

1 **Autonomous marine environmental monitoring: application in**
2 **decommissioned oil fields**

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12 **Abstract**

13 Hundreds of Oil & Gas Industry structures in the marine environment are approaching
14 decommissioning. In most areas, decommissioning operations will need to be supported by
15 environmental assessment and monitoring, potentially over the life of any structures left in
16 place. This requirement will have a considerable cost for industry and the public. Here we
17 review approaches for the assessment of the primary operating environments associated
18 with decommissioning — namely structures, pipelines, cuttings piles, the general seabed
19 environment and the water column — and show that already available marine autonomous
20 systems (MAS) offer a wide range of solutions for this major monitoring challenge. Data of
21 direct relevance to decommissioning can be collected using acoustic, visual, and
22 oceanographic sensors deployed on MAS. We suggest that there is considerable potential
23 for both cost savings and a substantial improvement in the temporal and spatial resolution

24 of environmental monitoring. We summarise the trade-offs between MAS and current
25 conventional approaches to marine environmental monitoring. MAS have the potential to
26 successfully carry out much of the monitoring associated with decommissioning and to offer
27 viable alternatives where a direct match for the conventional approach is not possible.

28

29 **Keywords**

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

32

33 **Highlights**

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

39

40

41 **1. Introduction**

42 There are 475 oil & gas (O&G) installations in UK seas that will have to be decommissioned
43 as a result of OSPAR Decision 98/3 (Oil and Gas UK, 2014). By 2018, over 50 of these will be
44 approaching or entering decommissioning. The OSPAR Convention prohibits the dumping,
45 and leaving wholly or partly in place, of most offshore installations, although some large
46 structures are exempt (derogation cases; OSPAR decision 98/3). The technical approaches
47 for decommissioning are becoming better understood, but are still being developed on a
48 case-by-case basis. The environmental consequences of decommissioning decisions are

49 relatively poorly known, can cause great controversy, and appear to have the potential for
50 cumulative impacts over a broad scale (Owen and Rice, 2003; Jørgensen 2012).
51
52 Pollutants, including oil, other chemicals, and radioactive residues, that can be associated
53 with O&G industry infrastructure were of primary concern during the controversy that
54 surrounded the decommissioning of the Brent Spar in the mid-1990s (Owen & Rice, 1999).
55 Furthermore, significant accumulations of drilling-related sediments, or cuttings piles, lie
56 underneath many oil and gas installations, and may be contaminated with oil and other
57 chemicals (Henry et al. 2017). These cuttings piles represent a disturbance of the natural
58 seabed system, alter faunal communities, and lead to changes in the functioning of seabed
59 ecosystems (Trannum et al. 2010). They also represent a potential hazard for the future as
60 currently stable piles containing harmful chemicals could be re-mobilised and redistributed.
61 Structures in the marine environment, including O&G installations, can also have potentially
62 positive impacts on marine ecology, providing habitat for animals that require hard surfaces
63 (Forteath 1982), focusing local production and / or biomass of fish and seafloor animals
64 (Claisse et al. 2014), and by acting as stepping stones to connect dispersed populations of
65 some species (Thorpe 2012). For example, many North Sea structures are rapidly colonised
66 and typically develop a high biomass ecosystem that may include conservation priority
67 species, such as the cold-water coral *Lophelia pertusa* (Gass and Roberts 2006), recently
68 synonymised with *Desmophyllum pertusum* (Horton et al, 2019). It has also been suggested
69 that the network of structures could also facilitate biological invasions (Glasby et al. 2007).
70
71 Decommissioning of obsolete O&G infrastructure is identified as an increasing source of
72 chemical contaminants entering the marine environment from marine sources (Tornero &

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

80

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

97 practice, but now require the development of effective and efficient approaches for
98 decommissioning monitoring.

99

100 Effective evaluation of impacts is aided by clear guidance on the most relevant
101 environmental factors to consider. The Global Ocean Observing System (GOOS) sets out
102 essential ocean variables (EOVs), parameters that are feasible to measure across platforms
103 and provide relevant information for conservation and management (Miloslavich et al.,
104 2018). In Europe, the Marine Strategy Framework Directive sets out 11 descriptors of Good
105 Environmental Status (GES) for European marine waters (MSFD, 2008). These may be useful
106 to consider in evaluating the optimal approach for monitoring associated with
107 decommissioning (Table 1). Decommissioning has particular potential to impact on several
108 of the GES descriptors. For example: seabed integrity will be disrupted, which may change
109 the functioning of the ecosystem (descriptor 6); underwater noise (descriptor 11) will
110 increase in decommissioning cases; removal of long-term structures from the seafloor and
111 water column will impact the water flow patterns (Cripps & Aabel, 2002) (descriptor 7); and
112 changing three dimensional structure that has been acknowledged to support fish
113 assemblages (Claisse et al., 2014, Fowler & Booth 2014) may have implications for
114 maintenance of biodiversity (descriptor 1) and commercial fish populations (descriptor 3).

115

116 Unmanned, self-contained systems (which we refer to as being “autonomous”) have been
117 used to monitor the marine environment for over a century (e.g. Ekman recording current
118 meter; Sverdrup et al., 1942). The greatest revolution in marine autonomous systems
119 (MAS), to date, started with the Swallow float (Swallow, 1955) and led to the global ocean
120 autonomous monitoring network “Argo”, an array of c. 4000 autonomous sensor systems

121 now surveying the upper 2000 m of the world's ocean (e.g. Medhaug et al., 2017). These
122 'simple' floats have further evolved to sophisticated particle sensing and capturing
123 instruments (Lampitt et al., 2008), and to highly successful underwater gliders (e.g. Rudnick
124 et al., 2004). The last two decades have seen a dramatic rise in the numbers and types of
125 autonomous systems operating in the marine environment, and in the types of sensors
126 these systems now carry (Wynn et al., 2014). Autonomy lends itself well to cost-effective
127 long-term and large-scale monitoring programmes, and is important in a variety of contexts
128 (Danovaro et al. 2016). The basin-wide decommissioning of North Sea O&G infrastructure
129 may be an important case in point. The environmental monitoring of these activities
130 presents a challenge with the standard approaches used that can be solved for the future
131 using MAS.

132

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

144

145 **2. Areas of interest for environmental monitoring**

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

154

155 2.1. Structures

156 North Sea O&G structures have been in place since the 1960s to serve drilling and
157 production operations. They are of two basic types: gravity based structures (GBS; e.g. Shell
158 Brent B) and steel jackets (e.g. BP Miller). GBS can be extremely large (e.g. Statoil Troll A is
159 472 m tall, weighing 683,600 t), however, steel jackets are the most common, at >200
160 compared to 8 GBS platforms (UK Oil and Gas Authority data 2016). Deep-water fields
161 typically do not use platforms, instead using subsea infrastructure connected via a riser pipe
162 to surface vessels or connected to other facilities via seafloor pipelines (Cordes et al., 2016).
163 In the North Sea, structures are rapidly colonised (Bell & Smith 1999) and typically develop a
164 highly productive ecosystem, e.g. ~2700 tons of marine life have been estimated to live on
165 the Shell Brent Alpha platform (Shell UK, 2017), including conservation priority species such
166 as *Lophelia pertusa*. These structures also likely increase, or at least focus, fish production
167 (Claisse et al. 2014), surrounding benthic biomass, diversity, and connectivity (Macreadie et
168 al. 2011).

169

170 A range of options exist for the decommissioning of O&G structures, each of which have
171 different financial, environmental, legal, and technological consequences (Schroeder and
172 Love, 2004). Typical options include (a) leaving the structure unaltered in its current
173 location; (b) toppling the platform; (c) partially dismantling the structure in its current
174 location (for platforms this is usually through “topping” – the removal of only the upper
175 portion of the platform); (d) relocating the structure either to another marine location or to
176 shore for recycling/disposal (Macreadie et al. 2011; Fowler et al., 2018). In the OSPAR area,
177 the assumption is that structures will be removed unless there are specific technical barriers
178 to this (OSPAR decision 98/3), which are listed in annex 1 of the OSPAR decision document
179 (derogation cases). Two UK installations have already received government approval for
180 decommissioning programmes with derogation from OSPAR 98/3, these are NW Hutton,
181 operated by BP, and Frigg MCP01, operated by Total. Several other installations (8 GBS, 31
182 large steel jackets) and pipelines (>5000 km) are likely to apply for OSPAR derogation owing
183 to their size and / or the difficulty of safe removal (FLTC, 2018). The legal regime for
184 decommissioning is highly variable across jurisdictions globally, leading to major differences
185 in regional practice. For example, in the US Gulf of Mexico, some 200+ structures were left
186 in place (usually unaltered, toppled or moved to a dedicated location) between 1987 and
187 2006 under the “rigs-to-reefs” programme (Kaiser & Pulsipher, 2005), while in the OSPAR
188 area almost all of the 129 installations decommissioned by 2012 were removed (Jørgensen,
189 2012).

190

191 There will be a need for an environmental assessment of plans for decommissioning of
192 structures, which will need to evaluate the results of recent (within 5 years) environmental

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

206

207 2.2 Pipelines

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

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

221

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

230

231 2.3 Near-field seabed

232 The seabed in the proximity of O&G platforms has typically been exposed to a variety of
233 impacts over the decades of life of the platform. Characteristically, drill cuttings piles are
234 present, formed by the deposition of rock cuttings and drilling mud (clays, barite suspended
235 in fluid such as oil, brine or water) onto or near the seabed (Gerrard et al., 1999). Drilling
236 muds were variously water-based, oil based (typical prior to 1992), or synthetic, and
237 contained a range of other chemical constituents, such as emulsifiers, lubricants, viscosifiers
238 and corrosion inhibitors (Neff, 2005). The sedimentary environment of cuttings piles is
239 therefore typically contaminated with hydrocarbons and metals (Breuer et al., 2004). The
240 initial 'smothering' of the seabed by cuttings deposition and subsequent contaminant-

241 related effects generally resulted in reduced abundance and diversity of the local benthic
242 community (meiofauna, Netto et al., 2009; macrofauna, Currie & Isaacs, 2005; megafauna,
243 Jones et al., 2006). In the northern and central North Sea, cuttings pile effects extended to c.
244 1 km from the wells and persisted for at least 6-8 years, potentially longer if the pile was
245 disturbed (Henry et al. 2017). In deeper waters, the effects may be detectable for years to
246 decades (Jones et al 2012, Gates & Jones 2012, Cordes et al. 2016). In contrast, in shallower
247 waters (e.g. Southern North Sea), where distinct cuttings piles may not form because of
248 stronger currents (Breuer et al., 2004), impacts on the fauna may be essentially
249 undetectable (Henry et al., 2017).

250

251 The options for decommissioning of cuttings piles include (i) leaving them *in situ*; (ii) treating
252 them *in situ*, for example through dispersal, dredging, burial or capping; or (iii) removal, and
253 then reinjection into existing wells or shipping ashore for treatment (Gerrard et al., 1999).

254 Most comparative assessments done to date, favour leaving cuttings piles *in situ* and
255 minimising disturbance during decommissioning operations (e.g. Shell UK Ltd, 2016; CNR
256 International, 2017). This option is likely to require the most intensive post-
257 decommissioning survey, especially as potentially harmful levels of hydrocarbons could be
258 released through leaching or if these cuttings piles are disturbed by natural (e.g. storms) or
259 anthropogenic events (e.g. fishing). Coordinated monitoring across many sites may be
260 necessary periodically over many years.

261

262 2.4. Far-field seabed

263 The seabed distant from O&G operations is likely a key environmental monitoring target,
264 serving as a 'control' with which to compare both local impacts and temporal change post-
265 decommissioning. The seafloor environment of the North Sea is heterogeneous,
266 encompassing several major gradients: water depth, sedimentology, water column mixing,
267 and organic matter supply (Basford & Eleftheriou, 1988; Dyer et al., 1983; Bricheno et al.,
268 2015). Nevertheless, coherent benthic assemblages can be identified (Basford et al. 1990),
269 as can broadscale biogeographic variations (Heip & Craeymeersch, 1995). It is a dynamic
270 system subject to seasonal change (Hiddink et al., 2015), where the benthos are also known
271 to respond to longer-term climate cycles (Dippner et al., 2014; Birchenough et al., 2015; see
272 section 2.5). The North Sea benthos are subject to numerous other impacts, not least
273 demersal fishing (Kaiser 1998). Monitoring should follow the same approach as for near-
274 field operations. However, distinguishing impacts and recovery post-decommissioning will
275 be complex and likely require a broadscale and long-term approach that acknowledges
276 other impacts, biogeographic variation, and climate-related change.

277 2.5. Water column

278 The water column immediately surrounding O&G installations may have locally enhanced
279 biomass (Claisse et al., 2014), including commercially important species (Fujii, 2015).
280 Evidence suggests that marine mammals may utilise these localised stocks as a food
281 resource (Todd et al., 2009). Consequently, removal of O&G infrastructure will diffuse these
282 local aggregations to the background populations or to other comparable physical habitats.
283 Post-decommissioning, other impacts might include seabed (cuttings pile; section 2.3), and
284 near-seabed (any remaining physical infrastructure; section 2.1) impacts, release of
285 contaminants, e.g. metals, hydrocarbons, and other organic chemicals (Shimmield et al.,

286 2000). It is conceivable that there may be some residual reefing effects, where some
287 infrastructure is left in place, but this is expected to be minor.

288

289 Any release of contaminants at or near-seabed in the near-field environment (section 2.3)
290 will be likely rapidly diffused to the background / far-field water column. Conventional
291 approaches for oceanographic assessment, such as Niskin bottle sampling or sensor-based
292 water column assessment (e.g. CTD), can be used to monitor changes in a wide range of
293 parameters, including physical, chemical and biological. Water column monitoring was often
294 considered lower priority than benthic assessment in typical industry surveys, but is now
295 receiving increased attention (Nilssen & Bakke, 2011) and may be important in
296 decommissioning applications. Water column monitoring is typically split into
297 environmental effects monitoring, which examines effects on caged organisms, and
298 environmental condition monitoring, which relates to temporal and spatial measurement of
299 water column conditions (Nilssen & Bakke, 2011). As noted in the far-field seabed case
300 (section 2.4), biological effects monitoring is likely to be complicated by the known impact
301 of long-term climate cycles, e.g. North Atlantic Oscillation and Atlantic Multidecadal
302 Oscillation, on the North Sea pelagic system and fish stocks (Gröger et al., 2010; Auber et al.,
303 2015); again suggesting the need for a broadscale and long-term monitoring approach.

304

305 **3. Autonomous systems for decommissioning monitoring**

306 The capability and use of marine autonomous systems (MAS) has increased rapidly in recent
307 years, enabling oceanographic observations at spatial and temporal scales impossible from
308 traditional ships (Rudnick et al., 2004; Hartman et al., 2012). MAS are increasingly applied in
309 marine geoscience (Wynn et al., 2014), habitat mapping (Robert et al., 2014), and benthic

310 ecology (Morris et al., 2016). MAS can be divided between static, fixed-point observatories
311 (FPO; Cristini et al., 2016), and a variety of mobile platforms. The latter can be broadly split
312 into underwater gliders, autonomous underwater vehicles (AUV), unmanned surface
313 vehicles (USV), and seabed landing and crawling vehicles.

314

315 3.1. Underwater gliders

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

333

334 3.2 Autonomous underwater vehicles

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

344

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

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

361

362 Depending on payload and energy capacity, AUVs can be equipped with a wide range of
363 sensors: acoustic systems (e.g. acoustic Doppler current profilers, multibeam echosounders,
364 sidescan sonars, interferometric sonars, sub-bottom profilers, passive acoustic monitoring),
365 geophysical tools (magnetometers, gravimeters), oceanographic sensors (conductivity,
366 temperature, depth, oxygen, turbidity, fluorescence, pH, REDOX, etc.) and optical systems
367 (conventional cameras, stereo cameras, laser scanners) (e.g. Caress et al., 2008, Connelly et
368 al., 2012; Morris et al., 2014; Sumner et al., 2013; Williams et al., 2010; Yoerger et al., 1998).

369 At present, AUVs have a very limited capacity for the collection of physical samples, largely
370 restricted to relatively small volume water samples (Harvey et al., 2012; Pennington et al.,
371 2016), though note that other samplers are in development and field testing is ongoing, for
372 example for a zooplankton sampler equivalent in performance to a high-specification towed
373 net system (Billings et al., 2017).

374

375 In decommissioning-related environmental monitoring, AUVs have capability for detailed
376 acoustic mapping and visual inspection of structures (Robert et al., 2017) and cuttings piles
377 (Gerrard et al. 1999), sensor-based assessment of chemical contaminant and suspended
378 solid concentrations (Camilli et al., 2010), photographic assessments of benthic and pelagic
379 marine life (Morris et al., 2016; Pedersen et al., 2010), and acoustic determination of fish
380 and marine mammal densities (see 3.1). AUVs may have particular application for
381 monitoring in O&G activity areas impacted by ice (Dowdeswell et al., 2008) including oil

382 spills (Kukulya et al., 2016). Long range vehicles may be well suited to regular monitoring of
383 many decommissioned sites spread over a wide geographic area.

384

385 3.3. Unmanned surface vehicles

386 This category includes both powerful boat-like vessels with diesel engines, and
387 environmentally-powered platforms that may use solar, wind, or wave energy. Diesel-
388 powered vehicles are generally used for short-term operations (hours, days) and may be
389 operated remotely or autonomously, usually within sight of the operator. Environmentally
390 powered vehicles can have considerable endurance, even crossing ocean basins (Goebel et
391 al., 2014), and can be controlled via satellite. Both classes may carry a range of sensors to
392 assess surface ocean conditions. Diesel-powered vehicles have application in seabed
393 mapping (Wilson & Williams, 2017). They have been used in the Gulf of Mexico to increase
394 the efficiency of metocean data collection, communicate with underwater vehicles (Leonard
395 and Bahr, 2016), detect hydrocarbons, and carry out passive acoustic monitoring (e.g. Pai,
396 2015). There may be potential for coupling of surface vehicles with aerial drones, for
397 example to carry out aerial photography (e.g. of seabirds, cetaceans, infrastructure) or make
398 atmospheric measurements.

399

400 3.4 Fixed-point observatories

401 Having developed from simple anchored, self-recording instruments, today's fixed-point
402 ocean observatories (FPOs) can provide multidisciplinary water column and / or seabed
403 environmental time-series data in real- or near-real time (Cristini et al., 2016). These
404 observatories variously apply acoustic, short-range radio, satellite link, and cabled data
405 transmission to shore stations (Ruhl et al., 2011). Sensors are frequently self-powered,

406 requiring routine servicing, though may be augmented by solar power, and in some cases
407 are supplied with cabled power (Martin Taylor, 2009). They are typically equipped with a
408 range of oceanographic sensors, including passive acoustic monitoring (Lin et al., 2015), and
409 optical systems, that may be arranged through the water column, and at the seafloor (Ruhl
410 et al., 2011). FPOs are increasingly used to provide long-term data on environmental
411 variability and have already been employed in O&G-related studies (Vardaro et al., 2013;
412 Osterloff et al., 2016). FPOs would allow high-temporal resolution data to be obtained
413 before, during and after decommissioning operations, tracking a range of parameters
414 including suspended solids, chemical contaminants, noise, light and faunal behaviour. They
415 may also offer an approach for long-term monitoring, although they usually require regular
416 maintenance (e.g. Juniper et al., 2013; Vardaro et al., 2013).

417

418 3.5. Seabed landing and crawling autonomous vehicles

419

420 Vehicles operating in contact with the seabed are currently the least common class of MAS,
421 with the best known systems operated in association with deep-water FPOs. The “Benthic
422 Rover” is a tracked vehicle that operates at the Station M long-term observatory site in the
423 NE Pacific (Smith et al., 2009). It is primarily equipped with seabed observing cameras and a
424 pair of flux chambers that can be inserted into the seafloor to measure sediment
425 community oxygen consumption (McGill et al., 2009). TRAMPER is also a tracked crawling
426 MAS and typically operates at the HAUSGARTEN observatory in the Fram Strait (Soltwedel et
427 al., 2016). It too is equipped with seabed observing cameras, and is primarily designed to
428 carry out sediment oxygen profiling using fibre optic-based optodes inserted into the
429 seafloor (Wenzhöfer et al., 2016). Both of these deep-water crawling vehicles are designed

430 for long-term studies of 6-12 months. A variety of seabed landing / interacting AUVs are in
431 development or concept (Wang et al., 2009; Matsuda et al., 2017) as is a hybrid crawl-
432 hover-class AUV (Pyo & Yu, 2016). Seabed landing and crawling vehicles may provide a
433 useful role in decommissioning monitoring, particularly in the monitoring of cuttings piles.
434 Here, the flux chamber or profiling electrode approach could be used to assess spatial and
435 temporal change in contaminant release and seabed ecosystem function.

436

437 **4. MAS sensors for monitoring decommissioning**

438

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

446

447 4.1. Geoacoustic sensors

448 Survey-class AUVs provide very attractive platforms from which to conduct geophysical
449 surveys (multibeam echosounders, MBES; sidescan sonars; synthetic aperture sonars; sub-
450 bottom profilers) by being decoupled from sea surface motion and holding a steady altitude
451 above seabed. As a result, this application is already very well developed in commercially
452 available vehicles. For example, O&G AUV-based MBES surveys are used to characterise new
453 exploration and exploitation areas (e.g. Jones et al. 2014), providing better quality (by

454 minimising pitch, roll and yaw variation) and higher resolution bathymetry data (m-scale
455 pixels) than can be achieved from surface vessels (10 to 100m pixels).

456

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

474

475 4.2. Visual sensors

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

478 (Solan et al., 2003; Durden et al., 2016). An option for seabed photography is already
479 available in a number of commercially available AUVs, having been employed from research
480 vehicles for some time (Jones et al., 2005; Morris et al., 2014). Similarly, time-lapse
481 photography is well-established in FPO operations (Bett, 2003; Bett et al., 2001), with O&G-
482 related examples including both long-term deep-water seabed observations (Vardaro et al.,
483 2013), and water column observations of infrastructure-associated fish populations (Fujii &
484 Jamieson, 2016). Water column imaging systems for the assessment of particle
485 concentration and plankton populations are well developed (Benfield et al., 2007), with
486 many suited to integration with MAS operations. Laser-based particle imaging has been
487 implemented on survey-class AUVs for the study of zooplankton (Pedersen et al., 2010) and
488 suspended sediment particles (Thompson et al., 2013). A development of these approaches
489 allows the monitoring of oil droplets, gas bubbles, and oil-coated gas bubbles, and has been
490 trialled in a submarine mining tailing placement study that may have particular relevance to
491 cuttings pile disturbance (Davies & Nepstad, 2017).

492

493 Laser-based imaging systems have also been employed to provide 3D reconstruction of the
494 viewed scene, using a variety of techniques (laser line scanning, laser striping, range-gated
495 imaging, structured lighting), that have been implemented in towed systems, Remotely
496 Operated Vehicles (ROVs), and AUVs (Massot-Campos & Oliver-Codina, 2015). Such
497 approaches have been further developed to combine conventional imaging (colour
498 photography) with 3D scene capture (Bodenmann et al., 2017), and have been successfully
499 deployed on a hover-class AUV (Nishida et al., 2016). These various imaging systems have
500 clear applications to post-decommissioning environmental monitoring, whether censusing

501 pelagic or benthic communities, quantifying particles in the water column, or examining the
502 3D structure of the seafloor or any remaining O&G infrastructure.

503

504 4.3. Oceanographic sensors

505

506 Many commercially available Argo floats, gliders and AUVs can be, or are routinely,
507 equipped with a basic set of oceanographic instruments comprising conductivity,
508 temperature, depth, oxygen, turbidity, and fluorescence sensors. Similar, and often more
509 extensive, sensor suites are typically fitted to FPOs (Hartman et al., 2012; Vardaro et al.,
510 2013). In addition to their typical use in assessing phytoplankton (chlorophyll), fluorescence
511 sensors have also been employed to monitor oil in water. Coloured (or chromophoric)
512 dissolved organic matter (CDOM) fluorescence can be used to detect crude oil, including use
513 on a survey class AUV in the mapping of the deep-water oil plume following the Macondo
514 blowout (Ryan et al., 2013). CDOM sensors are not specific to oil or particular oils, greater
515 specificity can be achieved by membrane inlet mass spectrometry (MIMS) and these
516 instruments have been developed for *in situ* operations (Schlüter & Gentz, 2008). Carried by
517 a hover-class AUV, this type of system was also used to map the Macondo deep-water oil
518 plume (Camilli et al., 2010; White et al., 2016). *In situ* chemical sensors are in a phase of
519 development, with some potentially suitable for MAS applications, for example dissolved
520 manganese sensors (Meyer et al., 2016), that have been carried by a hover-class AUV (Doi et
521 al., 2008). Sensors for *in situ* microbiological sensing are generally large and expensive at
522 present but innovations in technology and biochemistry are leading to potential for use in
523 offshore monitoring of water quality (McQuillan & Robidart, 2017).

524

525 4.4. Water column acoustics

526

527 Many MAS operations (gliders, AUVs, USVs, FPOs) include acoustic Doppler current profiling
528 instruments that enable assessments of water movements (Randeni et al., 2017), and have
529 the potential to estimate suspended sediment concentrations and movements as may result
530 from trawling or dredging activities (Van Lancker & Baeye, 2015). Larger MAS systems have
531 been used to obtain water column acoustic data for some time, and have now been
532 successfully incorporated in gliders (Guihen et al., 2014). The ability of acoustic systems to
533 detect particles in the water column is also exploited in hydro- / bioacoustic MAS
534 applications through the use of multifrequency or broadband fisheries echosounders
535 (Trenkel et al., 2009; Brierley et al., 2003). The geoacoustic sensors (section 4.1) commonly
536 deployed on AUVs can also be employed to assess fish stocks, using both MBES (Innangi et
537 al., 2016) and sidescan sonar instruments (Grothues et al., 2017). Similarly, gas escapes from
538 the seafloor can also be mapped using these techniques (MBES: Urban et al., 2017),
539 including survey-class AUV-mounted interferometric sidescan sonar (Blomberg et al., 2017).
540 MAS systems may be favoured over other methods because they can carry these range-
541 limited instruments closer to the targets of interest (e.g. Benoit-Bird et al., 2017), and being
542 generally quiet, may minimise observer bias (Griffiths et al., 2001). Despite this, some
543 mobile midwater organisms do exhibit escape responses to moving MAS (Dunlop et al.,
544 2018).

545

546 Active acoustic methods can be used to characterise a range of parameters of direct
547 relevance to decommissioning operations. Water column MBES measurements are also
548 used to characterise the full extent of large objects on the seabed (e.g. Hughes Clarke et al.,

549 2006). Gas escapes from the seafloor or pipelines can also be assessed by passive acoustic
550 monitoring (PAM) (Leighton and White, 2012), where MAS deployment may be the
551 preferred option (Blackford et al., 2015). The PAM approach can also be employed to
552 detect, and potentially localise, a wide range of natural and anthropogenic sounds in the
553 marine environment (Baumgartner et al., 2018). MAS applications, often targeting marine
554 mammals, have been successfully undertaken from simple FPOs (Merchant et al., 2014;
555 Hildebrand et al., 2015), cabled-FPOs (Lin et al., 2015; Caruso et al., 2017), an O&G-related
556 deep-water FPO (Vardaro et al., 2013), gliders (Suberg et al., 2014), and USVs (Bingham et
557 al., 2012).

558

559 **5. MAS data for monitoring decommissioning**

560

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

565

566 5.1 Geoacoustic data

567

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

573 AUV mapping approaches are well developed (e.g. Grasmueck et al., 2006; Dupré et al.,
574 2008) and have now also been adapted to the mapping of complex structures (e.g. Robert et
575 al., 2017). Navigational errors may pose challenges for acoustic mapping, particularly if data
576 for one survey are obtained over different dives or different parts of the dive. Solving this is
577 best done at the time of acquisition, but it is possible to correct the navigation based on
578 manual or automatic feature matching across overlapping sections of data (Barkby et al.,
579 2009). For most decommissioning applications spatial accuracy and precision requirements
580 will be very high, likely beyond that which can be achieved through dead reckoning alone.
581 The most robust solution to bound navigation errors is via regular acoustic position updates
582 throughout the dive, either via a network of seabed transponders or by acoustic
583 communication with a surface vessel (ship or USV).

584

585 5.2 Visual data

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

597 et al., 2016) and biological features (Gormley et al., 2018; Lüdtke et al., 2012; Kannappan et
598 al., 2014).

599

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

613

614 5.3 Oceanographic data

615

616 Underwater gliders collect water column profile data similar to a ship-deployed CTD
617 instruments. Increasingly complex sensor payloads collect high quality water column data
618 over relatively long time periods, including during weather conditions that may prevent
619 ship-borne operations (Peterson and Fer 2014). Internally stored position and engineering
620 data for the glider and its sensors are transmitted by Iridium or ARGOS satellite when the

621 glider is at the surface. At these times, return control communication is available to enable
622 adaptive mission planning. Low power and slow speed, particularly in coastal waters, and
623 dead-reckoning navigation between surfacing means that spatial precision can be low, but
624 temporal resolution of oceanographic processes is high.

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

635 Fixed-point observatories may be cabled or standalone, collecting a broad range of
636 oceanographic parameters at depths from the surface to the seabed (Cristini et al., 2016).
637 Standalone FPOs provide similar data to the temporary metocean moorings often used by
638 industry to inform engineering design of surface and subsurface infrastructure. They may
639 provide near real-time data via satellite communications with the surface buoy (e.g.
640 Hartman et al., 2012). Cabled observatories can offer direct communications to control the
641 instrumentation, collect real-time data, and can potentially interact with autonomous
642 mobile platforms such as AUVs (Howe et al., 2015). The different arrays of instruments and
643 sensors on FPOs require varying workflows but there are some common requirements, in

644 particular around quality assurance; these include automated and manual procedures (e.g.
645 Abeyirigunawardena et al. 2016). Algorithm-based event detection is also a very desirable
646 capability for long-term environmental monitoring. For example, autonomous geohazard
647 observatory systems may respond to particular pressure or seismicity changes by increasing
648 sampling rates and issuing an alert communication (Monna et al., 2014).

649 Common challenges for long-term instrument deployments include sensor calibration,
650 sensor drift, and biofouling. In the case of gliders, ship-borne CTD deployments can be
651 carried out at the launch and recovery points to account for sensor drift (Suberg et al.,
652 2014), and / or data can be cross-referenced between simultaneous glider deployments
653 (Ross et al., 2017). Ships of opportunity, and observatory servicing vessels, can play a similar
654 role in the calibration of FPO instruments (Beggs et al., 2012). Sensors deployed in the deep
655 ocean typically experience only modest biofouling, however, instruments deployed in the
656 surface ocean or coastal seas can be subject to extreme biofouling. The intended operating
657 environment and the nature of the sensor system will determine the need for anti-fouling
658 measures (Delauney et al., 2010; Rolin et al. 2011; Laurent et al., 2017).

659

660 5.4 Sound and Noise data

661

662 Passive acoustic monitoring (PAM) uses hydrophones to detect sound in the marine
663 environment and can be applied to ambient or anthropogenic sources (Merchant et al.
664 2014). Hydrophones have been deployed on fixed-point observatories (Caruso et al. 2017),
665 autonomous underwater vehicles (Mellinger et al. 2017) and unmanned surface vehicles
666 (Bingham et al. 2012). EU MSFD descriptor 11 sets out monitoring requirements for noise

667 pollution, including measuring the 10 Hz to 10 kHz frequency band for sound sources likely
668 to impact marine animals, and the annual average of continuous ambient sound (60 Hz -125
669 Hz; van der Schaar et al., 2017). Monitoring of bioacoustics is less prescriptive and may fall
670 within the MSFD biodiversity indicator suite. Cabled FPOs offer a flexible approach to
671 acoustic data flow and data processing. In contrast, stand-alone observatories or moorings
672 may have communication limitations and require on-board data storage (with compression)
673 and transmission of pre-processed data. Other considerations include acoustic interference
674 such as intentional noise (modems, ADCPs), mechanical noise (e.g. movement of the
675 platform) or electrical noise, which may be mitigated by decoupling the hydrophone from
676 other systems and / or data processing methods. Similar challenges exist for mobile
677 platforms, though submerged gliders may be well suited because of the lack of continuous
678 motor noise and sea surface noise (Mellinger et al. 2017).

679

680 Passive acoustic monitoring often produces high volume datasets. Van de Schaar et al (2017)
681 propose that for environmental impact assessment, a noise level and cetacean presence
682 report should be presented, including the levels over time and the distribution of cetacean
683 detection. For comparisons in space and time, standardised metadata protocols for PAM
684 datasets have been developed (Roch et al. 2016). PAM data is often classified manually,
685 aurally or visually from the spectrogram parameters (e.g. Klinck et al., 2012), although
686 advances are being made in automated classification (e.g. Frasier et al., 2017). Automated
687 systems have been demonstrated with varying levels of classification success depending
688 audio quantity, quality and number of species present (Gillespie et al. 2013), but are becoming
689 increasingly comparable with manual assessments (Korneliussen et al. 2016). In the case of
690 odontocete echolocation clicks, compressed acoustic data stored onboard gliders have been

691 screened autonomously using a detection algorithm (Klinck & Mellinger., 2011) and
692 successfully reported specific detection events back to shore during glider surfacing (Klinck et
693 al., 2012).

694

695 5.5 Active acoustic water column data

696

697 The mid-water acoustic datasets obtained by MAS are comparable to those obtained by
698 other means, although equivalent data are considerably slower to obtain with gliders than
699 with other MAS systems and ships (Guihen et al., 2014). To date the application of these
700 data has been to measure the abundance and distribution of midwater organisms, including
701 zooplankton, fish and marine mammals (Baumgartner et al., 2013; Dunlop et al., 2018;
702 Guihen et al., 2014; Klinck et al., 2012; Melvin et al., 2003). Depending on the platform,
703 careful processing of data may be necessary, as they are sensitive to vehicle attitude
704 (Guihen et al., 2014). Calibration of the sensor and the resultant data is important, but can
705 be complex for mid-water MBES as it relies on precise vehicle navigation (Dunlop et al.,
706 2018). Although additional steps may be required for processing, these are readily
707 automated and are unlikely to pose a significant challenge for monitoring operations. Mid-
708 water acoustic data, particularly that obtained by MBES are voluminous, which may present
709 some problems with storage and processing (Dunlop et al., 2018).

710

711 5.6 Data quality and management

712

713 The quality control of large data streams generated by MAS is important, particularly for
714 monitoring applications where datasets are compared that are collected on multiple

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

727

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

739

740 **6. Trade-offs between MAS and other approaches**

741

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

747

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

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

772

773 As a relatively novel tool for the monitoring of decommissioning, MAS data may not always
774 be directly comparable with the available legacy data (Table 2). Some parameters, which
775 cannot be assessed autonomously - those currently requiring physical samples, may
776 nevertheless be essential to understand specific environmental impacts. This linkage to
777 legacy data may be an important consideration, they have a clear role in understanding
778 long-term trends, particularly those associated with historic field development and those at
779 distant locations (control sites) beyond the immediate influence of O&G operations.

780 However, those data collected for baseline assessments and monitoring of O&G projects are
781 highly variable in quality and quantity, and many sites have insufficient data for any robust
782 time-series assessments to be made (Henry et al., 2017). Consequently, the true value of
783 such large existing industry databases (e.g. the UK Benthos Database; Henry et al., 2017) to
784 post-decommissioning monitoring is not clear. In the North Sea case, past-present-future
785 comparisons are further complicated by both: (a) the presence of a major demersal fishing
786 industry, with its concomitant impacts on the seafloor environment; and (b) major climate-

787 related systematic seasonal and inter-annual variations in the fauna (see Section 2.4, 2.5).
788 These factors again suggest the timely need to weigh the potentially major benefits of MAS
789 against maintaining the status quo in marine monitoring generally.
790
791 There are some risks associated with MAS operations, particularly in the vicinity of oil and
792 gas operations (Brito and Griffiths, 2016). These include risks of loss of the MAS themselves,
793 but also potential scenarios where other operations or even safety are compromised. These
794 more serious risks primarily relate to the potential for entanglement or collision between
795 MAS and vessels or infrastructure. Simultaneous operation of MAS and other vessels may
796 represent challenges, particularly if rapid response operations are necessary. These issues
797 are wider than decommissioning monitoring and present an area of active legal and
798 operational practice development (Showalter, 2004). MAS may also act to reduce risks of
799 monitoring, particularly when compared to vessel-based operations.

800

801 **7. Prospectus - basin-scale integrated monitoring**

802

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

810 consider the near-term possibilities of an integrated MAS approach that would potentially
811 be scalable to multiple fields or a complete basin.

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

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

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

848 It is likely that a major data acquisition effort will be focussed on describing environmental
849 conditions immediately post-decommissioning, with follow-up monitoring at intervals
850 subsequently. The first step in the post-decommissioning phase may be high-resolution
851 acoustic mapping of the area to establish baseline seafloor morphology, including any
852 remaining structures or other features of interest - a mission that survey class AUVs are
853 particularly well-suited to, and where they have an existing O&G industry track record
854 (Jones et al., 2014). The same or similar AUVs could also carry out visual imaging and / or
855 mapping of the seafloor, providing direct evidence of seafloor physical condition and

856 benthic biodiversity data. Other AUV sensor-based monitoring could include water column
857 temperature, turbidity, and contaminant levels (with common sensors also deployed via
858 FPOs and gliders). Within-sediment environment conditions could potentially be assessed
859 using FPOs and crawler class AUVs. Acoustic observations of the near-field water column by
860 USV, gliders, FPOs or AUVs could be used to quantify the presence and abundance of fish
861 and cetaceans in the water column. Remaining and / or buried or infrastructure could also
862 be specifically targeted using hover class AUVs, some of which have already been specifically
863 designed for such operations (Cormell, 2012; Liljebäck and Mills, 2017; Sverdrup-Thygeson
864 et al., 2016). Snake-like AUVs (e.g. the Eelume vehicle; Liljebäck and Mills, 2017; Sverdrup-
865 Thygeson et al., 2016) could be used to enter confined spaces to gather data, for example
866 from storage cells.

867 At present, several MAS systems can be launched from shore, aerial vehicles, small vessels
868 or vessels of opportunity (Phillips et al., 2017). In the near future, purpose-designed long-
869 range AUVs are likely to be able to make long (>100 km) transits to get to or move between
870 work sites (Roper et al., 2017; Kukulya et al., 2016). Such capabilities for self transiting will
871 greatly facilitate and reduce the cost of operations. Force multiplication by multiple vehicles
872 or multiple types of vehicles (e.g. AUVs coupled with USVs) offer opportunities for
873 improvements to surveys (e.g. by improving positional accuracy) or further efficiency gains
874 (Jung et al., 2009). It may also be possible to use any remaining (or nearby) infrastructure to
875 improve the performance of MAS, for example using power or data transfer capacities by
876 direct docking of AUVs and / or acoustic communication systems (Galletti di Cadilhac and
877 Brighenti, 2003; Qiao et al., 2017). Strategic operations shared between operators within a
878 region may further reduce costs, with MAS systems moving between multiple sites and
879 gathering directly comparable data. Such broad-scale operations might encompass

880 decommissioned sites, active O&G operations, and reference 'unimpacted' areas. A
881 regionally-consistent monitoring programme of this type would address the specific needs
882 of post-decommissioning monitoring, and would represent a very substantial contribution
883 to various international commitments concerning environmental protection - not least the
884 vision of the UN Decade of Ocean Science for Sustainable Development, that has as a
885 strategic objective the development of enhanced ocean observing networks, data systems,
886 infrastructure, and supporting cooperation and partnerships to service the demands of all
887 nations by 2030 (IOC 2018).

888

889 **8. Conclusions**

890

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

900

901 Here, we have shown that autonomous solutions now exist for many of the relevant
902 monitoring challenges, and that they already offer the potential to streamline some

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

916

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928

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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 monitoring¹
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 biogeochemistry (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.

¹AUV, 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)	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

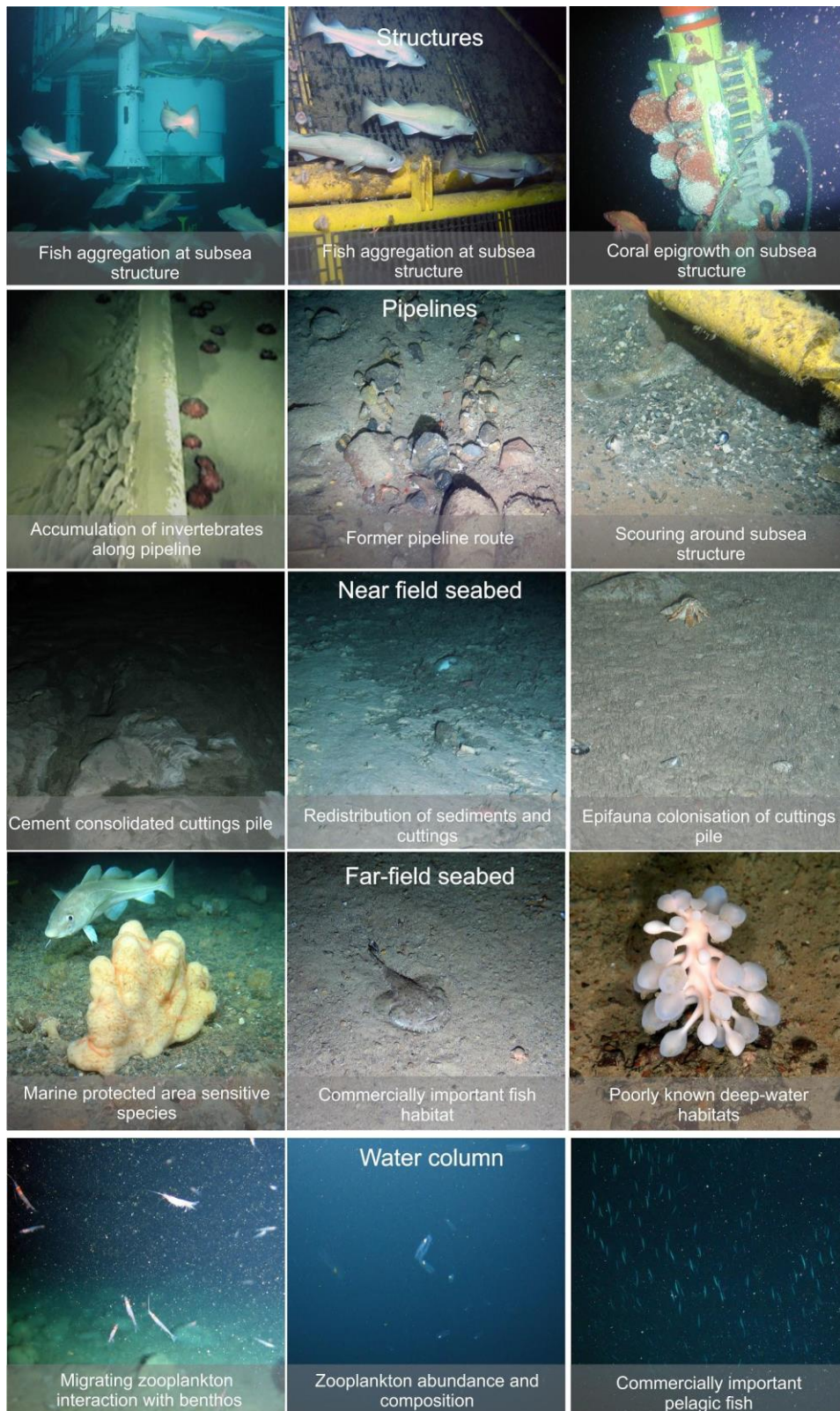


Figure 1: Photographs showing examples of habitats and impacts under consideration (photographs taken by the authors at active hydrocarbon drilling sites).