hover) AUV or USV	Bathymetry and backscatter amplitude (sidescan)	Common instrumentation
	Surface physical integrity	Monitoring post-decommissioning disturbance (subsidence, trawling) and erosion	Visual & acoustic survey from surface vessel (tow-body / diver / ROV)	Bathymetry, backscatter amplitude (sidescan) and imagery	Visual & acoustic survey by (cruise / hover) AUV (USV option in shallow water)	Bathymetry, backscatter amplitude (sidescan) and imagery	Common instrumentation
	Subsurface physical integrity	Monitoring seabed / cuttings pile condition and extent; monitoring potential fluid / sediment movement	Acoustic survey from surface vessel (tow-body)	Sub-bottom profiling	Acoustic survey by (cruise / hover) AUV (USV option in shallow water)	Sub-bottom profiling	Common instrumentation
	Chemical composition	Monitoring sediment contaminants	Physical sampling from surface vessel	Laboratory assessment (e.g. hydrocarbons, metals)	Sediment penetrating sensor survey by (crawling) AUV, or possibly FPO	Not established	Sensor data may be limited to water column / pore water only
	Sediment characteristics	Monitoring physical changes to the sediment	Visual and acoustic survey from surface vessel (tow-body / diver / ROV); physical sampling	Visual / acoustic description; particle size data from samples	Visual and acoustic survey by AUV; acoustic survey by USV	Visual / acoustic description	Common instrumentation for visual and acoustic data; sampling not possible

	Sediment fauna	Biological effects	Primarily physical sampling from surface vessel; some visual assessment (ROV)	Typically macrofaunal abundance and composition; some visual surveys of epibenthos	Visual survey by (cruise / hover) AUV; visual monitoring from FPO	Epibenthos abundance and composition	Biodiversity metrics, but not for macrofauna
	Epifaunal communities	Biological effects	Visual survey (tow-body / diver / ROV) from surface vessel; some limited physical sampling (trawl / ROV)	Epifaunal abundance and composition	Visual survey by (cruise / hover) AUV; visual monitoring from FPO	Epifaunal abundance and composition	Common instrumentation or comparable data
	Aggregation of mobile species	Biological effects	Visual / acoustic survey from surface vessel (tow-body / ROV)	Abundance and composition of mobile species (e.g. large invertebrates / fish)	Visual / acoustic survey by (cruise / hover) AUV, acoustic surveys from USV or AUV; visual monitoring from FPO	Abundance and composition of mobile species (e.g. large invertebrates / fish)	Common instrumentation
Water column	Oceanography	Primary environmental characterisation	Moored (FPO) and ship-deployed instruments.	Temperature, salinity, oxygen, pH, turbidity, current speed etc.	Sensors deployed by glider, AUV or FPO	Temperature, salinity, oxygen, pH, turbidity, current speed etc.	Common instrumentation
	Water quality (chemical contamination)	Monitoring contaminants	Physical sampling and sensors from surface vessel; in situ ecotoxicology	Contaminant concentration	Sensor deployment by glider, (cruise / hover) AUV; USV, FPO; very limited sampling capacity	Contaminant concentration or proxy value	Largely sensor only; limited sampling capability
	Zooplankton	Biological effects	Physical sampling, acoustic / visual survey from surface vessel (tow-body / ROV)	Zooplankton abundance and composition	Visual and acoustic survey by (cruise / hover) AUV, FPO and USV (acoustic)	Zooplankton abundance and composition	Common instrumentation for visual and acoustic methods; limited sampling capability
	Fish	Biological effects	Physical sampling, acoustic and visual survey from surface vessel (tow-body / ROV)	Pelagic fish abundance and composition	Visual and acoustic survey by (cruise / hover) AUV, FPO and USV (acoustic)	Pelagic fish abundance and composition	Common instrumentation for acoustic and visual methods; no sampling capability
	Marine mammals	Biological effects	Visual survey; passive acoustic monitoring	Marine mammal abundance and composition	Visual survey by UAV; passive acoustic survey by AUV / USV / FPO	Marine mammal abundance and composition	Potentially comparable visual survey data; common instrumentation for passive acoustics

Far-field seabed	Surface physical integrity	Monitoring post-decommissioning disturbance (subsidence, trawling) and erosion	Visual & acoustic survey from surface vessel (tow-body / diver / ROV)	Bathymetry, backscatter amplitude (sidescan) and imagery	Visual & acoustic survey by (cruise / hover) AUV (USV option in shallow water)	Bathymetry, backscatter amplitude (sidescan) and imagery	Common instrumentation
	Subsurface physical integrity	Monitoring potential gas / oil seepage	Acoustic survey from surface vessel (tow-body)	Sub-bottom profiling	Acoustic survey by (cruise / hover) AUV (USV option in shallow water)	Sub-bottom profiling	Common instrumentation
	Chemical composition	Monitoring sediment contaminants	Physical sampling from surface vessel	Laboratory assessment (e.g. hydrocarbons, metals)	Sediment penetrating sensor survey by (crawling) AUV, or possibly FPO	Not established	Sensor data may be limited to water column / pore water only
	Sediment characteristics	Monitoring physical changes to the sediment	Visual and acoustic survey from surface vessel (tow-body / diver / ROV); physical sampling	Visual / acoustic description; particle size data from samples	Visual and acoustic survey by AUV; acoustic survey by USV	Visual / acoustic description	Common instrumentation for visual and acoustic data; sampling not possible
	Sediment fauna	Biological effects	Primarily physical sampling from surface vessel; some visual assessment (tow-body / diver / ROV)	Typically macrofaunal abundance and composition; some visual surveys of epibenthos	Visual survey by (cruise / hover) AUV; visual monitoring from FPO	Epibenthos abundance and composition	Biodiversity metrics, but not for macrofauna
	Epifaunal communities	Biological effects	Visual survey (tow-body / diver / ROV) from surface vessel; some limited physical sampling (trawl / ROV)	Epifaunal abundance and composition	Visual survey by (cruise / hover) AUV; visual monitoring from FPO	Epifaunal abundance and composition	Common instrumentation or comparable data

Table 3: Advantages and disadvantages for using autonomous systems for measuring key environmental indicators for decommissioning environmental impact.

Indicator	Advantages of autonomous systems	Disadvantages of autonomous systems	Recommendations
Bathymetry and seabed fabric	**1.** High-quality and high-resolution data; can access restricted areas; multiple sensor operations; potentially significant time / money / carbon footprint / risk savings	**1.** Potentially reduced navigational accuracy; potentially reduced reliability / increased risk of loss; increased initial costs; currently lower availability	**1.** In broad-scale surveys, use partnered surface ship or USV to improve navigation where necessary; for local repeat surveys, use seabed features / deployed markers / deployed acoustic transponders to improve navigation where necessary
Visual characterisation of the seabed	**2.** Greatly increased areal acquisition rate / areal coverage (statistically robust data); improved consistency in image quality and prospect of (semi-) automated data generation; greater temporal resolution (e.g. during winter storms)	Primary limitations as **1.**	Primary recommendations as **1.** **2.** Survey class AUV for efficiency in open ground; hover class AUV for capability in restricted areas / complex terrain; FPO for local-scale time-series monitoring
Physical sediment characterisation	Essentially none; physical sampling unlikely to become practicable; (alternatives may be as valuable)	No physical sampling	Consider objectives; is the physical sample essential; are proxy measures (visual assessment) sufficient
Sediment chemistry	Well-developed science use in flux measurement (chamber and profiling systems); likely only viable for FPO operations	No physical sampling	Consider use / further development of existing flux measurement systems; and potential application via crawling AUV

Primary oceanographic data	**3.** Greatly increased temporal and spatial resolution; scope for remote intervention in form of reactive / adaptive surveys; excellent support for satellite monitoring	Very strictly limited physical sampling capability	Consider objectives; is the physical sample essential; directly addresses primary "essential ocean variables"; should be rapidly established as an environmental monitoring norm
Epifauna (epigrowth) abundance and composition	Primary advantages as **1.** and **2.**	Primary limitations as **1.** Absence of physical samples may limit taxonomic resolution / precision	Primary recommendations as **1.** and **2.** Consider objectives; is taxonomic precision essential; is open nomenclature sufficient **[Note a]**
Infauna abundance and composition	Essentially none; physical sampling unlikely to become practicable; (alternatives may be as valuable)	No physical sampling.	Consider objectives; is the physical sample essential; are proxy measures (visual assessment of epifauna) sufficient; non-destructive sampling may be highly desirable in localised repeat monitoring operations (e.g. cuttings piles)
Marine mammal abundance and composition	Primary advantages as **3.** Low noise / disturbance may be of particular importance	Difficult to obtain data directly equivalent to that from marine mammal observers; photography from UAV or USV may assist	Consider the potential use of passive acoustic monitoring on gliders and FPOs as a norm
Fish abundance and composition	Primary advantages as **3.** Low noise / disturbance may be of particular importance	Limited availability of directly comparable historic data	Consider as a routine addition to assessment of epifauna abundance and composition; may be of particular value in the case of FPOs deployed to monitor remaining infrastructure

[Note a] Open nomenclature – the uncertainty or provisional status of specimen identifications can be expressed by a set of terms and abbreviations known as "open nomenclature" (see e.g. Sigovini et al., 2016), and / or the identification of specimens to morphological categories (see e.g. Althaus et al., 2015).

Figures

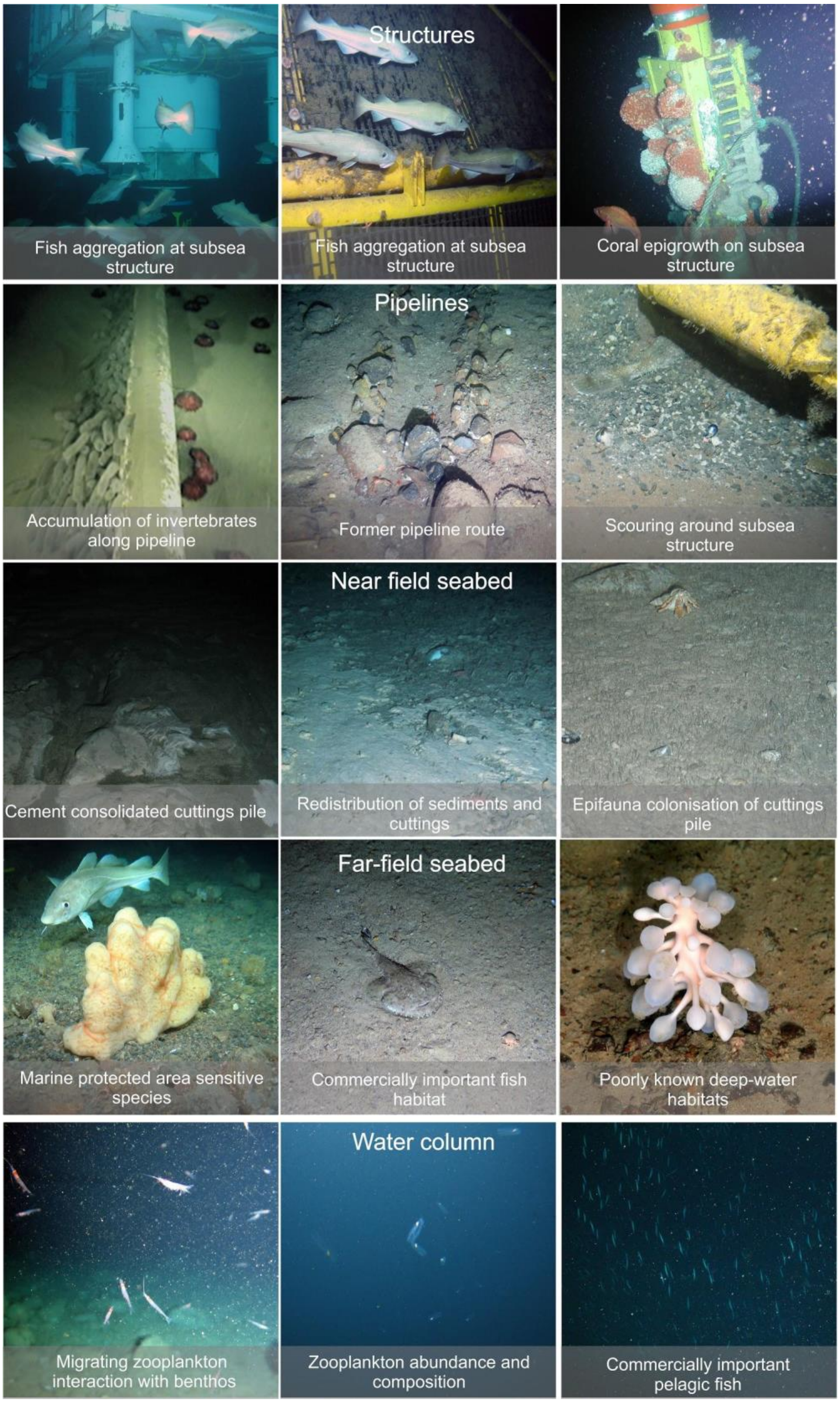

Figure 1: Photographs showing examples of habitats and impacts under consideration (photographs taken by the authors at active hydrocarbon drilling sites).