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REVIEW
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A Review of the Tools Used for Marine Monitoring in the UK: Combining Historic and Contemporary Methods with Modeling and Socioeconomics to Fulfill Legislative Needs and Scientific Ambitions

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Marine environmental monitoring is undertaken to provide evidence that environmental management targets are being met. Moreover, monitoring also provides context to marine science and over the last century has allowed development of a critical scientific understanding of the marine environment and the impacts that humans are having on it. The seas around the UK are currently monitored by targeted, impact-driven, programmes (e.g., fishery or pollution based monitoring) often using traditional techniques, many of which have not changed significantly since the early 1900s. The advent of a new wave of automated technology, in combination with changing political and economic circumstances, means that there is currently a strong drive to move toward a more refined, efficient, and effective way of monitoring. We describe the policy and scientific rationale for monitoring our seas, alongside a comprehensive description of the types of equipment and methodology currently used and the technologies that are likely to be used in the future. We contextualize the way new technologies and methodologies may impact monitoring and discuss how whole ecosystems models can give an integrated, comprehensive approach to impact assessment. Furthermore, we discuss how an understanding of the value of each data point is crucial to assess the true costs and benefits to society of a marine monitoring programme.

Keywords: UK, sensors, ecosystem, modeling, research vessel, OSPAR, MSFD, CFP

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INTRODUCTION

The United Kingdom of Great Britain and Northern Ireland has one of the largest coastlines in Europe and maintains stewardship of around 860 thousand square kilometers of neighboring sea bed; this is ∼3.5 times that of the total land area (Table S1; 1). The marine area and the resources, habitats, and ecosystems that it encompasses have been under increasing pressures for decades resulting from technological advances, population expansion, and increased prosperity (Eastwood et al., 2007). The development of management systems to preserve the overall "health" of the marine environment whilst allowing exploitation of resources at a level that balances conservation with economic sustainability and growth with continual assessment of their effectiveness has been enshrined in legislation. Since 2010, many of the legislative drivers for marine monitoring within the EU have been amalgamated into the Marine Strategy Framework Directive (MSFD) (Council Directive, 2008/56/EC), which adopts the ecosystem approach to management of our seas as established by the Convention on Biological Diversity (CBD) at the 1992 Earth Summit (Ekebom, 2013). As much of this legislation was driven by the European Union, departure of the UK in 2019 has the potential to result in a change of law. At the time of writing the assumption is that much of EU legislation will be directly transcribed into UK law and that non-EU agreements (for example OSPAR; Oslo-Paris convention) will remain in place. Moreover, regardless of contemporary politics, the issues facing the marine environment will remain the same and the UK will continue to aim for its vision of "clean, safe, healthy, biologically diverse and productive seas and oceans" as stated in both the UK Marine Policy Statement and the MSFD (Boyes and Elliott, 2016) and its reporting under the CBD to meet the Aichi targets (UNEP, 1998). As such the wider-reaching scientific requirements in this area will be comparable 5 years from now, even as the legislative framework adapts.

To assess compliance with marine legislation, it is necessary to measure the state or health of the ecosystem or ecosystem components periodically, and the MSFD has instigated reviews of management options and opportunities both at the member state level (the present review) and at a broader EU level (Danovaro et al., 2016). Significant marine monitoring has been undertaken since the start of the Twentieth century in response to societal concerns about the sustainability of fishing activities and to a Royal Commission on Sea Fisheries from 1863 (HC Deb 02 June 1863 vol 171 cc261-76). Since then, marine monitoring has diversified into a complex array of programmes (**Figure 1**, **Table 1**). The most expensive and intensive marine monitoring is that of the UK's subtidal environment and is primarily undertaken on bespoke multimillion pound government research vessels. These offshore surveys are complemented by monitoring nearshore and coastal areas by small boat and inshore surveys. Much of this sampling continues to be done by traditional methods such as trawling or sediment coring. However, that work is now augmented with an array of "innovative technical approaches" (discussed below), some of which is used opportunistically for research, but much of which is incorporated, after proof of concept, into monitoring programmes. Today, monitoring of UK coastal and marine seas provides data to understand the impact of pressures from many activities including removal of biomass by fishing, damage and loss of habitat on the seabed from fishing, the construction and presence of physical structures, pollution and other chemical changes from land and marine based sources, introduction of invasive species from commercial shipping, recreational activities, mariculture, noise from construction and operational activities and litter from a wide range of sources (UKMMAS, 2010).

Management measures and monitoring drivers are typically (but not exclusively) weighted toward measuring the impact of defined pressures e.g., fishing or pollution. As such monitoring programmes are undertaken under various themes (**Table 1**), employing a variety of platforms from which equipment or sensors are deployed to measure the variables and parameters of interest. New technology and innovative methodologies have always changed the way in which we monitor our seas and the current rapid development of marine technology (Mills et al., 2014) will ensure that monitoring methods for the marine environment will be very different 10 years from now. Here, we have summarized the scientific themes that drive the monitoring of threats to the marine environment, the way in which the monitoring is carried out (methods and sensors), and review the potential for new platforms and techniques to change or improve the way that marine evidence and science is delivered. Finally, we speculate on what the biggest changes are likely to be over the next decade.

THE MARINE ENVIRONMENT, SOCIETY, AND THE DRIVERS FOR MONITORING RISK: A UK PERSPECTIVE

The UK Government set out its vision of achieving clean, healthy, safe, productive, and biologically diverse oceans and seas in the first marine stewardship report (Defra, 2002). It highlights the necessity of finding a balance between activities (including management measures) that: (i) contribute to economic development (or "Blue Growth"); (ii) have an impact upon the health of the marine environment; (iii) help maintain ecosystem health; and (iv) may hamper commercial or recreational human activities. Legislation, regulation, and licensing control the extent of human pressures, whereas their impacts are measured against criteria that require scientific assessment and research. Internationally, this sits within the United Nation's high level political forum target to "conserve and sustainably use the oceans, seas and marine resources for sustainable development" (HLPF Goal 14; Table S1; 2).

Monitoring the status and health of the marine ecosystem, and compliance with minimum standards are crucial components of national and European legislation. The adoption of the MSFD in 2008, the reform of the Common Fisheries Policy (CFP) implemented in 2014, and other existing marine environmental drivers such as MACAA (Marine and Coastal Access Act), WFD (Water Framework Directive), HABSDIR (Habitats Directive) and OSPAR have substantially increased the demand to collect

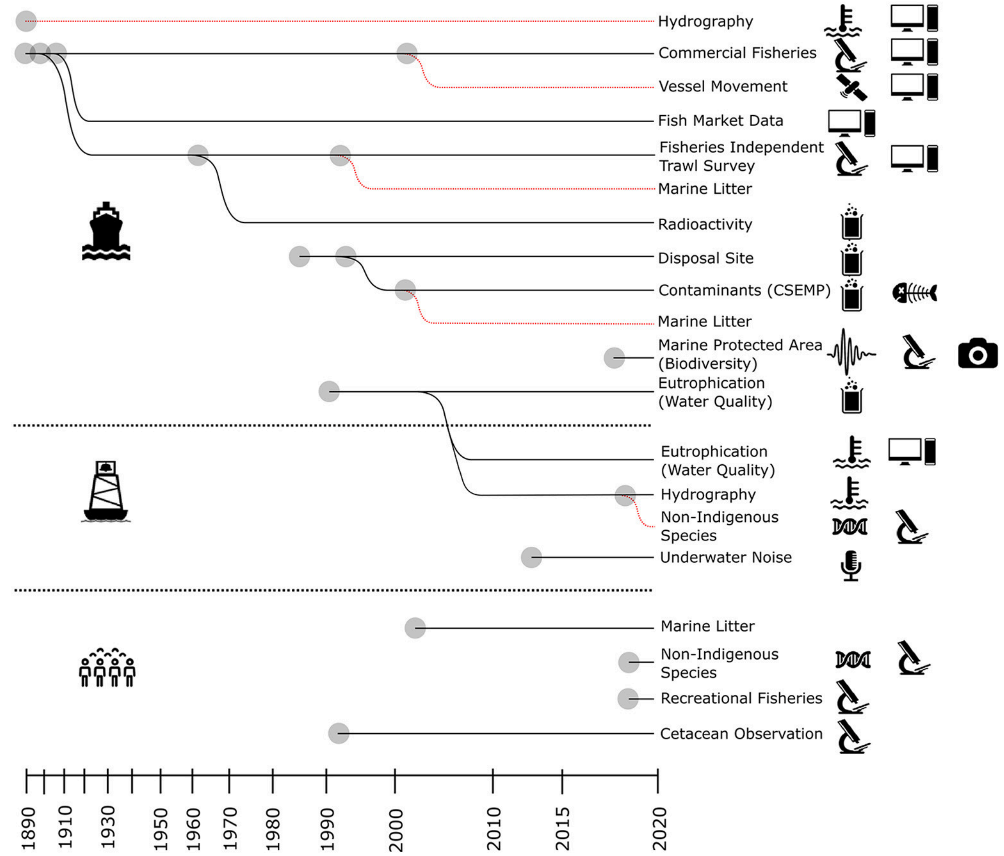

FIGURE 1 | Development of MSFD linked monitoring programmes (vessel, fixed point observing system, or citizen science). Gray dots mark start of a new survey programme and point of origin, red lines denote opportunistic sampling. Symbols are explained in detail in **Tables 2**, **3**. The computer symbol denotes the use of computational modeling.

evidence on the status of the marine environment. Although these are the most prominent drivers, they are by no means the whole list. Boyes and Elliott (2014, 2016) have outlined in detail the legislation that surrounds use of the marine environment, demonstrating a complex evolution of requirements in the so-called legislation "horrendogram." To date, this complex set of drivers has been addressed with a gradually evolving monitoring programme. This evolution has resulted in a programme of monitoring broken down into the subject areas as detailed below. Given current financial pressures and political change, it is unlikely to be sustainable into the future. As demands for data and assessment information increase, more efficient and flexible ways of providing environmental status assessments will need to be developed that address the needs of national (and potentially EU) policy in the most cost-effective way. Opportunities to use new, more efficient technology should be taken, and methods should be continually reviewed and improved to ensure they are fit for purpose.

An overview of the development of marine observations in the UK (Owens, 2014) has highlighted the complex network of organizations that are now involved with marine monitoring. These networks offer the opportunity to bring marine observations together to help build an integrated shelf seas observing system, and to assist with more integrated, detailed, and reliable assessments of ecosystem health. Comprehensive assessments of the state of the UK seas have been carried out within Charting Progress and Charting Progress 2 (UKMMAS, 2010) as a way of assessing progress toward this vision. Independently, Halpern (2008) identified the shelf seas around the UK as very highly impacted by human drivers of ecological change, in particular the North Sea and the English Channel. However, a more recent assessment suggests that impact decreased over the intervening 5 years (Halpern et al., 2015) or that earlier datasets over-estimated the level of pressure on the marine environment. As such, there is still uncertainty concerning the degree to which our seas are impacted by human activities, raising the question whether our current monitoring programmes provide sufficient data to support UK marine policy. The integration of traditional techniques with recent technological innovation, coupled with innovation in modeling, may provide data that are currently either too difficult or too expensive to gather.

TABLE 1 | Contemporary marine monitoring programmes led by Department for Environment, Fisheries and Rural Affairs, UK.

Monitoring Theme (section in manuscript)	Programme	Legislative driver	Indicators monitored	Platforms used	Analysis methods used	Start Date	Legacy data	Notes
Hydrography (Marine Climate) (Hydrography)	No specific monitoring programme. Data collected as part of most oceanographic monitoring	MSFD (Descriptor 7)	Characteristics of the marine environment (Temperature and Salinity of the water column)	Shipboard observations, autonomous moored instrumentation, ships of opportunity, citizen science	Electronic instrumentation (CTD, thermometer, salinograph)	<1890	Temperature and salinity have been collected in various forms throughout the modern scientific record.	Provides baseline data used to inform other indicators on “prevailing conditions
Fisheries (Fisheries Stock Assessment)	Fishery-independent trawl surveys (IBTS/BTS/Pelagic/Young fish)	EU CFP; Habitat Directive; MSFD (Descriptors 1, 3, 4)	Spatial distribution; Commercial stocks and ‘fish communities’; Size composition and relative abundance; Biological data (length, weight, sex, maturity) for commercial fish; Age determination (otolith or scale)	Research Vessel; Commercial Fishing Vessels, incl. through discard observer programmes	Visual identification; Electronic morphometrics; Otolith microscopy;	1902	Long term data with various changes of equipment, various levels of QA	Also use of externally captured data (EDC, GARi, Observer, FSS, iBIS)
	Commercial fisheries data	EU CFP; MSFD (Descriptor 3)	Fleet size, fishing effort, landings, quantity, and value of landings. Size composition and relative abundance; Biological data (length, weight, sex, maturity, otoliths) for commercial species	Commercial Fishing Vessels, market sampling, discard and observer data	Visual identification; Manual measurement and recordings	1886	Lots of legacy data, with various levels of QA	Includes discard and observer data as well as vessel monitoring systems
	Market sampling data	MSFD (Descriptor 3); CFP (pre- and post-reform)	Landed fish length, weight, age, catch composition	Human observation	Manual measurements and recordings	Early 20th Century	Lots of legacy data, with various levels of QA	Potential for automisation via cctv, weighing and grading machines
	Vessel movement monitoring	MSFD (Descriptor 3); CFP (pre- and post-reform)	Vessel position and speed, activity (from cameras, log books)	Vessel mounted AIS (automated identification systems) operating through VHF and satellite.	GIS algorithms	Early 2000s	Some Legacy data exists, maintained by MMO	Opportunity for greater inclusion, but some legislative issues re: confidentiality
	Recreational fisheries	CFP	Number of anglers and effort, catch composition, releases, spend	Online and diary surveys	Manual measurements and recordings	2012	Minimal legacy data; opportunistic observations only.	

(Continued)

TABLE 1 | Continued

Monitoring Theme (section in manuscript)	Programme	Legislative driver	Indicators monitored	Platforms used	Analysis methods used	Start Date	Legacy data	Notes
Radioactivity (Radioactivity Monitoring)	Monitoring radioactivity in food and the environment	MSFD (Descriptor 8); OSPAR; Article 66 of the Euratom Directive	Concentration of radionuclides in biota, sediment and seawater (activation and fission products including Cs-137, Sr-90, Pu-239+240 discharged from the nuclear industry	Ship based sampling	Radiometric and radiochemical methods (α, β and γ counting)	1960s	Over 50 years of published monitoring data and continuous QA'd radioanalytical data since 1990s	Sampling appended to other research surveys
Contaminants (Contaminants Monitoring, Biological Effects of Contaminants)	Monitoring of disposal sites at sea	OSPAR	Chemical analysis of Sediment and benthic macrofaunal biodiversity	Ship based sampling; Hamon Grab	Analytical chemistry	1985	Continuous QA'd data for chemistry and biological effects since 1985	
	Clean Seas Environment Monitoring Programme (CSEMP)	MSFD (Descriptor 8); OSPAR; WFD;	Conc. of Hg, Cd, Pb, PAHs, PCBs, PBDEs in biota and sediment; Imposex in dog whelks; Assessment of biological effects in fish (micronuclei, bile metabolites, EROD, fish disease);	Ship based sampling; Granton trawl; day grab	Analytical chemistry; Biological assessment (External fish disease, toxicologic pathology, EROD, bile)	1993	Continuous QA'd data for chemistry and biological effects since 1993	Reduced to biennial survey in 2011
	Persistent Organic Pollutants in marine mammals	ASCOBANS Treaty	Chemical analysis of POPs in marine mammals	Opportunistic sampling of stranded animals	Analytical Chemistry	1990	Continuous QA'd data for chemistry since 1990	POPs in marine mammals Funded under Cetacean Stranding Investigation
Marine Litter (Marine Litter)	Assessment of macroscopic Litter in UK waters	MSFD (Descriptor 10); OSPAR Regional Action Plan on Marine Litter; G7 Marine Litter Action Plan	Quantification and categorization of litter on seafloor; beach litter; stomach content in fulmars	Ship based beam trawl and otter trawl Surveys; Beach Surveys (Citizen Science)	Visual identification;	Beam trawl data from 1990.	Various types of opportunistic sampling with limited QA and continuity	Sampling appended to other research surveys
	Assessment of microplastic contaminations in UK waters	OSPAR Regional Action Plan on Marine Litter; G7 Marine Litter Action Plan	Quantification and characterization of microplastics; Modeling sources and pathways	Ship based Microparticle Automated Extraction System (auto sampler)	FTIR/Raman microscopy; visual identification	Initial surveys undertaken;	Minimal legacy data; opportunistic observations only.	Sampling appended to other research surveys

(Continued)

TABLE 1 | Continued

Monitoring Theme (section in manuscript)	Programme	Legislative driver	Indicators monitored	Platforms used	Analysis methods used	Start Date	Legacy data	Notes
Biodiversity (Contaminants monitoring)	Marine Protected Areas	MSFD (Descriptors 1 and 6), Habitats Directive (HD); Marine and Coastal Access Act (MCAA)	Remote sensing survey; Conservation feature presence and extent (habitat maps); Ground-truth survey; Benthic Biodiversity, feature conservation status	Research Vessel, commercial survey vessels	Multibeam Echosounder; Side-scan sonar; Grab sampling; Sea bed video analysis; Visual identification of benthic macrofauna, Sediment PSA.	Recent	Baseline assessment data from 2012 to 2018, Cetacean survey	Data archived via MEDIN
	Cetacean observations	MSFD (Descriptor 1); ASCOBANS Treaty	Visual Observation of species and counting	Citizen Science and Volunteer Observing Ships	Visual observation by certified person	1991 with Sea Watch	Legacy data from SeaWatch. Many other organizations have since arisen	SeaWatch foundation, MMOA, SMRU
Eutrophication (Water Quality) (Eutrophication Monitoring)	Defra's Clean Seas Environment Monitoring Programme (CSEMP)	MSFD (Descriptors 5 and 8); OSPAR; WFD	Dissolved nutrients load and concentrations, chlorophyll a, phytoplankton community, dissolved oxygen for measurement of state	Ship; autonomous moorings	Continuous flow analysis for inorganic nutrients; fluorescence determination of chlorophyll; dissolved oxygen by Winkler method and optode; salinity by conductivity;	Ship based surveys from 1990; autonomous moorings from 2001	QA'd data held in ICES and at Cefas	Further information available from Earth Observation data. Satellite data useful to access large spatial datasets.
Non-indigenous species (Marine Non-indigenous Species)	Marine Non-Natives	MSFD (Descriptor 2); OSPAR; WFD; EU Alien Species Regulations; Ballast Water Convention	Absence/Presence (minimal requirements); New introductions; Spread of introduced species	Citizen Science (observation); Focused surveillance at high risk locations (modeled);	Visual Identification; DNA based diagnostics (PCR, qPCR)	Planning underway	N/A	Risk based directed monitoring; Programme under development (2016)
Underwater Noise (Marine Noise)	Underwater noise	Habitats Directive; MSFD (Descriptor 11); OSPAR regional assessment	Underwater noise levels; spatial and temporal distribution of impulsive noise sources Pressure	Static autonomous acoustic recorder	Manual measurements and recordings	To be fully operational by 2018	Baseline data from 2013 to 2014	Provides baseline data to MMO and Natural Resources Wales

MONITORING EQUIPMENT AND TECHNOLOGY

There are two basic categories of technology used to monitor our seas: (1) the platform from which a measurement is taken, such as a research vessel, a static observatory, or an unmanned automated vehicle; and (2) the actual sensor or methodology used to take the measurement, such as a multibeam sonar array, a sea bed camera or a chemical analysis of a physical sample. These categories have seen rapid advances and a potential to move away from traditional operator-based approaches to a technology based solution. However, it is crucial to choose the right technology for the job, to understand the implications of using those technologies and, to ensure that the transition between and integration of technologies is managed from both scientific and policy perspectives. Here we provide an overview of the platforms (**Table 2**) and sensors (**Table 3**) that are currently used for monitoring in the UK and those that are likely to have a future role.

Platforms

Table 2 Summary of the current and future applications of different platforms for making measurements in the marine environment.

Research Vessels

The primary method of collecting the data during the most recent assessment of the UKs seas, Charting Progress 2 (UKMMAS, 2010) was by manual techniques deployed from research vessels. An independent report about UK research vessels and their uses by Marine Science Co-ordination Committee (2013) identified two primary groups of vessels: those operated by UK government agencies and those operated by the Natural Environment Research Council (NERC). The government agency vessels are primarily used for fisheries research and marine monitoring classified as "Sustaining and increasing ecosystem benefits," with an additional 20% of the time for ecosystem function research. The NERC vessels are primarily used for ecosystem function and climate change research and response, often in polar regions, rather than for the statutory monitoring in UK waters. All the vessels are highly capable platforms and can be adapted to most common requirements from fishing through to seabed mapping or assessment of marine pollution. In addition to the primary "offshore" vessels, UK scientists also have access to a range of smaller vessels suitable for coastal and inshore work, such as those operated by the Environment Agency (EA), Inshore Fisheries and Conservation Authorities (IFCAs), Marine Scotland (MS), academic and research institutes or by commercial operators who can provide very flexible platforms for a range of oceanographic survey work.

Fixed Point Marine Observation Systems

Fixed-point marine observation systems have been deployed globally, including in UK waters, to make *in situ* sustained Eulerian observations of a variety of biogeochemical and physical variables. Various platforms have been deployed, including fixed-depth or profiling moorings, fixed piles, towers and seabed landers that employ instrumentation capable of long term, autonomous operation. European programmes (e.g., FixO3 (Table S1; 3, Cristini et al., 2016), Jerico (Table S1; 4, Sparnocchia et al., 2016) have been successful at linking data streams from many of these platforms, greatly increasing the geographical spread and availability of monitoring data across Europe (Table S1; 5). Current sustained fixed point—observation systems include open ocean sites such as those under the global OceanSITES programme (Table S1; 6) (Hartman et al., 2015); and coastal seas locations such as the German COSYNA project (Table S1; 7), the SmartBuoy and WaveNet programmes within the UK (Mills et al., 2005, Table S1; 8) and the moorings at stations L4 and E1 in the Western Channel Observatory (Table S1; 9). Such platforms can resolve processes that are episodic and/or have high temporal variability, which traditional platforms such as research vessels are less able to resolve. Parameters determined on such platforms include inorganic nutrients, sea surface salinity and temperature, chlorophyll, dissolved oxygen, phytoplankton species, turbidity and the underwater light climate. These data are used within the OSPAR eutrophication assessment (Foden et al., 2011). In addition, these data have enabled better design of robust monitoring programmes (Heffernan et al., 2010), validation of models (Große et al., 2016; van der Molen et al., 2016) and satellite marine products (Neukermans et al., 2012), and for studying ecosystem behavior (Devlin et al., 2009; Blauw et al., 2012; Capuzzo et al., 2013, 2015; Johnson et al., 2013; Hull et al., 2016).

Fixed-point moorings are also used for making measurements of the wave climate. WaveNet is the UK strategic operational wave monitoring network. It provides near real-time data on the wave climate to the UK Coastal Flood Forecasting Service (Table S1; 10) to help improve coastal flood forecasting models and the assessments of flood risk in the UK. In addition, WaveNet maintains the primary UK archive for wave data, which is used by engineers to design coastal sea defenses and offshore structures. Additional example programmes within the UK include Marine Automatic Weather Stations (MAWS) on moored buoys (Table S1; 11) and the Channel Coastal Observatory (Table S1; 12).

In CP2, data from fixed point platforms were used for assessment of marine air temperature, salinity, sea surface temperature, wave climate, ocean circulation, suspended particulate matter and eutrophication (UKMMAS, 2010).

Voluntary Observing Ships and Ships of Opportunity

Voluntary observing ships (VOS) and ships of opportunity (SOO) are vessels (or potentially platforms) undergoing routine operations that make some of their capacity available for making observations of the marine environment. FerryBox systems (Table S1; 13), installed on ships of opportunity (SOO) are automated systems making observations of biogeochemical and meteorological parameters (reviewed by Petersen, 2014). They must be reliable and have minimum maintenance to be used unattended on a SOO. These systems provide repeated measurements over a defined transect and potentially provide a relatively cost-effective means of monitoring, as ship costs are already met through the routine business of the commercial vessel. However, changes to shipping routes can

TABLE 2 | Summary of the current and future applications of different platforms for making measurements in the marine environment.

Platform (section in manuscript)	Sensor availability	Current uses	Future uses	Limitations
Research vessel (Research Vessels)	Acoustics, sample collection, CTD, camera/light imaging, hydrophone, passive sampler, visual taxonomy, FerryBox	Virtually all monitoring	Continued use for sampling and monitoring. Likely to be used as platform to launch autonomous vehicles and service fixed point observation systems	Expense, availability
Fixed point marine observation systems (Fixed Point Marine Observation Systems)	Some sample collection, CTD, camera/light imaging, hydrophone, passive sampler	Wave height (WaveNet); water quality (e.g., SmartBuoy)	Increased network, potential for increased sample collection (water), mounting for biosensors, mounting for plankton microscopy	Expense of servicing, limited locations (not in shipping channels)
Other vessel (Voluntary Observing Ships and Ships of Opportunity)	Variable availability: acoustics, sample collection, CTD, camera/light imaging, hydrophone, FerryBox	Fisheries research; sea-bed mapping; FerryBox	Continued use alongside citizen science for fisheries monitoring; FerryBox	Requires good-will, limited to certain sea areas (e.g., ferry routes)
Mobile platform (Subsurface Floats, Remotely Operated and Autonomous Vehicles)	Acoustics, CTD, camera/light imaging, water sample collection (limited)	Argo Float fleet; sea-bed mapping (trials)	Large potential for oceanographic measurements, acoustics and potential for some sampling	Power usage (battery life), must be launched and recovered
Unmanned aerial vehicle (Remotely-Piloted Aircraft)	Camera, GPS	Commercial shoreline surveys, not yet used for environmental monitoring	Increased range to target greater areas, longer battery power, greater degree of automation, launch from RV	Battery power, legal limits to flight patterns (up to 1 km from pilot)
Citizen Science (Citizen Science)	Species ID, eDNA sample collection, litter sample collection, catch diaries	Non-indigenous species; marine litter; biodiversity recording (limited); recreational fishing	Large potential to record data and collect samples for shore based and shallow water studies	Expertise, data quality, reliability, continuity
Satellite (Satellite)	Camera/light imaging, data transfer from automated platforms	Water quality (algal bloom)	Increased sensor types, increased resolution and increased coverage	Initial expense, cloud cover reduces capability, only sea surface measurements

give interruptions to time series. FerryBox systems are also operated on some research vessels within Europe, giving wider spatial coverage but more limited repeat information. The potential for data from FerryBoxes to be used for assessment of ecosystem health such as the OSPAR eutrophication assessment was highlighted by Hydes et al. (2010).

Extensive use of VOS and SOO has been made in the long running Continuous Plankton Recorder (CPR) marine monitoring programme (Table S1; 14) and for making marine air temperature measurements (Rayner et al., 2003). In CP2, data from VOS and SOO were used for the assessment of marine air temperature, ocean acidification and plankton (UKMMAS, 2010). Currently, CPR data contribute to indicator assessment for pelagic habitats (plankton) for UK waters and the OSPAR region.

In the UK, citizen science programmes use VOS as host vessels for certified volunteers (from the marine mammal observer association, Table S1; 15) to observe cetacean and seabird numbers throughout daylight hours for the duration of a vessels transit. Natural England and JNCC use the data for assessment of MSFD descriptor 1 and adherence to ASCOBANS.

Subsurface Floats

Subsurface floats are autonomous Lagrangian platforms, which make observations of the ocean by moving with it (Swallow, 1955). A float is designed to be neutrally buoyant at the depth of interest and parameters can be monitored as it moves. Tracking its location can be done either at depth by acoustics or by making floats that can vary their buoyancy and return to the surface to be tracked by satellite. Initially, floats were designed to measure the ocean flow field but modern floats provide a platform for other hydrographic measurements (e.g., temperature, salinity, oxygen) and data is sent back via satellite. Advantages of float-based monitoring are the potential for global coverage, continual direct data supply, ease of deployment, cost efficiency, power of analysis for large groups of floats, horizontal resolution at target depth and vertical resolution during surfacing and sinking. Disadvantages are that they can be lost and that the geographical location of measurements is dependent on arbitrary movement. As such, targeting the observations to spatially limited processes or systems can be difficult. Strong quality control and calibration protocols are needed for instruments that are not recovered regularly. Full water column sampling by this method is limited by the depth of buoyancy control by the float (Davis et al., 2001; Roemmich et al., 2009).

The defining subsurface float design is the Argo float, which has revolutionized the way the internal workings of the oceans are monitored (Gould et al., 2004). The global Argo programme (Table S1; 16) has been operational since 1999, with a peak deployment of over 5,000 profiling drifting floats measuring depth, temperature and salinity in the upper 2,000 m of the world's oceans (Riser et al., 2016). The capacity to make biogeochemical measurements from Argo floats is also developing (Emerson et al., 2002; Johnson et al., 2009; Claustre et al., 2010). Argo data have been used to study topics including: water mass properties and formation, air-sea interaction, ocean circulation, mesoscale eddies, ocean dynamics and seasonal-to-decadal variability. In the UK, Argo float data are utilized in real time by the Met Office for ocean forecasting (National Partnership of Ocean Prediction), where information is required to integrate models of deep ocean behavior for 7-day forecasts of global sea temperature (GloSea5/FOAM).

Remotely Operated and Autonomous Vehicles

To date, remotely-operated vehicles (ROVs) and autonomous vehicles have only been used opportunistically and not routinely in UK monitoring programmes. ROVs are generally tethered to a ship and are used as a platform from which to make measurements and observations under the control of an active operator. The cabling supplies power and transfers data making intensive and detailed operations possible. They provide the opportunity to make observations in new and difficult environments and inspect and guide specific measurements or activities during the survey (see e.g., Huvenne et al., 2011, 2016a,b; Wynn et al., 2014). Powered, autonomous, underwater vehicles (AUVs) maintain many of the capabilities of ROV operation although under their own propulsion, thus extending the range and area covered relative to a control base. Mission parameters are generally predefined or refined when remote communications are established and mission lengths generally vary from hours to days (Griffiths et al., 1998; Wynn et al., 2014). Advances in size and power of AUVs are enabling missions lasting weeks or months with ranges of 1,000s of km that can reach 1,000s of m deep (Furlong et al., 2012). These developments have been trialed for use in ecosystem monitoring (Suberg et al., 2014).

Submarine or buoyancy gliders are a relatively recently-developed instrument platform for measuring the internal ocean. By shifting their internal mass and adjusting their buoyancy, gliders navigate rather than simply drift with the current. They operate independently of ships but communicate via satellite enabling data upload, mission planning and updating. The design of gliders facilitates very low power consumption allowing them to be deployed for months at a time.

To complement the underwater vehicles is the new group of unmanned surface vehicles (USVs) that include Liquid Robotics Wave Glider, Autonaut and ASV's C-Enduro. The former two primarily use wave power for propulsion, leaving the internal batteries (which are generally kept topped-up by solar panels) for navigation, communications and sensor payload. Generally capable of between one and three knots, they are faster than buoyancy gliders but do not have the speed of survey/research vessels. However, their lower operating costs (compared to manned vessels), robustness and long-term endurance make them an ideal platform to take measurements in surface waters under conditions where operating a manned vessel would not be deemed safe. USVs can be fitted with a range of sensors including water quality, passive and active acoustics, current profiling, etc. In addition, USVs can be re-tasked as required, via their web-based navigation and operating software, should an interesting or unplanned event occur.

Remotely-Piloted Aircraft

Remotely Piloted Aircraft (RPA) are small flying vehicles capable of carrying various sensors, typically some form of camera system. They can be divided into rotary-wing or fixed-wing categories, with numerous sub-types and sizes existing with a wide range of capabilities. Such craft are equipped with hardware and software for navigation, control and data acquisition (Madden et al., 2015). In the UK, intertidal data collection can be achieved using RPA, making them capable of fulfilling monitoring requirements including those made by Development Consent Orders (DCOs) for nationally significant infrastructure projects, and Marine Licences (MLs). DCOs and MLs may include monitoring requirements based upon many different legislative drivers. RPA typically acquire aerial imagery and digital terrain models can also be produced by post-flight image processing using the correct image geographical referencing and appropriate software (Westoby et al., 2012). Data from RPA has shown to be more appropriate for mapping and assessing marine vegetation dynamics than measurements made by satellites (Phinn et al., 2008; Su and Chou, 2015), largely due to the greater spatial resolution. The development and incorporation of light weight nIR cameras into RPAs has provided opportunities for use in intertidal monitoring (e.g., Young et al., 2010; Su and Chou, 2015).

Developments in camera technology and image processing are likely to lead to further utility in intertidal vegetation monitoring and monitoring other intertidal features of ecological interest such as polychaete reefs, shellfish beds, cetaceans and birds; and RPAs are now employed as part of statutory monitoring programmes. RPA offer potential advantages over traditional human-based intertidal survey techniques: greater speed and coverage of data acquisition and the ability to produce data with smaller teams more quickly. These advantages can offer better data collection at reduced cost, provided an appropriate platform and sensor combination is available and the required survey location is logistically suitable.

Citizen Science

Citizen science is one of many terms used to describe the collaborations between professional and amateur scientists (Miller-Rushing et al., 2012), whereby volunteers with no formal training in science, contribute to the collection, processing or analysis of scientific data (Silvertown, 2009; Dickinson et al., 2012; Hyder et al., 2015b). There has been a recent proliferation of studies in the marine environment, with a 2014 review identifying 227 publications with a reference to citizen science (Thiel et al., 2014). The value of citizen science to support monitoring is significant (Levrel et al., 2010; Defra, 2011; Theobald et al., 2015) and governments are recognizing the potential benefits of using citizen science (Postnote, 2014).

There are many good examples of using citizen science to develop the evidence base that underpins decision making (Hyder et al., 2015b) including: prevailing conditions (e.g., Wright et al., 2016); fisheries (e.g., Fairclough et al., 2014); and marine litter (e.g., OSPAR, 2010). Despite the potential benefits, the uptake and use of citizen science in support of decision making has been low, mainly due to challenges around data quality, access to data, motivation of volunteers and physical location (Hyder et al., 2015a,b). However, this is changing with studies demonstrating the quality of data (e.g., Lewandowski and Specht, 2015), access to data through web portals (e.g., National Biodiversity Network, Table S1; 17), better understanding of motivation (e.g., Measham and Barnett, 2009; West, 2015; Geoghegan et al., 2016); and an increase in new technologies (e.g., SmartPhones apps—Venturelli et al., 2016) that allow engagement regardless of location (Newman et al., 2012). There are significant costs of delivering effective citizen science (Roy et al., 2012). However, given the potential to collect and process much larger data sets than could be done by traditional science alone, there is potential for citizen science to have an important role in marine monitoring in future, as part of a holistic solution alongside traditional monitoring, remote sensing and modeling (Hyder et al., 2015b).

Satellite

Earth observation (EO) data have the potential to provide considerable support to *in situ* and/or field-based marine monitoring; offering synoptic observations of systems at relatively high temporal frequencies. Indeed, ocean color EO data are becoming widely used to provide information on indicators of water quality at increasingly relevant spatio-temporal scales (Tyler et al., 2016). The uncertainties associated with EO products have raised concerns about their applicability to monitoring activities under official directives, such as MSFD. However, in the UK's optically-complex coastal and shelf sea waters, satellite retrievals of chlorophyll-a (Chl-a), suspended particulate matter (SPM), turbidity (Kd) and colored dissolved organic matter (CDOM) have benefited substantially from the recent development and validation of tailored algorithms (Mitchell et al., 2016; Tilstone et al., 2017). Integration of EO data with *in situ* data from research vessels, AUVs and ROVs, fixed point marine observing systems, SOO and subsurface floats is essential for validation of EO products. Recent validation studies of MERIS chlorophyll (Cristina et al., 2015) support the feasibility of integrating EO data for marine monitoring, specifically for MSFD Descriptor 5 (minimizing eutrophication).

In continuity of MERIS, the ESA has launched the Sentinel-3 OLCI instrument for improved and complete coverage of oceans at 300 m full resolution every 1–4 days. EO measurements from next-generation satellites have the potential to improve data collection for a range of current and future monitoring requirements, including identification and differentiation of phytoplankton functional types for harmful algal bloom detection, measuring of total suspended particulate materials, pigmented fraction of dissolved organic matter, and changes to systems in response to changes in climate (Cristina et al., 2015; Tyler et al., 2016).

Satellite data collected from the above system are generally used to produce and overlay maps (e.g., GeoTIFF, GeoJSON, and netcdf formats) by measuring variables in space and time. Satellites are collecting petabytes of data annually but these are held by the satellite owner (usually NASA or ESA) and only the relevant data, orders of magnitude smaller, are analyzed locally using relevant software (e.g., Matlab, Python or R).

Data Collection

Here we consider the current and future applications of different techniques and sensors for taking measurements in the marine environment (summarized in **Table 3**; note some general fields of measurement not described below are also include in **Table 3**.)

Sensors

There is a wide range of sensors available for marine monitoring including chemical, biogeochemical, physical and biological parameters (Kröger et al., 2009; Mills and Fones, 2012) some of these are employed within the UK programmes described in this paper. These include CTD systems routinely deployed from research vessels and sensors for measuring salinity, temperature, oxygen, turbidity, chlorophyll fluorescence, light and nutrients on fixed point moorings (Section Fixed Point Marine Observation Systems) and FerryBox systems (Section Voluntary Observing Ships and Ships of Opportunity). Whilst autonomous surface and underwater vehicles are not currently deployed within statutory monitoring programmes in the UK, many of the sensors described can also be integrated with these vehicles. Considerations of power requirements, size, weight and degree of autonomy typically determine which platforms the sensors may be deployed on. Recent developments in smaller and cheaper electronic components has enabled low-cost sensors to be developed, including for the marine environment, to measure parameters such as chlorophyll fluorescence, turbidity, pH, temperature and salinity (Radu et al., 2010; Leeuw et al., 2013; Murphy et al., 2015; Sendra et al., 2015). Given sufficient stability and sensitivity, these have the potential to be incorporated into monitoring programmes where appropriate.

There are challenges to data sharing and sensor integration with increasing numbers and diversity of sensors and the volume of numerical data produced. The Sensor Web Enablement initiative of the Open Geospatial Consortium (Table S1; 18) provides the framework and standards to enable the

TABLE 3 | Summary of the current and future applications of different measurement techniques in the marine environment.

Observation type/ Sensor/Technique (section in manuscript)	Current uses	Mode of use	Future Availability (<5 years)	Limitations
CTD (Sensors)	Salinity (via conductivity), temperature, depth	RV or other vessel, animal tag, citizen science, mobile or static autonomous platform	As current, perhaps with further miniaturization	Limited variables
Acoustics (Acoustics)	Depth measurement, sea bed mapping	RV, mobile or static autonomous platform	As current	Large data storage required, often requires specialist vessel
Camera/light imaging (Cameras)	Eutrophication, biodiversity, fish stock assessment	RV, citizen science, mobile or static autonomous platform, satellite, UAV	Continued development in resolution and non-visible light	Images may require expert analysis, large data storage required, power use on remote platforms
HF Radar [High-Frequency Radar]	Wave height	Onshore or offshore static platform	As current	Initial expense and upkeep, limited function.
Visual Taxonomy (High-Frequency Radar, Visual Taxonomy—Benthic Macrofauna, and Visual Taxonomy—Plankton)	Fish stock assessment, biodiversity, non-indigenous species	Sample collection: RV, citizen science. Analysis: RV or laboratory	Reduced capacity due to reducing expertise	Cost and expertise
Biosensors (Biosensors)	None within ecosystem monitoring	RV, animal tag, citizen science, mobile or static autonomous platform	Species ID, phytoplankton and zooplankton analysis	Complex, still under development
Molecular biology techniques (Molecular Biology Techniques)	Fish stock ID, non-indigenous species	Sample collection: RV, citizen science, mobile or static autonomous platform. Analysis: RV or laboratory	Possibility of automation of analysis in deployable form, uses for biodiversity	Cost and expertise, molecular databases, large data storage required
Passive Sampler (Passive Samplers)	Chemical monitoring	Sample collection: RV, Ferry box, Static (autonomous) platform. Analysis: laboratory	Continued development of equipment and methods	Not universally accepted as a substitute for analysis of biota
Analytical Chemistry	Chemical monitoring, water quality	Sample collection: RV, citizen science, mobile or static autonomous vehicle. Analysis: RV or laboratory	Continued development of equipment and methods	Expensive equipment
Biological effects	Chemical monitoring, eutrophication	Sample collection: RV Analysis: RV or laboratory	As current	Expensive and laborious sampling
Hydrophone	Underwater noise	Usually static platform, animal tag, RV	Increased sensitivity, miniaturization	

interoperability of sensors and a complete environmental data management system (Rueda et al., 2009; Conover et al., 2010; Bröring et al., 2011).

Acoustics

Acoustic technology products are used to ensonify the seabed and water column, and interpret the returning signal. This provides and information to help construct habitat maps and topographic visualizations of bed forms, of hydrographic properties and to provide information on the abundance, (vertical) distribution and behavior of biota such as fish and zooplankton in the water column. Various systems are available, with single or multiple beams and range from lightweight towed or pole mounted gears to larger hull mounted arrays. A multi-beam echosounding (MBES) sonar utilizes a focused swathe of beams (of a single frequency) to measure depth across a ribbon of sea bed. As the vessel moves forwards, this cross section of seabed is linked together and can be assembled into a bathymetric map, that accounts for vessel movement and changing water depths resulting from ebbing and flooding tides. MBES also provides limited information on the seabed type by interpreting the strength of the returning signal. MBES is currently used on all UK research vessels as the primary remote sensing method of sea-bed mapping (Kenny et al., 2003), is heavily utilized for assessment of MSFD descriptor 6 (The sea floor integrity ensures functioning of the ecosystem) and is widely employed in monitoring the UKs Marine Protected Areas. Side-scan sonar (SSS) typically uses a towed torpedo-shaped device that emits a conical/ fan shaped beam into the water column providing greater detail of objects and formations protruding from the seabed (Kenny et al., 2003).

Fisheries acoustic methods traditionally use single beam echosounders to measure objects in the water-column. Pelagic fish are particularly suited to be studied acoustically as many pelagic species tend to display highly aggregative behavior and the resulting patchy distribution suggests that trawling alone, would provide unrepresentative data on the target species' distribution and abundance. Acoustic backscatter strength from fish and zooplankton is frequency-dependent and this frequency dependence, i.e., frequency response, can be used to make inferences about the species composition and size distribution of the acoustic scatterers (e.g., Holliday and Pieper, 1995 and references therein). A more recent development in commercial echo sounders, broadband, further utilizes this concept by chirping across a broader band width. Advantages include the combination of a controlled transmit signal, more suitable transmit repetition rate, and pulse-compression processing, resulting in much higher vertical resolution (Stanton et al., 2010, 2012).

Recent technological developments in fisheries acoustic methods have included the use of omni-directional (including MBES) sonars with benefits in fisheries research include improved sampling of fish close to the seabed (in the acoustic dead-zone), and to resolve multiple targets at the same range simultaneously, by reducing the transducer beamwidth and combining multiple split-beams (Trenkel et al., 2009). The omni-directional multibeam sonar were specifically developed to make observations in the acoustic blind zone between the sea surface and the position of the downward facing transducers, either on the hull or a drop keel (Andersen et al., 2006) and to image the entire shape of a school instantaneously using multiple (100s) directional beams. Neither systems are probably currently not widely accessible or used in monitoring.

As summarized previously (Trenkel et al., 2011), acoustic-derived abundance indices have long been used in single stock assessments and will remain important under descriptor 3. Fisheries acoustic data could however have applications beyond that: the spatial range, distribution or other measures of spatial occupancy of a species (Woillez et al., 2007) could also be included as important indicators and are readily extracted from acoustic survey data. Due to complexities in species identification in acoustic data, biodiversity indicators (MSFD descriptor 1) at species level remain a challenge. However, in the absence of species-specific information, surrogates for species, such as coarser taxonomic groupings, size groups, or groups distinguished by their multi-frequency backscattering could well prove useful (Godø, 2009; Trenkel et al., 2011).

The amount of data produced during acquisition depends on the size of the survey site and on the acoustic survey method. These data are then processed into a final product for interpretation or visualization. One to ten terabytes of data are produced per MBES survey (over a 3 week period). Acoustic data that have been acquired to a minimum specification could be stored with the United Kingdom Hydrographic Office or British Geological Society. (Table S1; 19, 20, respectively).

Cameras

Seabed imagery, in the form of video footage and digital photographs, is useful for a multitude of marine research and monitoring purposes. High definition cameras can be mounted on towed or drop frames in combination with sensor arrays that record changes in various environmental parameters and can be deployed in habitats, such as over rocky reefs or in protected or areas with sensitive species, where other sample collection methods are inappropriate or destructive.

Real-time analysis can be carried out e.g., when looking for specific features of interest or for stock assessment (ICES, 2007; Campbell et al., 2009), determining the presence of target non-indigenous species (Whomersley et al., 2015) and for ground-truthing of acoustic MBES data where visual confirmation of predicted transitions in sea bed composition is required (Kenny et al., 2003). Cameras are also employed in Sediment Profile Imagery (SPI) for *in situ* assessment of the interface between sediment and overlying water (Birchenough et al., 2013) and baited remote underwater video systems (BRUV) can be used to supplement or replace more traditional collection survey methods (Roberson et al., 2017).

More detailed processing can be carried out following acquisition using both manual and automated image analysis methods to understand communities associated with certain habitat types or to build a more comprehensive inventory of species that are present in an area. Seabed imagery typically produces 10's of gigabytes of data per survey including video and digital still images and species abundance and habitat information. There is currently a requirement for a bespoke data archive center which can store seabed imagery data and facilitate analysis of multiple datasets.

Satellite Sensors

Ocean color sensors aboard different satellites can measure the small proportion of incident radiation (reflected sunlight) not absorbed by the ocean and its constituent components. This is an average derived from the surface to "one optical depth"—the depth to which satellites can "see" (McClain, 2009). In the most optically non-complex (clear) waters, this depth averages to around 20–25 m (Kemp and Villareal, 2013). Today, the marine environment is simultaneously monitored by the NASA MODIS (National Aeronautics and Space Administration's Moderate Resolution Imaging Spectroradiometer), NOAA VIIRS (Visible Infrared Imaging Radiometer Suite) and the ESA OLCI (Ocean and Land Color Instrument) sensors. As with all ocean color sensors through time, these are carried on polar-orbiting satellites in sun-synchronous, low-Earth orbit. Coverage is global, measured in the visible and rear-infrared spectral range (400–900 nm), reaches up to 300 m at full resolution, and revisit times range from daily to once every 4 days. Importantly, these data are also freely available through their respective NASA and ESA portals.

Daily overpasses and detailed spectral information make ocean-color remote sensing an excellent tool for large-scale environmental monitoring (Vos et al., 2003; Heim et al., 2005; Wu et al., 2009; Sokoletsky et al., 2011; Lim and Choi, 2015). However, the quality of measurements retrieved from space can be significantly impacted by cloud cover and other atmospheric factors, as well as glint, the curvature of the earth and optical properties of the water itself. Data collected in coastal zones, polar regions and/or areas with persistent high cloud cover tend to be associated with higher uncertainty. *In situ* validation is key for "water-truthing" EO data, and spectral information collected from marine regions of higher uncertainty benefit greatly from integrated, tailored algorithms (IOCCG, 2000).

Unlike ocean color sensors, radar satellites are active sensors; they make use of radio waves to read the resulting backscatter. Measurements can therefore be taken through cloud, at night, and through all types of weather. In the marine context, freely available imagery from the ESA Sentinel-1 C-band Synthetic Aperture Radar is extremely useful for a range of applications, including monitoring of oil spills, sea ice, wave fields and wind fields, capillary waves and internal waves, and ocean currents. When combined with AIS or VMS data, radar imagery can also be utilized for detection of vessels.

High-Frequency Radar

High frequency radar is typically statically mounted on land and used to measure wave height, period and direction as well as surface water velocity, and to estimate wind speed and direction (Lipa et al., 2014). This is particularly useful since the measurements can cover up to 100 s of km range with temporal resolution of hours, spatial resolutions for different frequency operations range from meters to kilometers (Wyatt, 2006). Because high frequency radar is based on land, it can make observations almost independently of weather conditions and can be used in a wide range of monitoring activities around the world. The Brahan Project (Table S1; 21) successfully monitored conditions between Orkney and Shetland in 180 km arcs to the northwest and south east of the Fair Isle gap. HF radar was also installed as part of the Liverpool Bay Coastal Observatory to measure the wave and current climate (Wolf et al., 2011; Robinson et al., 2013). The use of HF Radar to measure waves and surface currents requires a robust data strategy due to the quantity of data produced. Depending on the particular installation and system type then raw data or processed data can be distributed, the raw data for a single installation is collected at a rate of ∼16 TB per year while the size of derived and processed data will be orders of magnitude lower than this.

Visual Taxonomy—Benthic Macrofauna

Following the onset or cessation of a human-generated pressure, various monitoring studies assess changes in, and/or the recovery of, the benthic environment based on the macroinvertebrate infaunal community (Bolam, 2014, and Section Biodiversity). Many of the assessment indices and analytical methods rely upon the determination to species (or nearest taxonomic level) of benthic specimens to calculate numerical density and biomass in a quantitative manner (Waye-Barker et al., 2015; Bolam et al., 2016). This is routinely carried out by taking advantage of their distinct morphological characteristics to identify taxa to an accepted Genus/Species. Accurate identification relies on a comprehensive taxonomic literature resource e.g., peer-reviewed publications; specialist faunal guides, including the Synopses of the British Fauna field guides; and dichotomous keys, including those developed through the North East Atlantic Marine Biological Analytical Quality Control (NMBAQC) benthic invertebrate scheme (Worsfold et al., 2010; Musk et al., 2016). An experienced taxonomist, using the above keys and a binocular microscope, can successfully identify most species present in the UK. However, it should be noted that there are a limited number of experienced taxonomists and if requirements for precise benthic taxonomy increase then it may be necessary to further optimize visual identification methods to take account of this. For example, there is currently a need for a UK wide bespoke database to facilitate using high quality infauna datasets in large scale community analyses. Alternatively, it may prove necessary to use tools such as DNA based species identification (Section Molecular Biology Techniques).

Visual Taxonomy—Plankton

Full-community microscopic analysis of fresh- and brackish-water phytoplankton is currently undertaken for compliance with the EU Water Framework Directive and contributes to water-body characterizations in the UK. Cell density and the suspended sediment load will often dictate the methods of phytoplankton examination chosen. In the case of zooplankton, general community data is used for biodiversity, ecosystem, and impact assessment. Fish eggs and larvae are also used for both ecosystem and fish stock assessment. Quantitative sampling is usually done aboard ship: zooplankton is traditionally collected using the deployment of nets, vertically in the water column or towed behind the vessel (e.g., Gulf VII, Nash et al., 1998), and the sample must be preserved prior to organism enumeration and identification.

Microscopic analysis of both zooplankton and phytoplankton is time-consuming and requires a considerable amount of taxonomic expertise. It is possible to combine microscopy with more rapid assessments such as flow cytometry as a qualifying enhancement to the analysis. Furthermore, FlowCam^{TM}, Zooscan and other semi-automated analysis methodologies exist, although still require a taxonomist to validate identification performed by the instrument. Continuous automated surface water sampling on a research vessel can describe broad geographic patterns in zooplankton biodiversity and taxonomic composition (Pitois et al., 2016). It can be integrated within existing multidisciplinary surveys at little extra cost and without requiring additional survey time making it a particularly useful tool as part of integrated monitoring to underpin policy areas such as the MSFD. More recent advances in image recognition algorithms allow for in-flow instruments for imaging and identifying zooplankton in near real time as a ship is transiting (Culverhouse et al., 2015, 2016). The use of in-flow plankton image analysis will potentially produce tens of terabytes of data per survey which can be processed on-board, but needs to be stored on servers until then. Image recognition algorithms are used to identify the zooplankton species and/or taxonomic groups; these require intensive computational processing power to output a list of species or taxonomic groups, their density and size distribution.

Biosensors

While the use of physical and chemical sensors is widespread and well understood in marine science and monitoring, biosensors have not yet realized their full potential. The term biosensor refers to a large array of sensor types and complex analytical instruments, ranging in their biological sensing element from entire cells to individual molecules such as antibodies, enzymes or nucleic acids, and in their detection element from optical to electrochemical, acoustic and beyond. Several papers and book chapters have reviewed existing technology (e.g., Kröger et al., 2002; Justino et al., 2015). These publications highlight potential applications and combinations with many of the platforms discussed above, although pitfalls including limited sensor stability, availability of the biological sensing element and lack of commercialization for marine applications (the most successful biosensors have been developed for other fields such as medical point-of-care diagnostic, biosecurity and food analysis). With rapid advances in the field of molecular biology, the use of molecular diagnostics and molecular-probe-based sensors for many marine applications, such as the detection of harmful algal blooms, invasive species, or studies into population dynamics, are becoming more affordable and routine, thus creating opportunities for their inclusion in marine monitoring.

Examples of current commercially available marine biosensors are a nitrate and nitrite sensor based on immobilized whole microorganisms (Unisense, Denmark, Table S1; 22) and the Environmental Sample Processor capable of collecting and analysing marine water samples for a wide range of parameters such as chemicals, biologicals (microbes, larvae) and particulate matter (Table S1; 23). Biosensors can produce a range of data types, depending on the combination of biological sensing element and transducer employed. In general, the data volume produced is low, and if necessary for analysis can be reduced to qualitative yes/no answer or a relatively simple quantitative response.

Molecular Biology Techniques

Molecular biology is the analysis of DNA, RNA or proteins and is perhaps most commonly exploited in the fields of disease diagnostics, forensic science, and taxonomic analyses. There are many molecular tools (e.g., PCR, high-throughput sequencing and allozyme markers) that can be utilized for the analysis of marine samples (for review, see Bourlat et al., 2013). However, it is perhaps more appropriate here to focus on the end aims of downstream analyses and what can now be achieved with new technology. The most common application for using molecular tools is species identification, whereby a cryptic individual, pathogen, or a partly processed fish sample (Miller and Mariani, 2010) can be identified by a specific DNA-based assay. Species ID techniques can also be used in a quantitative manner; in marine systems example uses include quantification of fecal contamination at swimming beaches (Griffith and Weisberg, 2011) or for direct quantification of zooplankton that are otherwise difficult to identify (Vadopalas et al., 2006). The identification of species within a sample can now be taken a level further. Analysis of DNA from environmental samples (often known as eDNA) in combination with high throughput DNA sequencing methods, can be used without prior knowledge to assess the species diversity present in, for example, a stomach content sample (Leray et al., 2015), a benthic macrofaunal sample (Lejzerowicz et al., 2015), or a water sample as a surrogate in fish stock analysis (Thomsen et al., 2016). This approach can potentially reduce the need for expensive and time consuming taxonomic identification by experts, opening the possibility of automation, although these techniques still require a large amount of validation and are not yet capable of replacing traditional methods for marine monitoring. In addition to high levels of specificity, molecular techniques can often provide an exceptional level of sensitivity, providing enough data to inform questions about the presence, absence and movement of species through an ecosystem, without actually catching the species in question. e.g., non-indigenous species (Zaiko et al., 2015; Davison et al., 2017), large pelagic fishes (Thomsen et al., 2012), or microscopic indicators of water quality (Pochon et al., 2015). There are additional molecular tools for data collection during monitoring. For example: population genetics can be used to assess genetic introgression between fish stocks (Tysklind et al., 2013); gene expression analyses to diagnose where animals may be impacted by novel, or emerging contaminants (Hutchinson et al., 2013); and ecosystem function can be inferred either through metagenomic (Langille et al., 2013), or metatranscriptomic (Durkin et al., 2012) analyses of the species present. However, these techniques are likely to inform decision making on how to monitor, rather than being part of a monitoring programme *per se*. Generally, the biggest advance in molecular tool capability has been (and will continue to be for the foreseeable future) the development of high throughput sequencing systems, which have made large scale sequencing exponentially quicker and cheaper. These tools are becoming cheaper and smaller and it is likely they will be used on vessel based, or unmanned platforms for rapid identification of single species, or for large scale studies of biodiversity. It is worth noting that DNA sequencing for species identification will produce tens of terabytes of data per annum. This data will need storing, either on accessible online databases (For example EMBL, Table S1; 24) or on servers with the relevant responsible authority. Raw data analysis requires intensive computational processing power, via Linux cluster, to reduce information to a species list or indicator index, as in Aylagas et al. (2014).

Passive Samplers

New technology to aid assessment of chemicals in the water has developed in the form of passive samplers (Booij et al., 2016). Passive samplers offer the opportunity to derive a single extract from a sampler which can be used to analyse for a wide range of compounds. Passive samplers do not currently encompass the full suite of contaminants that require monitoring, although methods are constantly being investigated and improved. Inter-laboratory comparisons have also begun as part of QA/QC requirements for inclusion in the CEMP (Section Contaminants Monitoring). The results obtained from a passive sampler can be calculated back to a dissolved water concentration or bioavailable sediment concentration, which are more environmentally relevant in terms of exposure to an organism that the total concentrations traditionally measured. The samplers have been deployed on fixed point systems (Section Fixed Point Marine Observation Systems) and have also been incorporated into a FerryBox system on a research vessel (Sections Research Vessels and Voluntary Observing Ships and Ships of Opportunity), allowing continuous sampling of water and exposure of the samplers when the research vessel is at sea. If a vessel is operating within a well-defined spatial area, then this has the potential to provide valuable monitoring data. Passive sampling has the potential to offer lower cost sampling, if current policy can adapt to accept the calculated results obtained over traditional water, sediment and biota analysis.

MONITORING PROGRAMMES

Monitoring has developed since the early Twentieth century from simple fish enumeration into a complex multifaceted group of measurements, tasks, programmes, and objectives. Here we describe the UKs principal marine monitoring programmes (**Table 1**), and have differentiated between i) legacy programmes, which have a long time-series of data, and ii) contemporary programmes, which have been recently implemented and are perhaps more amenable to the introduction of novel technology.

Long Running Monitoring Programmes

Fisheries Stock Assessment

The primary objective of fisheries monitoring is to underpin management to achieve maximum sustainable yields (MSYs) for all commercial fish and shellfish species. This has been an integral part of the EU's Common Fisheries Policy (CFP), which was first implemented in 1983. It has been gradually acknowledged that commercial fisheries have dramatically changed the structure of marine ecosystems and that fish stocks should be managed as part of the ecosystem. Currently, a policy framework to support the integration of European environmental and fishery management is largely in place (Jennings and Le Quesne, 2012). The main policies driving this integration are the Habitats Directive (Council Directive 92/43/EEC), the CFP (Council Regulation (EC) No, 2371/2002) and more recently the MSFD (Council Directive, 2008/56/EC). The CFP aims to fulfill its objectives by defining regional fisheries multi-annual management plans that take account of species and fishery interactions in establishing conservation and technical measures to achieve the targets (Lynam and Mackinson, 2015).

The core methods of fisheries monitoring have remained largely the same. Fisheries-independent data are generally collected during research vessel based surveys (Section Research Vessels). Trawler gears are deployed from vessels to obtain (semi) quantitative samples of fish species that can be further processed to provide biological information, including age, maturity, length and weight. These variables are key to understanding the quantitative patterns that exist in fundamental life-history traits of marine populations. Sorting of the catch and collection of biological data is still conducted manually although some technological advances have led, for example, to automation of logging the data into electronic databases. The aggregative behavior of small pelagic fish species makes fisheries acoustics more suitable to quantify and map this group, although trawl sampling is nearly always also required to validate species composition and collect biological data (Simmonds and MacLennan, 2005). Beyond the commercially important species, trawler survey data are increasingly used to describe the abundance, distribution and environmental biology of a wide range of species in studies of climate change and fishing effects.

Biological data collected as part of market sampling programmes provide valuable information on the species and size ranges that are commercially landed. Fish landing weights by area, season and effort (catch per unit effort, CPUE) still provide some of the key, and often sole, input data into fish stock assessments. However, landings data can be inaccurate, due to, for example, misreporting and discarding practices at sea. The growing time-series of vessel monitoring systems (VMS, Sections Satellite and Satellite Sensors) is beginning to allow fisheries scientists to consider the fine-scale spatial and temporal dimensions of commercial fisheries data (Mills et al., 2007; Lee et al., 2010). EU and National Legislation requires all fishing vessels over 12 m in length to carry VMS. This enables the UK's Marine Monitoring Organisation (MMO) to oversee fishing fleets by satellite, and the daily assignment of catch data from logbooks to VMS positions has produced unbiased information on distribution patterns (Gerritsen and Lordan, 2011). The AIS continuous identification system (Sections Satellite and Satellite Sensors) was primarily implemented to improve maritime safety and communication between vessels and authorities. However, with improved access to increasingly precise spatial data on fishing patterns, satellite AIS is increasingly utilized as a means of tracking fishing activity. For example, high-resolution maps of fishing effort have been developed from the Swedish trawling fleet using AIS data alone. Validation with logbook entry data proved this approach was accurate for calculating fishing effort, but also for identifying key fishing grounds (Natale et al., 2015). Complications around access to data from such vessel monitoring systems, due to legal and confidentiality constraints, need to be resolved (Gerritsen and Lordan, 2011).

Despite progress in the development of new sampling technologies, such as "deep vision," which enables identification and length measurements of fish using a non-invasive camera system in the trawl cod-end automated technologies are unlikely to replace manual-based biological sampling methods at a large scale in the near future. The growing use of CCTV camera systems on board commercial vessels and progress in image recognition may enable length measurements to be automated. Within fisheries acoustic methods (Section Acoustics), recent commercialization of broadband systems may resolve limitations of current narrowband systems related to species identification. This removes some of the need of trawling, although it also means that these fisheries acoustic methods can be deployed more opportunistically on fishing vessels (Fässler et al., 2016) or on autonomous vehicles (Section Remotely Operated and Autonomous Vehicles, Suberg et al., 2014). Other developments in habitat modeling (Section Modeling in Current Monitoring Programmes) may be used to adapt survey designs making more efficient use of vessel time.

Finally, there has been some progress in the use of eDNA for fish stock assessment (Section Molecular Biology Techniques, Sigsgaard et al., 2016; Thomsen et al., 2016). These techniques have great potential for fish stock assessment, being rapid, cheap and less damaging to the environment than traditional fishing, although they will require a high level of optimization and validation prior to use in UK monitoring programmes.

Contaminants Monitoring

In the UK, the monitoring of contaminant concentrations and their biological impacts in offshore marine waters is funded by Defra. At offshore locations, the long-term contaminant monitoring programmes are derived from our commitments to OSPAR Joint Assessment and Monitoring Programme (JAMP) carried out through the Co-ordinated Environmental Monitoring Programme (CEMP) (Table S1; 12). These programmes are now the basis for our assessments of Good Environmental Status (GES) for Descriptor 8 under the MSFD and align with policy drivers (e.g., Water Framework Directive, WFD) that also produce data relating to inputs of chemical contaminants into transitional and coastal waters (Council Directive, 2000/60/EC). Current efforts are focused on alignment of the two directives to ensure a common approach from coast to ocean and therefore efficiency of subsequent monitoring and assessment programmes across member states (Borja et al., 2010; Lyons et al., 2010; Wernersson et al., 2015). This broad approach adopts the analysis of chemical pollutants in a range of matrices (water, sediment and biota) along with the observation of biological effects in selected (fish and shellfish) sentinel species (Thain et al., 2008, See Section Biological Effects of Contaminants). These programmes rely on the use of a research vessel for sample collection (Section Research Vessels).

The CEMP is currently focussed on the monitoring of the concentrations of priority-action contaminants in the marine environment. These include metals, organotins and a range of organic compounds in biota and sediment (Table S1; 25). However, research and development work continues into analytical protocols, QA/QC procedures and assessment tools for some determinants and until this work is complete, these assessment procedures will not be adopted in routine monitoring. Within the OSPAR, environmental assessment criteria have been established for a range of contaminants, including PAHs, PCBs and metals in sediments and these have been used previously in wide scale assessments such as Defra's charting progress 2 (UKMMAS, 2010). It is expected that future assessments will use a combination of these along with those adopted as environmental quality standards under the WFD (Table S1; 26). While the concentrations of contaminants reaching the environment have decreased, due to measures such as tertiary sewage treatment and monitoring of industrial discharges, the number of compounds being released continues to increase (Hutchinson et al., 2013).

Biological Effects of Contaminants

Over the last three decades, an increasing number of techniques to measure the biological effects (e.g., bioassays, biomarkers, and disease) of contaminants haves been incorporated into national and international monitoring activities undertaken within the UK (Thain et al., 2008). These techniques are currently used to assess whether Descriptor 8 of the MSFD (Concentrations of contaminants are at levels not giving rise to pollution effects) is being met. Biological-effect methods indicate links between contaminants and ecological responses (van der Oost et al., 2003; Lyons et al., 2010; Hylland et al., 2017) and biological samples are collected using the research vessel (Section Research Vessels) alongside samples collected for the determination of contaminants in water and sediment. Such an approach can be used to indicate the presence of substances, or mixtures of substances, that had not been identified previously as being of concern, and identify regions of reduced ecosystem health. The application of biological effects within the UK has focused on their ability to detect and monitor specific contaminants, or classes of contaminants, that are known to cause problems (e.g., organotins, PAHs, and selected metals), although the effects observed are rarely caused solely by a single chemical contaminant. Reflecting this, there are only a few methods that relate directly to specific contaminant classes (e.g., bile metabolites to detect PAH exposure in fish, or imposex as a marker of TBT exposure in gastropods). Most assays to measure biological effects applied respond to a wider range of contaminant classes, such as the use of the Ethoxyresorufin-Odeethylase (EROD) assay, which is known to respond to PAH-exposure whilst being affected by other planar contaminants, including non- and mono-orthopolychlorinated biphenyls (PCBs) and dioxins (dibenzofurans and dibeno-p-dioxins) (Kammann et al., 2005). The monitoring of externally visible and microscopic marine fish diseases is used in UK waters and throughout the North-East Atlantic region to investigate acute and chronic biological effects of contaminants at the population and individual fish levels (Stentiford et al., 2009, 2010; Vethaak et al., 2009). In addition to the identification of chronic toxicopathic diseases such as neoplasia (cancer) associated with an array of chemical classes e.g., metal and PAHs, the identification of conditions related to specific classes of chemical compounds such as oestrogens, is also possible e.g., ovotestis intersex (Bateman et al., 2004). It is worth noting here that OIE notifiable diseases discovered under this or other monitoring programmes, are reported to the relevant authority as required by EU law (Council Directive, 2006/88/EC).

Radioactivity Monitoring

Radionuclide concentrations in surface and coastal waters of the British Isles were first reported in 1967 (Mitchell, 1967). A series of UK technical reports followed, latterly published as the Radioactivity in Food and the Environment Report (RIFE) report series (e.g., Environment Agency et al., 2015). The marine pollution monitoring management group (MPMMG) commissioned a review of the information relating to the Irish Sea, to identify and place into context the principal issues of concern as regards the transport and ultimate fate of radionuclides, and the associated risks (Kershaw et al., 1992). The subsequent RIFE reports and the associated monitoring programmes conform to the requirements in Article 36 of the Euratom Directive laying down basic safety standards for protection against the dangers arising from exposure to ionizing radiation (Council Directive, 2013/59/EURATOM), report UK submitted OSPAR data and contribute to the MPMMGs Marine Strategy Framework. Internationally, the Commission of European Communities (CEC) set up a project (the "MARINA" study) to look at the radiological impact of radionuclides, both natural and human produced, in northern European waters in the late 1980s (CEC, 1990). As for other contaminants, radiological monitoring and assessment became more formalized within the OSPAR Convention, and is still a regular commitment. As such, the OSPAR Radioactive Substances Strategy is to ensure that by the year 2020 discharges, emissions and losses of radioactive substances are reduced to levels where the additional concentrations in the marine environment above historic levels, resulting from such discharges, emissions and losses, are close to zero.

Seawater samples are primarily collected primarily by research vessel (Section Research Vessels) and the concentrations of radionuclides are determined using a variety of radiometric and radiochemistry techniques and alpha, beta and gamma counting instruments. Biota samples (including fish, shellfish, crustaceans and seaweed) are collected by a variety of methods and the edible fraction is isolated and counted by high resolution gamma-ray spectrometry to determine the radiological exposure (dose) from consumption.

Eutrophication Monitoring

Marine eutrophication is an issue of global concern. It has been given a high priority of action at the European (EC) and Regional seas (OSPAR) level through Directives and Strategies, which seek to manage the undesirable consequences of nutrient enrichment. The UK have been signatory to several water-related directives for the protection and maintenance of coastal and marine water quality. Various EU directives consider the assessment of eutrophication through measurement of key indicators such as concentrations of nutrients, Chl-a and DO (Devlin et al., 2011), e.g., the Urban Waste Water Directive (Council Directive, 91/271/EEC), the Nitrates Directive (Council Directive, 91/676/EEC), the Habitats Directive (Council Directive, 92/43/EEC), the WFD (Council Directive, 2000/60/EC) and the MSFD (Council Directive, 2008/56/EC), the Oslo Paris Convention (OSPAR, 2003a,b).

The UK has an extensive coastline, many estuaries and a large maritime area to manage for the impacts of elevated nutrients. Important locations for eutrophication monitoring are areas that are susceptible to the increase in nutrients. Assessments typically combine a selection of key indicators that enable reasonable evaluation of the overall status of eutrophication in coastal and marine waters, enabling managers and policy makers to make mitigation decisions linked to nutrient enrichment (Devlin et al., 2011).

Within the complex WFD, MSFD, OSPAR, and UK legislative requirements, EU member states must deliver timely and reliable eutrophication assessments. This has been traditionally done through *in situ* measurements from research vessels (Section Research Vessels) and, in recent years, a move toward automated high frequency sampling using an array of electronic sensors on fixed point marine observation platforms (Section Sensors, Section Fixed Point Marine Observation Systems, e.g., SmartBuoys). High frequency data can provide greater certainty in the assessment and provide greater detail around the areas that are moving away or toward GES. In more recent years, innovation has continued to provide more detailed eutrophication assessments, with the ability to model hydrodynamic and biogeochemical processes confidently across the UK marine seas as well as modeling the input of pollutant loads into the coastal zones (Section Modeling in Current Monitoring Programmes). Modeling of loads can provide direct links of activity back to the programme of measures around urban and agricultural activity. In addition, the use of Earth Observation data, from remote satellites has now provided the scope to integrate a source of data across large temporal and spatial scales (Sections Satellite and Satellite Sensors). The high variability of water quality variables in time and space demands a high number of measurements (high frequency, dense spatial coverage) to attain the required accuracy and confidence in trend and threshold analysis. As such, the use of satellites may provide an alternative cost-effective data source and common ground for consistent basin-wide maps of water quality information across the UK national and international seas, although this requires validation and calibration with *in situ* data.

Hydrography

Alongside each of the specific programmes mentioned here is the study of hydrography, for which parameters such as temperature and salinity are assessed as a matter of course. These measurements have been ongoing since pre-1900 and continue today using a combination of discrete samples and electronic sensors (Section Sensors) on research vessels (Section Research Vessels), ships of opportunity (Section Voluntary Observing Ships and Ships of Opportunity) and on autonomous platforms (Sections Fixed Point Marine Observation Systems, Subsurface Floats, and Remotely Operated and Autonomous Vehicles). High Frequency Radar (Section High-Frequency Radar) installations on land have demonstrated the potential to monitor further physical parameters such as waves and currents. Hydrography does not have a specific monitoring programme but is nonetheless an important field of study alongside all other aspects of marine science.

Contemporary Monitoring Programmes

Biodiversity

A well-managed UK marine protected area (MPA) network (comprising both European marine sites and national MPAs) is intended to be the primary mechanism by which obligations to achieve Good Environmental Status (GES) of benthic habitats and species under the MSFD are to be met, including biodiversity (descriptor 1) and sea floor integrity (descriptor 6). Domestic reporting on MPAs (as detailed in s124 of the Marine and Coastal Access Act 2009, c. 23.; s103 of the Marine (Scotland) Act 2010; and s21 of the Marine Act (Northern Ireland) 2013, c. 10.) similarly follows a 6-year cycle (with the initial report due 2018). This should essentially include several reporting aspects: (1) assessment of the extent to which implementation of a network of conservation sites has been achieved and the extent to which the network contributes to the conservation of the wider environment and any further steps required. (2) assessment of management implemented and progress toward maintaining/achieving conservation objectives for each MCZ; and (3) summary of site and network level monitoring plans (delivered by SNCBs as directed by the appropriate authority).

This requires a structured evidence base comprised of seabed feature habitat maps of conservation importance, an assessment of designated feature conservation and finally monitoring of these features. This data is currently and has traditionally been collected using vessel mounted MBES Multibeam Echosounder and SS Sidescan Sonar (Sections Research Vessels and Acoustics). In addition, each site has accompanying "ground truth" sampling comprising sea bed imagery and sediment sampling for particle size analysis and infaunal analysis (Section Visual Taxonomy—Benthic Macrofauna). Imagery is provided by vessel-towed seabed camera (Section Cameras), and grab samples are collected by vessel based sediment grabs (such as Hamon grab) and processed manually on board. Whilst the grab sample data provides a high level of detail relating to sediment particle size and infaunal community characteristics, local variability can be inferred by analysing the point sample data in the context of the more spatially comprehensive seabed imagery data.

Because this is a new programme, there would be few limitations on the implementation of novel technologies as part of the routine monitoring, so long as it is fit for purpose and provides either the equivalent or greater data collection capability of current techniques at a lower expense. Potential applications of novel technology include: acoustic data acquisition using automated platforms, AUVs and ROVs (Section Acoustics); Ground-truth data acquisition (seabed imagery, Section Cameras), also using AUVs & ROVs (Section Remotely Operated and Autonomous Vehicles); and molecular techniques (Section Molecular Biology Techniques) for determining presence and distribution of species of conservation importance.

Marine Litter

There is strong evidence that our oceans are heavily contaminated with litter derived from human activities. The term "Marine Litter" has been introduced to describe discarded, disposed of, or abandoned human-produced objects present in the marine and coastal environment. Marine litter originates primarily from land-based sources (littering, fly tipping, poor waste management practices, untreated sewage and storm water discharges, riverine inputs, industrial facilities, tourism, extreme natural events) and to a lesser extent ocean-based sources (fishing vessels, cargo ships, stationary platforms, fish farming installations, pleasure crafts and other vessels) (UNEP, 2009).

Numerous marine litter-related actions are being taken at global and regional levels (Galgani et al., 2013; Newman et al., 2013; UNEP, 2016). In Europe, the MSFD defines GES under descriptor 10 as "Properties and quantities of marine litter so not to cause harm to the coastal and marine environment." However, good practices for adequate monitoring or impact determination are relatively sparse. Approaches to detect, locate and estimate the quantity and type of litter can either be targeted or opportunistic. Direct detection from ships (Section Research Vessels) remains primarily as traditional visual observation (typing, measuring and photographing all objetcs). Cefas has 25 years of seafloor litter data, which was generated as byproduct on existing fisheries and environmental surveys using a bottom trawl, and floating litter is monitored by Fulmar stomach analysis. In addition, beach litter monitoring has a long history in the UK, carried out by Marine Conservation Society to fulfill MSFD obligations. As with all visual detection systems, vessel and weather conditions at the time of observation will affect detection. One method that has so far proven invaluable in the monitoring of marine litter is citizen science (Section Citizen Science) through the use of public reporting applications for direct shoreline data collection (Nelms et al., 2017).

There are many possibilities to improve detection, coverage and accuracy at sea. For example, image collection and recognition systems on the bow of the vessel (Sections Research Vessels and Cameras) and unmanned aerial systems equipped with sensors (Sections Remotely-Piloted Aircraft and Sensors) could further automate the process in conjunction with image recognition software (MSFD GES Technical Subgroup on Marine Litter, 2011). It is important to focus the limited resources on areas of potential elevated presence or concentration. For example, computer models can be used to simulate movement of marine litter (Section Modeling in Current Monitoring Programmes) and retrospective satellite-derived wind and current information can be used to estimate where marine litter has been (Sections Satellite and Satellite Sensors). Forecasted conditions can also be used to predict where it is going (Mansui et al., 2015).

Although less litter monitoring in done by aircraft and/or satellite, these platforms have the ability to cover a larger area more rapidly than the other platforms, and have been useful to identify large litter patches (Goldstein et al., 2013). Satellite imagery and aerial photos immediately following the Japanese Tsunami captured images of buoyant materials forming large litter patches near Japan's coast until these fields became too dispersed, though monitoring of the tsunami's impacts continues (Table S1; 27). Detection capability, access and processing cost are some of the limiting factors to using satellites. They do provide information useful for targeted clean up actions at floating hotspots and the model calibrations that predict pathways and accumulation areas.

Future efforts should focus on the development of systems that collect high-resolution images of marine litter items from existing platform such as ships, airplanes and satellites paired with automated image recognition to quantify the items while keeping processing costs down. Similar automated techniques should be developed to detect microplastics in marine environments. Finding ways to partner and integrate marine litter monitoring with existing surveys is crucial, although there is a need to standardize and/or expand opportunistic reporting.

Marine Non-indigenous Species

Non-Indigenous Species (NIS), also known as non-native or alien species, are organisms that have been moved into new areas outside their natural range by human activities e.g., shipping, recreational boating, and aquaculture. Some NIS become invasive and can exert pressures on the marine environment with possible social, economic, or environmental impacts (Copp et al., 2005). The Convention on Biological Diversity (CBD) has identified a three-tiered hierarchal approach for managing invasive species: (i) preventing the introduction of invasive species, between and within states, is generally more cost-effective and environmentally desirable than measures taken following introduction and establishment of an invasive species; (ii) early detection and rapid action to prevent the establishment of invasive species; and (iii) containment and long-term control measures should be implemented, to prevent further spread of an introduced species. To achieve these goals, several international measures have been put in place and are currently being enhanced: The Regional Seas Conventions (e.g., OSPAR in relation to the UK); the EC Regulation on the use of Alien Species in Aquaculture (Council Regulation (EC) No, 708/2007); the MSFD descriptor two (Council Directive, 2008/56/EC); the WFD; the EC Regulation on Invasive Alien Species of EC Concern (Council Regulation (EU) No, 1143/2014); and the IMOs International Ballast Water Convention (e.g., Olenin et al., 2016). For all these drivers, it is key to assess the level of risk of entry (introduction), of establishment, of secondary dispersal and of impacts.

Targeted monitoring and surveillance for NIS is currently driven by an initial risk screening protocol. The UK has established a NIS risk analysis scheme (Baker et al., 2008), which is used to identify high priority marine NIS (Stebbing et al., 2015), consisting of invasive NIS established in the UK and horizon species, to facilitate targeted risk based monitoring and surveillance. This "species-based" approach in risk analysis is complemented by pathway analysis, which encompasses the geographical routes by which NIS are transported, either by natural or human-assisted means (both direct and indirect), and the transport vectors (e.g., ships, contaminated gear, tsunami debris). Thus, pathway analysis provides a means of identifying high risk areas for NIS introductions, such as has been done for the UK (Tidbury et al., 2016). The monitoring currently being implemented is based around the utilization of existing statutory monitoring efforts utilizing research vessels (Section Research Vessels), where priority NIS species are recorded and reported (Stebbing et al., 2016), with some enhancement by citizen science (Section Citizen Science, e.g., Waugh, 2009). Furthermore, NIS data can be integrated with habitat and biodiversity data to examine long term impacts that NIS are having, and where the issue is most serious, possibly requiring remediation.

The gold standard of NIS identification is visual ID by a trained scientist, but the way NIS monitoring is most likely to develop in the next 10 years is through increased specificity and standardization of techniques, with molecular tools playing an increasing role (Section Molecular Biology Techniques). It is likely that DNA sequencing technologies will become cheaper, more accessible, and more sensitive, and as such assays will not have to be targeted by PCR but instead samples will be sequenced entirely and later screened *in silico*. If this is the case, then general molecular (eDNA) samples taken from UK waters could be sequenced and used to assess many things, including biodiversity, pathogen presence, and the presence of NIS. For example, the presence of *Mnemiopsis leidyi*, regarded as one of the worst invasive marine NIS (e.g., Lowe et al., 2000; Streftaris and Zenetos, 2006), was detected in UK waters for the first time in 2014 using eDNA based screening (Créach, 2015). The use of this molecular technique was critical in this particular case because *M. leidyi* is difficult to sample and to see in the water due to its fragile character and transparency.

Marine Noise

Underwater noise from human activities can have adverse physical, physiological, and behavioral effects on marine fauna. Since underwater noise became recognized as a significant pollutant in the 1990s, most research effort has focused on marine mammals, though in recent years the number of studies on fish and invertebrate species has grown substantially (Williams et al., 2015). Sources of underwater noise can be categorized as impulsive or continuous, and each type requires a different approach to management which is reflected in current environmental indicators for underwater noise pollution (Cefas, 2015). Impulsive sound sources are brief with a sudden onset (e.g., explosions), and may be repeated for extended periods (e.g., percussive pile driving, geophysical surveys using seismic airguns). Noise from shipping is the predominant continuous sound source; other examples include dredging and drilling activity. The most comprehensive legislative instrument addressing underwater noise within EU waters is Descriptor 11 of the MSFD, which comprises two Indicators: Indicator 11.1.1 maps the spatiotemporal distribution of low and mid-frequency impulsive noise sources, while Indicator 11.2.1 tracks levels of continuous low-frequency noise within specified frequency bands. Indicator 11.2.1 requires long-term field measurements of underwater noise levels, although EU member states have yet to establish monitoring programmes, and historical data are lacking. Cefas has led the first baseline assessment of noise levels in UK waters (Merchant et al., 2016), and is now implementing an ongoing monitoring programme in partnership with academic institutions engaged in marine research; this will become operational in 2017. Noise levels will be monitored using autonomous underwater acoustic recorders (Section Acoustics), which are moored to the seafloor (Section Fixed Point Marine Observation Systems) and periodically serviced to replenish the power supply and to recover data. Such static recorders remain the most suitable method to monitor underwater noise for management purposes, given the requirement to track long-term trends and the relative expense of installing and maintaining cabled systems. Glider technology (Section Remotely Operated and Autonomous Vehicles) has been mooted as a possible solution to underwater noise monitoring, and has been applied in several demonstration projects (e.g., Matsumoto et al., 2011; Wall et al., 2012). While monitoring from mobile platforms such as gliders lacks the power to detect long-term temporal trends in noise levels, the spatial coverage has potential uses in ground-truthing modeled maps of noise levels over large areas. Such models (e.g., Erbe et al., 2012; NOAA, 2012), based on spatiotemporal distributions of noise sources (e.g., using AIS ship-tracking data), could provide more comprehensive spatial coverage than field measurements alone, although to date these models have not been thoroughly validated using field measurements.

OPTIMIZING MARINE MONITORING

Modeling in Current Monitoring Programmes

Holistic assessments of the marine environment are required to support Ecosystem Based Management, therefore integrative modeling is key to turn monitoring data into assessment products (de Jonge et al., 2006). The EU has implemented this through the MSFD (Council Directive, 2008/56/EC), which aims to maintain biodiversity and protect ecosystem function with modeling being required at each step of the assessment cycle (Lynam et al., 2016). Beyond improving our assessments of state, models are an integral part of the decision-making process, since they allow assessment of the performance of policies and potential management measures alongside quantification of the risk and uncertainty (Hyder et al., 2015a; Lynam et al., 2016). Models can also be used to assess the value of different configurations of monitoring networks, although further development is required in this area (Kupschus et al., 2016).

Models have the potential to provide consistent products that pull together monitoring from different sources (e.g., vessel, AUV, remote sensing) and account for uncertainty in the data. Models of the ocean and shelf seas are commonly used to develop reanalysis products, where monitoring data are assimilated into the model and used to produce consistent gridded products that are provided to the scientific community (Table S1; 28). For example, the Atlantic- European North West Shelf- Ocean Physics Reanalysis uses the Forecasting Ocean Assimilation Model 7 km Atlantic Margin Model (FOAM AMM7). Similarly, the European data-portal EMODnet provides interpolated maps derived from monitoring data (Table S1: 29).

To support decision making and management of the marine environment, models are commonly used for fisheries stock assessments, but multi-species modeling approaches have had much less acceptance. There are some significant challenges surrounding the uptake and use of complex models by decision makers (Hyder et al., 2015a; Lynam et al., 2016) relating to understanding of models in the following ways; production of functional outputs, quantifying uncertainty, and availability of quality standards. The availability of products and decision making timescales are often at odds with model development (Hyder et al., 2015a; Queirós et al., 2016). Communicating the outcomes and limitations of complex models to stakeholders is one of the main challenges when it comes to uptake and should be dealt with as part of the model building process (Cartwright et al., 2016).

Despite these challenges, there are still good examples of the integration of modeling and monitoring to develop solutions. Models have been used to provide advance-warning of algal blooms in support of the EU Bathing Waters Directive (Shutler et al., 2015), assessment of eutrophication OSPAR (Lenhart et al., 2010) and the identification of areas at high risk from the introduction of non-indigenous species (Tidbury et al., 2016). Model information has also been used to estimate the physical loss of potential habitat supporting common eelgrass, *Zostera marina* beds and northern horsemussel, *Modiolus modiolus,* reefs that are important in European waters (ICES, 2016a). The STRIKER v.4.0 model (fully described in Appendix 9.4 of the Tidal lagoon Swansea Bay Plc Environmental Statement; TLSB, 2016) models risk of injury to salmon by turbine strikes. Fisheries management within the ICES area depends greatly on stock assessment models to integrate survey data with commercial catch information (ICES, 2016b) and population modeling is used similarly to evaluate the abundance of gray seals in UK waters using count data on the production of pup at colonies (Table S1; 30). The distribution of cetaceans has been modeled from line-transect survey data to develop an indicator assessment for OSPAR (Table S1; 31). However, the pressing need is for multi-species modeling to support advice on ecosystem status for fisheries and food webs in general.

There is a broad marine ecosystem modeling capability within the UK and there is potential to increase the use of models to support marine environmental management (Hyder et al., 2015a). Further development of models integrating monitoring data is needed to better assess changes over time, predict future trends and develop more efficient monitoring programmes (Carstensen, 2014; Hyder et al., 2015a). Discussed further in Section Total Ecosystem Approach.

Modeling to Understand Data Gaps

Within an ecosystem approach to management, monitoring programmes should be adaptive to ensure that data are collected to support those assessment areas that are most uncertain, and/or showing the strongest degradation (Shephard et al., 2015). Risk analysis is required to draw attention to activities that pose a risk to biodiversity and ecosystem function (e.g., Pinnegar et al., 2014; Katsanevakis et al., 2016). Adaptive monitoring to tackle uncertainties and risks should be cost-effective and lead to information being generated where it is most needed (de Jonge et al., 2006). Modeling can help to understand "the value of information," "reduce uncertainty" and how best to integrate new technology appropriately in our monitoring programmes. As a result, we can build a more thorough understanding of the way we collect data and generate a quantitative weighting of any gaps that exist in the programme.

A greater spatial understanding of the system monitored, including an identification of ecologically important areas, can be gained through habitat modeling, ideally including their associated species, and connectivity between them (Baker and Harris, 2012). A range of tools (Piroddi et al., 2015; Peck et al., 2016) have been developed to map habitats and communities. Distribution modeling can predict the spatial patterns in habitats using observations of environmental variables (Stephens and Diesing, 2015) and statistical models can provide information on uncertainty. Such approaches can indicate where changes in monitoring can reduce the variance in the distribution model, or if multiple indicators are supported by one monitoring programme this can be optimized by minimizing a weighted average of the indicators' variances (Carstensen and Lindegarth, 2016). The power needed to detect change in given indicators can be assessed leading to operational decisions on how many data types can be collected whilst maintaining sufficient overall precision and accuracy (Shephard et al., 2015).

Value of Information

Monitoring plays a strategic role in the decision-making process; it helps to identify and compare the baseline status relative to an objective and helps improve the relevance, efficiency, and effectiveness of policies (UNICEF, 2008). Given this, the benefit of establishing a monitoring programme is to address uncertainties or gaps in knowledge to improve quality and outcomes of decision making (MacAuley, 2005). This means that economic considerations when developing these programmes should focus on value for money; the value of the benefits from gaining additional information should at least equal the value of the resource required.

To calculate the costs, the different inputs and activities should be identified and the associated financial costs calculated and added together. Identifying and measuring the benefit is not as straight-forward. To a decision maker, the value of the benefit of gaining additional information can be measured by their willingness to pay to obtain this before making a decision; often referred to as "value of information" in the literature (e.g., Raiffa and Schlaifer, 1961; Wendt, 1969; MacAuley, 2005). The concept of the value of information has often been applied to human health issues (e.g., Yokota and Thompson, 2004), marketing (e.g., Barron and Targett, 1986) and financial risk management (e.g., Huber et al., 2008). However, this has also been applied in the management of marine and coastal resources; for example, in identifying optimal funding allocation for marine mammal monitoring (Bisack and Magnusson, 2014) and in valuing additional fisheries benefit due to improved spatial information (Costello et al., 2010). The benefit of additional information can also be measured by the loss that is avoided (Lark and Knights, 2015) because of the availability of this information. This focuses on the value of the loss that will be incurred due to erroneous or insufficient information used in decision making, which could be avoided if additional information is obtained.

Several recent studies have assessed frameworks for quantifying the costs and benefits of Programmes of Measures within the MSFD (Börger et al., 2016; Nygård et al., 2016; Oinonen et al., 2016). As well as the above "willingness to pay" assessment there is also the option of manually identifying and measuring the actual monetary benefit of monitoring. Nygård et al. (2016) used the example of Finnish zooplankton monitoring to measure real cost and value. This data demonstrated there can be magnitudes of difference between cost and value of monitoring and suggests it may be worth tailoring the money spent on monitoring to match the value of the data, rather than the cost of the data (Nygård et al., 2016). However, it should be noted that the reality of marine planning can be very different from the academic optimal. In fact, the UK response to implementation of the MSFD was very practical, and it elected to use the existing programmes of measures to achieve MSFD good environmental status where possible (Boyes et al., 2016). An approach which may not be optimal in terms of "value of information" but which does result in rapid, practical implementation of tools that fulfill new legislation.

THE FUTURE OF MONITORING

Total Ecosystem Approach

The "total ecosystem approach" to monitoring is a coherent evidence-to-advice package, supported by a fully-integrated ecosystem monitoring programme, and potentially a way to implement many of the new approaches identified above (Borja et al., 2016; Kupschus et al., 2016). At the center of this package is a dynamic model of the ecosystem function and its responses to pressures based on process relationships. Monitoring data help to parameterize the relationships with individual states that contribute to one or more parameter estimates (Kupschus et al., 2016). Ideally, legislative assessments of ecosystem state are produced from results of this model, and future states are predicted for different sets of pressure and environmental trajectories. Such an idealized system offers several benefits and improvements over the current monitoring approach:

1) Ecosystem processes are fixed over evolutionary timescales; what differs are the rates of the processes based on current conditions, and the interactions. One data point influences multiple output states, and one output state is influenced by multiple data points. The rigidity/redundancy this creates means that data collection can be more flexible. In contrast to current, status-based monitoring, which lacks the stabilizing effects, it is possible to alter or improve monitoring design and to implement modern technology as it becomes relevant.
2) Quantitative assessments of ecosystem information provide the opportunity to evaluate the efficiency of the monitoring programme and assess the efficacy of alternative monitoring options allowing for a feedback loop to data collection. Thus, data collection can be targeted specifically at the model uncertainty to increase precision of key outputs or to reduce model error through thorough hypothesis testing.
3) Modeled quantities are in absolute terms, which means they can be compared across different sampling methodologies

appropriate for different regions such as catchment-coast-marine provided that the biological components are interacting sufficiently between the sampled regions in order to support a coherent model.

4) Predictions from the model provide an internally-consistent ecological view of the system under different management actions. Such outputs provide the opportunity to evaluate the societal view of management options through socio-economic simulations. Such analysis of key risks and concerns for society can be used to weight ecosystem model uncertainties and provide an opportunity for further feedback on data collection to ensure monitoring meets societal needs.

Integration of New Technology and Associated Challenges

The challenge of introducing new technologies is to ensure that (as appropriate) they are validated. Integration and validation can be a simple process, e.g., replacing and upgrading a camera system, or can require a complete reworking of equipment, sampling methodology, data analysis and finally interpretation of that data to meet policy requirements. The recent overview by Danovaro et al. (2016) demonstrates some of the ways this could be done, with specific emphasis on molecular and automated solutions. Incorporating new technology into long-running monitoring programme clearly has different implications to when doing so within a new or contemporary programme due to the interruption of well managed practices and loss of time-series data i.e., preventing comparison between new and old data sets. Implementation of the total ecosystem model, as discussed above in Section Total Ecosystem Approach, would mitigate this challenge, allowing new sources of data to be directly integrated into a model of ecosystem health. However, where a status based monitoring approach is used then it is normal to validate new equipment by running old and new systems side-by-side until some form of comparison or calibration can be made- a time consuming and expensive endeavor, which should only be completed where long-term efficiency gains are probable. In a new monitoring programme, there is less issue with data continuity and greater potential to use innovative technology. However, this should not absolve responsibility to design and deploy a programme that will allow continuity when future changes become possible i.e., it is crucial to realize that although we are currently seeing a lot of change in automation, molecular capability, and large-scale data gathering, this is not the end of technological development. The implementation of any new objective should therefore be accompanied by a strategy for continual updating of our monitoring programme to take advantage of new technology, such as using modeling practices discussed earlier. However, translating data from models into policy-relevant information is possibly the biggest issue. This lies in understanding the true objective of what is trying to be achieved, i.e., is it the collection of data or is it, for example, to understand the function of an ecosystem. If the latter then, it should be possible to use any technology to answer the question.

Finally, there is the issue of accepting new methods within set legislative guidelines (i.e., achieving policy level agreement for change in method). In open discussion about technological development, this is often cited as the primary reason not to use progressive technology. However, this is not always the case. OSPAR Annex 2 states that "On the assessment of the quality of the marine environment... contracting parties shall... take into account scientific progress which is considered to be useful for such assessment purposes," clearly opening the door to new methodology (OSPAR, 2003a). The more recent MSFD, however, is less clear and states there is a "Need to develop technical specifications and standardized methods for monitoring at Community level, so as to allow comparability of information." (Council Directive, 2008/56/EC) suggesting that standardization of methods is paramount. In any situation, there will be scope for development but it is crucial that legislative limitations are understood and that efforts are placed in the right area to effect positive change.

Data Management and Communication

The development of new technology and methods outlined in this paper will increase the already substantial variety and volume of data collected for marine monitoring. This resource relies on good data management practices to support quality science outputs and improve reuse and integration across disciplines and institutions (Table S1; 32). The five key principles of "Open Data by Default," "Quality and Quantity," "Useable by All," "Releasing Data for Improved Governance," and "Releasing Data for Innovation" agreed by the G8 (Table S1; 33) are perfectly relevant to marine monitoring.

The creation and sharing of information about data (metadata) is an essential aspect of marine monitoring, researchers are expected to record key data aspects (timescale, spatial coverage, methods, data formats etc.). Various metadata catalogs at an institutional, national or global level publish this information to allow greater collaboration and integration, increase re-use and decrease duplication of effort. A federated approach to sharing metadata allows institutional repositories (e.g., CefasDataHub, DASSH Table S1; 34, 35) to feed into national (e.g., MEDIN, DGU; Table S1; 35, 36) and international (e.g., INSPIRE, EUROGOOS; Table S1; 37, 38) portals. The shared use of controlled vocabularies and common metadata standards facilities this approach.

Alongside metadata, is it increasingly common to make data accessible for sharing and use, known as "open data" (Table S1; 39). UK government data are generally made available under the Open Government Licence (Table S1; 40), unless considered sensitive or personal (which would contravene the data protection regulations). Serving open data via application programming interfaces (APIs) enables researchers to build tools which bring together data and metadata via a direct connection to the original source. This facility, alongside increased used of cloud based platforms for data analysis and storage, unleashes great potential for interconnected monitoring. The "collect once, use many times" approach strengthens the scientific and economic value of open data as well as facilitating the integration and analysis of "big data" to help with the key challenges within marine monitoring such as finding gaps, delivering value for money and promoting innovation.

Whilst progress has been made, there is still a long way to go before all valuable marine monitoring data is available for general use. The majority of commercial data and legacy government data has not, to date, been made open and the diverse methods of collection, storage and publishing data limit the interoperability of datasets. Drives to encourage data sharing across business and institutions and establish consistent approaches to data collection and curation are key to maximizing the value of data for marine monitoring.

CONCLUDING REMARKS

Offshore marine monitoring in the UK is undertaken though a complex array of individual programmes that have evolved in response to increasing and diverse threats and legislation (**Table 1**, **Figure 1**). Each programme focusses on individual components of the marine ecosystem leading to fragmented, albeit effective, assessments. Given current economic, political, and societal change, there is the opportunity to design a fully-integrated ecosystem monitoring program for the UK. In this paper, we have outlined the drivers for marine monitoring, the technologies used within long-running and contemporary monitoring programmes, and recent technological advances relating to data gathering. Appropriate inclusion of innovative technologies guided by socio-economic and model analysis has the potential to facilitate a monitoring programme design which meets current legislation and can also adapt to future monitoring needs. Integration of data into improved ecosystem models will also allow marine ecosystem forecasts to be made.

In summary, economics and politics are forcing methods of monitoring the UK marine environment to change. If this upheaval is used to re-assess our current data requirements, identify where and when the valuable data can be collected, and exploit the most appropriate technology to collect it, then our monitoring programmes will be more efficient, more scientifically integrated, and consequently more valuable than before.

AUTHOR CONTRIBUTIONS

TB and NG drafted the manuscript. TB, NG, RB, LB, JPB, JB, GC, MD, SD, SF, LF, DF, KH, CJ, JV, SiK, SvK, CL, KL, CPL, BL, TM, EN, SM, PM, NM, LP, DP, SP, PS, BT, SW, OW, and DR made substantial contributions to the conception, design, and revision of the whole manuscript and to drafting fundamental sections. All authors approve the final version for publication and agree to be accountable for all aspects of the work relating to accuracy and integrity.

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