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Triton Field Trials - Changes in Habitats, a Literature Review of Monitoring Technologies

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Prepared for the U.S. Department of Energy
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Pacific Northwest National Laboratory
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Summary

Marine energy devices are installed in highly dynamic environments and have the potential to affect benthic and pelagic habitats around them. Regulatory bodies often require baseline characterization and/or post-installation monitoring to determine whether changes in these habitats are being observed. However, a great diversity of technologies is available for surveying and sampling marine habitats. Selecting the most suitable instrument to identify and measure changes in habitats at marine energy sites can become a daunting task.

We conducted a thorough review of journal articles, survey reports, and grey literature to extract information about the technologies used, the data collection and processing methods, and the performance and effectiveness of these instruments. We examined documents related to marine energy development, offshore wind farms, oil and gas offshore sites, and other marine industries around the world over the last 20 years, as well as national and international guidelines for surveying habitats around offshore activities. A total of 120 different technologies were identified across six main habitat categories: seafloor, sediment, infauna, epifauna, pelagic, and biofouling. The technologies were organized into 12 broad technology classes: acoustic, corer, dredge, grab, hook and line, net and trawl, plate, remote sensing, scrape samples, trap, visual, and others. Visual was the most common and the most diverse technology class, with applications across all six habitat categories.

Sampling designs varied considerably among the reviewed studies but transect was the predominant design for surveying seafloor, epifauna, and pelagic habitats. The most common data analyses were univariate and multivariate statistical analyses aimed at calculating and comparing biodiversity indices, characterizing faunal assemblages or sediment classes, or modeling the distribution of animals related to abiotic parameters. Technologies and sampling methods adaptable and designed to work efficiently in energetic environments have greater success at marine energy sites. In addition, sampling designs and statistical analyses should be carefully thought through to identify differences in faunal assemblages and spatiotemporal changes in habitats.

Acknowledgments

We thank Joseph Haxel, Alicia Amerson, Samantha Eaves, and Garrett Staines for their assistance with this report and helpful reviews and comments. Susan Ennor provided technical editing, and Stephanie King created an original illustration.

Acronyms and Abbreviations

ANOSIM	analysis of similarity
ANOVA	analysis of variance
BACI	before after control impact
BOEM	Bureau of Ocean Energy Management
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CHIRP	compressed high intensity radar pulse
CMECS	Coastal and Marine Ecological Classification Standard
CR	control/response
DEM	digital elevation model
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FERC	Federal Energy Regulatory Commission
GAM	generalized additive model
GLM	generalized linear model
HSD	honestly significant difference
JNCC	Joint Nature Conservation Committee
MBES	multibeam echosounder
MDS	multidimensional scaling
MMS	Minerals Management Service
NOAA	National Oceanic and Atmospheric Administration
NTL	notice to lessees
OCS	outer continental shelf
PERMANOVA	permutational analysis of variance
PNNL	Pacific Northwest National Laboratory
PRIMER	Plymouth routines in multivariate ecological research
SIMPROF	similarity profile
U.S.	United States

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1.0 Introduction

In 2020 and 2021, the Triton team conducted a literature review for the U.S. Department of Energy Water Power Technologies Office, as part of the Changes in Habitat task under the Triton Field Trials project. This review investigated the technologies and methods commonly used worldwide to monitor and survey benthic and pelagic habitats, and changes in these habitats in relation to the installation and operation of marine energy devices.

1.1 Issue

In numerous countries around the world, regulatory authorities require that potential impacts on the marine environment be assessed prior to any industrial development at sea, including activities such as offshore drilling, dredging, or installing marine energy infrastructure. For example, European countries are required by the European Water Framework Directive (European Parliament and European Council, 2000), Habitat Directive (European Parliament and European Council, 1992), and Marine Strategy Framework Directive (European Parliament and European Council, 2008) to monitor the status of the ecological quality of their bodies of freshwater and saltwater and the various habitats they host, and to maintain sustainable use of these water bodies. In the United States (U.S.), water quality is regulated by the Clean Water Act (1972) and associated acts, while habitats and species of special concern are regulated by various policies such as the Endangered Species Act (1973), Fish and Wildlife Coordination Act (1980), and Magnuson-Stevens Fishery Conservation and Management Act (2007). In accordance with these regulations, environmental monitoring requirements for marine energy projects often include the identification and measurement of changes in benthic and pelagic habitats and, while long-term surveys are necessary to rule out extreme and rare events from occasional samplings, settling on the appropriate sampling technologies, methods, and analyses is as important as having the spatiotemporal coverage to identify changes (Bender et al., 2017, Hemery, 2020). For instance, sampling gear such as grabs and statistical analyses able to describe the sediment community composition are usually recommended when documenting and monitoring environmental changes due to marine pollution (Gray and Elliott, 2009, Holte and Buhl-Mortensen, 2020). In addition, biological communities are dynamic systems that change over time until reaching a state of persistence, a certain level of equilibrium that allows for temporal variation (Callaway, 2016, Grimm and Wissel, 1997), which needs to be accounted for when designing and interpreting the results of surveys.

1.2 Background

Scientists interested in marine ecology have characterized marine habitats for many decades using a great diversity of technologies and methods, in one of the oldest disciplines in marine sciences. In some places, there are local preferences and long histories of developing and using specific technologies. Over time, field sampling studies have been organized into four different types (i.e., baseline, impact, monitoring, and ecological pattern and process; Kingsford and Battershill, 1998), and some technologies are more suitable than others for specific habitats and field sampling studies. The diversity of sampling tools available for characterizing habitats and measuring changes range from gear inspired by or similar to artisanal and commercial fishing equipment to sophisticated and constantly improved acoustic and optical technologies (Bender et al., 2017, Hubert et al., 2012, Thistle, 2002). Acoustic techniques for characterizing seafloor and sediment properties often require ground-truthing using physical sampling or optical imaging technologies, especially when monitoring physical disturbances due to anthropogenic activities at sea (Birchenough et al., 2006). Choosing the right technology depends on the study’s goal and the habitat and depth targeted, as well as the trade-off between sample size, number of replicates, and field costs (Holte and Buhl-Mortensen, 2020).

To help scientists pick the appropriate technologies and design their sampling methodologies, many institutions have established guidelines and recommendations that address various habitats, industries, and categories of technologies. Two sets of guidelines created by the International Organization for Standardization (ISO) aim to assist with quality assurance and standardization of monitoring surveys for soft-bottom macrofauna (ISO 16665; ISO, 2014) and hard-substrate communities (ISO 19493; ISO, 2007) by recommending sampling strategies related to the habitats covered. In the U.S., while the U.S. Environmental Protection Agency (EPA) has published guidance manuals for testing dredge material (EPA, 1998) and for sampling designs for environmental data collection (EPA, 2002), the Bureau of Ocean Energy Management (BOEM, formerly Minerals Management Service [MMS]) has released a number of guidelines and notices to lessees targeting various ocean industries and a diversity of habitats: biological survey and reporting requirements (MMS, 2006), shallow hazards (MMS, 2008), biologically sensitive underwater features and areas (MMS, 2009a), deep-water benthic communities (MMS, 2009b), benthic habitat surveys (BOEM, 2019a), fisheries related to renewable energy development (BOEM, 2019b), and geophysical, geotechnical, and geohazard guidelines (BOEM, 2020). In the United Kingdom, the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) has established guidelines for benthic studies at dredging sites (CEFAS, 2002) and data acquisition to support offshore renewable energy projects (CEFAS, 2011), and the Joint Nature Conservation Committee (JNCC) has published a marine monitoring handbook that presents numerous procedural guidelines, including topics such as acoustic seabed mapping, side-scan sonar, sediment profile imagery, towed imagery, and sediment grabs (Davies et al., 2001).

Despite these guidelines and manuals, identifying habitat changes resulting from human activities such as marine energy development has proven to be challenging, particularly because of the high-energy environments targeted by this industry (i.e., channels that have strong tidal currents or open coasts that have large waves). In addition, environmental impact assessments and monitoring plans are often industry-, site-, and project-specific, making it difficult to compare protocols and results, and transfer lessons learned from one project to another (Garel et al., 2014, Gonzalez et al., 2019). If not standardization, at least consistency in technologies and methods used would facilitate baseline surveys and environmental monitoring, and ultimately the development and permitting of marine energy projects (Copping et al., 2020, Gonzalez et al., 2019). In challenging environments such as those suitable for marine energy projects, traditional sampling and surveying technologies may prove to be inappropriate and lead to sampling bias and inaccuracies, analogous to issues highlighted when monitoring fish around artificial aggregating devices (e.g., Dempster et al., 2002). Innovative methods and technologies may sometimes be required, yet the consistency of data and results, and the affordability of new technologies remains to be assessed (Greene, 2015, Mack et al., 2020).

1.3 Report Purpose, Scope, and Organization

The present literature review aims to provide parties involved in surveying and monitoring the environmental effects of marine energy development with an overview of the technologies commonly used for characterizing habitats and assessing changes associated with marine energy projects, and to understand why some technologies are selected over others. This report expands the literature review beyond what is presented in the journal manuscript (Hemery et al. 2022) by providing descriptions of analyses commonly used through the reviewed literature to assess data collected by various technologies, and by including summaries of the different guidelines and recommendations listed above. We reviewed journal articles, survey reports, and grey literature to extract information about the instruments used, their characteristics, and the methodologies, as well as the performance and effectiveness, of these technologies. We investigated documents describing field methods for baseline characterization and monitoring surveys at marine energy sites, as well as at offshore wind farms, oil and gas offshore sites, and other marine industries around the world over the last 20 years. This review aimed to highlight the pros and cons of each technology as they apply (or not) to the marine energy context in the U.S., in order to help parties involved with site characterization and monitoring select the most appropriate technology(ies) for a specific marine energy project. Determining which habitats to survey and what constitutes a change can sometimes be challenging. For this study, we considered a change to be any difference in state before and after a specific event, or any sudden or gradual transformation through space and time. Because a habitat is the natural environment of an organism comprising the array of physical and biological resources necessary to its survival and reproduction (Thomas, 2019), we considered changes in seafloor and sediment characteristics, benthic and pelagic communities, and biofouling assemblages.

The methods section describes the search process for relevant literature along with how the synthesis metrics guiding the extraction of pertinent data were developed. The results section summarizes the diversity of technologies identified in the reviewed documents, and provides an overview of commonly used sampling designs and statistical analyses. Also included is a content summary of existing national and international guidelines for surveying and monitoring marine habitats around offshore activities. The discussion section details common themes identified during the literature review, examines the relevance of various technologies to the specific needs of surveying and monitoring at marine energy development sites, and emphasizes the importance of a sound sampling design and data analysis plan. Overall, this report provides guidance for selecting technologies to monitor changes in habitats at marine energy sites.

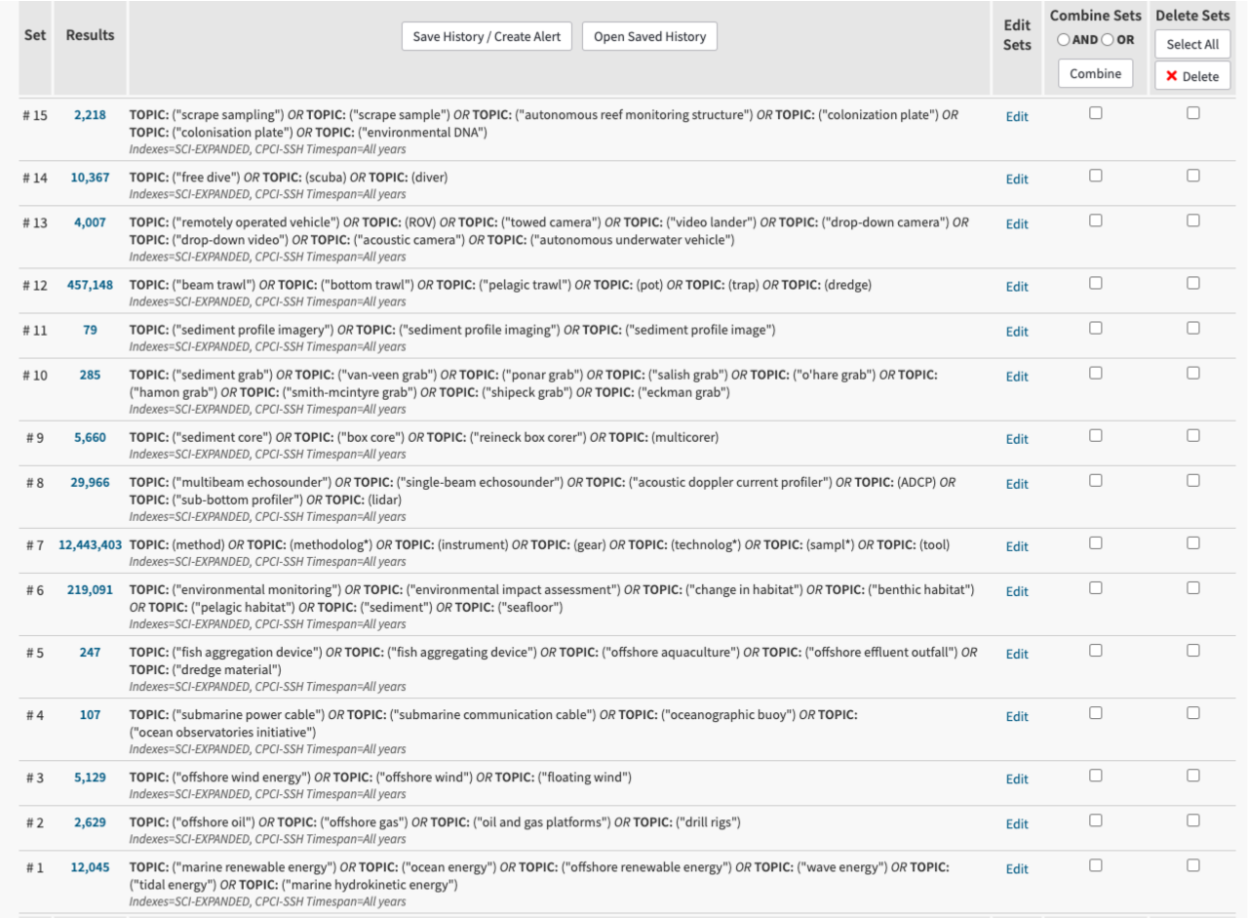
2.0 Methods

The literature review involved two main steps: (1) identifying and collecting the relevant literature, and (2) extracting and synthesizing the information from the documents.

2.1 Literature Reviewed

The initial search for literature describing methodologies and technologies employed for characterizing changes in habitat was carried out in the Tethys online knowledge base (https://tethys.pnnl.gov; Whiting et al., 2019), and involved screening all past and current marine energy project sites around the world that were listed in the knowledge base as of August 2020. All research articles, environmental impact assessment documents, and baseline and monitoring survey reports publicly available in English associated with these project sites were reviewed. Useful references cited in these documents were also examined when available in English. In addition, relevant literature cited in the 2016 and 2020 State of the Science reports about the environmental effects of marine energy development around the world (respectively Copping et al., 2016 and Copping and Hemery, 2020) was also examined. Once the marine energy literature was evaluated, we also assessed documents related to marine industries that have analogous effects on habitats, such as offshore wind, oil and gas activities, dredging, cable laying, and offshore aquaculture, focusing primarily on U.S. waters. We first explored websites from U.S. environmental regulatory agencies (e.g., BOEM, National Oceanic and Atmospheric Administration, U.S. Geological Survey) for baseline and monitoring survey reports. We then completed the investigation with a keyword search in Web of Science (https://apps.webofknowledge.com) using 15 sets of keywords and various combinations of these sets to narrow down the results (Figure 1). The relevance of the articles listed by each combination returning fewer than 100 entries was gauged by reading titles and abstracts. Finally, we hand-picked a selection of research articles in the general field of marine ecology if they described relevant fieldwork methodologies, especially if applied in environments similar to those targeted by marine energy development or describing new technologies for characterizing the expected changes in habitat.

Extracted information from the reviewed documents was organized into six main habitat categories: seafloor (e.g., bathymetry, topography), sediment (e.g., sediment type, mean grain size), infauna (i.e., animal species living within the sediment), epifauna (i.e., animal species living on top of the sediment), pelagic (i.e., animal species living in the water column; here limited to fish), and biofouling (i.e., organisms growing on artificial structures). Within each of these habitat categories, 15 fields of information were filled for each document (Table 1). Some fields covered the document’s metadata, others covered technical aspects of the technologies and methods described in the documents, and others feedback about and the usability of technologies and/or data obtained.



Set	Results		Edit Sets	Combine Sets	Delete Sets
# 15	2,218	**TOPIC:** ("scrape sampling") *OR* **TOPIC:** ("scrape sample") *OR* **TOPIC:** ("autonomous reef monitoring structure") *OR* **TOPIC:** ("colonization plate") *OR* **TOPIC:** ("colonisation plate") *OR* **TOPIC:** ("environmental DNA") *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 14	10,367	**TOPIC:** ("free dive") *OR* **TOPIC:** (scuba) *OR* **TOPIC:** (diver) *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 13	4,007	**TOPIC:** ("remotely operated vehicle") *OR* **TOPIC:** (ROV) *OR* **TOPIC:** ("towed camera") *OR* **TOPIC:** ("video lander") *OR* **TOPIC:** ("drop-down camera") *OR* **TOPIC:** ("drop-down video") *OR* **TOPIC:** ("acoustic camera") *OR* **TOPIC:** ("autonomous underwater vehicle") *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 12	457,148	**TOPIC:** ("beam trawl") *OR* **TOPIC:** ("bottom trawl") *OR* **TOPIC:** ("pelagic trawl") *OR* **TOPIC:** (pot) *OR* **TOPIC:** (trap) *OR* **TOPIC:** (dredge) *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 11	79	**TOPIC:** ("sediment profile imagery") *OR* **TOPIC:** ("sediment profile imaging") *OR* **TOPIC:** ("sediment profile image") *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 10	285	**TOPIC:** ("sediment grab") *OR* **TOPIC:** ("van-veen grab") *OR* **TOPIC:** ("ponar grab") *OR* **TOPIC:** ("salish grab") *OR* **TOPIC:** ("o'hare grab") *OR* **TOPIC:** ("hamon grab") *OR* **TOPIC:** ("smith-mcintyre grab") *OR* **TOPIC:** ("shipeck grab") *OR* **TOPIC:** ("eckman grab") *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 9	5,660	**TOPIC:** ("sediment core") *OR* **TOPIC:** ("box core") *OR* **TOPIC:** ("reineck box corer") *OR* **TOPIC:** (multicorer) *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 8	29,966	**TOPIC:** ("multibeam echosounder") *OR* **TOPIC:** ("single-beam echosounder") *OR* **TOPIC:** ("acoustic doppler current profiler") *OR* **TOPIC:** (ADCP) *OR* **TOPIC:** ("sub-bottom profiler") *OR* **TOPIC:** (lidar) *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 7	12,443,403	**TOPIC:** (method) *OR* **TOPIC:** (methodolog*) *OR* **TOPIC:** (instrument) *OR* **TOPIC:** (gear) *OR* **TOPIC:** (technolog*) *OR* **TOPIC:** (sampl*) *OR* **TOPIC:** (tool) *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 6	219,091	**TOPIC:** ("environmental monitoring") *OR* **TOPIC:** ("environmental impact assessment") *OR* **TOPIC:** ("change in habitat") *OR* **TOPIC:** ("benthic habitat") *OR* **TOPIC:** ("pelagic habitat") *OR* **TOPIC:** ("sediment") *OR* **TOPIC:** ("seafloor") *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 5	247	**TOPIC:** ("fish aggregation device") *OR* **TOPIC:** ("fish aggregating device") *OR* **TOPIC:** ("offshore aquaculture") *OR* **TOPIC:** ("offshore effluent outfall") *OR* **TOPIC:** ("dredge material") *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 4	107	**TOPIC:** ("submarine power cable") *OR* **TOPIC:** ("submarine communication cable") *OR* **TOPIC:** ("oceanographic buoy") *OR* **TOPIC:** ("ocean observatories initiative") *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 3	5,129	**TOPIC:** ("offshore wind energy") *OR* **TOPIC:** ("offshore wind") *OR* **TOPIC:** ("floating wind") *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 2	2,629	**TOPIC:** ("offshore oil") *OR* **TOPIC:** ("offshore gas") *OR* **TOPIC:** ("oil and gas platforms") *OR* **TOPIC:** ("drill rigs") *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐
# 1	12,045	**TOPIC:** ("marine renewable energy") *OR* **TOPIC:** ("ocean energy") *OR* **TOPIC:** ("offshore renewable energy") *OR* **TOPIC:** ("wave energy") *OR* **TOPIC:** ("tidal energy") *OR* **TOPIC:** ("marine hydrokinetic energy") *Indexes=SCI-EXPANDED, CPCI-SSH Timespan=All years*	Edit	☐	☐

Figure 1. Summary of the Web of Science search with the 15 sets of keywords that were combined in various ways to narrow down the results.

2.2 Information Synthesis

Once all documents were reviewed, the information extracted for six of the fields (technology, reason for selecting technology, sampling design, data processing, successful identification of change, and feedback after use) were synthesized by habitat category. To do so, entries for four of these fields were assigned a group option (Table 2), based on the information provided in the documents or on our expert judgment. Sometimes, entries could be assigned to more than one group and were thus given a primary and secondary group. Entries from the technology field were sorted into broad technology classes. Most common data analyses and software were synthesized from the data processing field by habitat category.

We considered any technology or suite of sensors that were specifically assembled, adapted, or modified for the goal of the reviewed studies, or by the studies' authors for multiple related projects, to be "custom-made", as opposed to commercial technologies readily available off the shelf. "Historically or geographically preferred" was attributed to cases in which technologies were selected for the results to be comparable to long-term assessments, or to studies conducted many years ago or carried out in nearby areas. We cataloged as "opportunistic" any use of technology or data obtained from a third party (e.g., industrial routine survey of structures). “Ubiquitous” was used for technologies that were somewhat wide-ranging and could be applied to various study goals, habitats, or sampling designs.

The options for categorizing sampling designs were based on the most common designs used in marine ecology (EPA, 2002, ISO, 2007, ISO, 2014). Before after control impact (BACI) and control/response (CR) refer to sampling designs that look at highlighting differences between impact and reference sites on a temporal and/or spatial scale. A gradient design usually refers to increasing distance or depth from an impact site.

Table 1. Information extracted from the documents surveyed in this literature review.

Field of information	Description
Technology	Specific technology/gear used.
Source reviewed	Citation (reference) of document reviewed.
Document name	Name given to the document internally.
Study goal	Brief description of the general aim of the study in the document reviewed.
Site characteristics	Brief description of the site: depth, relative distance to shore, bottom type if known, current speed, etc.
Reason for selecting technology	Brief description, if provided, of why authors selected the technology.
Brand and model	If specified, the brand and model of technology used.
Characteristics	If provided, a list of specific characteristics such as size, penetration depth, frequency, resolution, etc.
Methods	Brief description of the steps used to implement the technology.
Sampling design	Numbers of stations, transects, replicates, and the like.
Data processing	Brief description of how samples were handled from collection to analysis of results.
Successful identification of change	Brief description of the differences observed and the timeline, if any spatial and/or temporal changes and/or differences in habitat were observed.
Feedback after use	If provided, pros and cons of using the technology for achieving the study's goal.
Usability for modeling	Expert judgement on whether the data obtained can be used for modeling (as dependent or independent variables).
Notes	Any additional notes upon reviewing documents.

Table 2. Group options for each field for which the information was synthesized across entries.

Field of Information	Group Options
Reason for selecting technology	Custom-made; historically or geographically preferred; opportunistic; ubiquitous.
Sampling design	Before after control impact or control/response; gradient; stratified; transects; stations; other; no information.
Successful identification of change	Baseline characterization; change/differences detected; no change/differences detected; no information.
Feedback after use	Positive; neutral; negative; no information.

Stratification is a design where sampling locations are distributed throughout the diversity of habitats and/or depth previously known in the study area. Several studies did not use these well-defined sampling designs; instead, they followed transects to canvas an area, collected unclassified stations (i.e., not impact or control sites) randomly or on a predefined grid, or any other design that could not easily be classified. Often, two or more sampling designs were used in conjunction (e.g., stratification with transects, before/after gradient with stations).

Several of the documents reviewed for this study focused on characterizing baseline habitats before any project (e.g., marine energy or offshore wind developments) would start, sometimes highlighting differences in habitats. Others focused on detecting whether changes and/or differences in habitats and communities were observed after an event or as distance increases from a point of impact (e.g., artificial structure, dredge material dump site). “No information” was used for studies that did not provide details about whether they looked at detecting changes or differences in habitats. Here, too, two or more group options were sometimes applicable at the same time (e.g., a baseline study that identified different communities of mobile epifauna but no difference in sessile epifauna).

Not all documents reviewed here provided feedback on their use of specific technologies. However, when they did provide feedback, it was classified as either positive (e.g., the gear provided good quality samples in challenging settings), negative (e.g., the technology was difficult to maneuver underwater), or neutral (e.g., the instrument worked as expected). For several studies, the feedback could be classified as a combination of two or three options, when it was positive for some aspects of the work, negative for others, and neutral for yet others.

Results from the six fields of information analyzed were presented either as bar plots based on group option percentages, or as heatmaps based on frequencies of entries. As much as possible, results are presented and discussed in the following sections by habitat category.

3.0 Results

A total of 259 documents were reviewed (Appendix A); of them, 139 pertained to marine energy, 24 to offshore wind, 44 to extraction activities (e.g., oil, gas, dredging), and 52 to more general topics. Numerous documents described the use of technologies related to more than one habitat category, which resulted in 533 entries. In this review, 83 entries were found to be related to seafloor, 117 entries to sediment, 64 to infauna, 139 to epifauna, 96 to pelagic, and 34 to biofouling.

3.1 Technology Diversity

The review highlighted that as many as 120 different technologies were used across the six habitat categories, which were organized into 12 broad technology classes: acoustic, corer, dredge, grab, hook and line, net and trawl, plate, remote sensing, scrape samples, trap, visual, and others (Table 3, Figure 2). Visual was the most diverse technology class, including surveys with divers, remotely operated vehicles (ROVs), drop or towed cameras, among others. Not all technologies were employed within each habitat category and some technologies were more commonly used than others (Figure 2 and Figure 3).

Acoustic technologies, especially echosounders (e.g., fisheries echosounders, multibeam echosounders [MBESs]), were the main means of characterizing the seafloor and pelagic communities, although visual technologies were also common for pelagic habitats (e.g., divers and ROVs). Reflecting the diversity of the market, several different brands and models of MBESs and side-scan sonars were used to assess seafloor characteristics; the most common MBES brands were Kongsberg, Reson, and R2 Sonics, and the most common side-scan sonar brands were EdgeTech and Klein. Acoustic technologies for characterizing pelagic communities were mainly acoustic cameras (mostly the ARIS, Imagenex, or Sound Metrics brands) and fisheries echosounders (predominantly the Simrad brand).

Corers (mostly the box corer and Gray O’hare corer) and grabs (primarily Van Veen grab, but also Day, Hamon, Shipek, and Smith-McIntyre grabs) were only used for sampling sediment and infauna. Visual technologies like drop cameras and sediment profile imaging (SPI; with or without plan view) were also often employed for these two habitat categories. Dredges (pipe or scallop dredge) were more prominently used for sampling infauna but also a few times for sampling sediment and epifauna.

While several studies used nets and trawls (mainly beam trawls) to sample epifauna, and a few used traps, most of the technologies fell within the visual class, with a predominance of ROVs. Many different brands and models of ROVs were used, from micro-ROVs (e.g., VideoRay) to work class types (e.g., ROPOS), and most of them featured at least high-resolution still and/or video cameras, lights, and sizing lasers. Characteristics such as depth rating, ability to collect samples, or positioning system varied greatly among ROV models. Benthic video sleds, drop cameras, and towed cameras were often of various shapes and sizes, made of a light-weight frame, and carried high-resolution still and/or video cameras facing downward (drop camera) and/or forward (sleds and towed cameras). Visual technologies were also the most common tools for assessing biofouling communities (mainly photos and videos collected in situ by divers or onshore collectors), although scrape samples, plates, and traps were also used.

Table 3. Complete list of the sampling/surveying technologies compiled from the literature review and organized in technology classes. Technology acronyms are provided within brackets, while secondary technologies are provided within parentheses.

Acoustic	Net and Trawl
Acoustic backscatter	Beam trawl
Acoustic camera	Benthic trawl
Acoustic Doppler Current Profiler [ADCP]	Bongo net
Acoustic Doppler Velocimeter [ADV]	Box trawl
Acoustic ground-discrimination systems [AGDS]	Campelen trawl
Autonomous Underwater Vehicle [AUV] (+ bathymetric sonar)	Drifting gillnet
Boomer seismic profiles	Electric pulse trawl
Compressed High Intensity Radar Pulse [CHIRP]	Fyke net
Dual-frequency echosounder	Gill net
Fisheries echosounder	Hyperbenthic sledge
High-definition sonar [Dual-frequency Identification Sonar - DIDSON]	Mid-water trawler
Multibeam echosounder	Otter trawl
Multibeam sonar	Pelagic trawl
Passive acoustic telemetry	Plumb-staff beam trawl
Side-scan sonar	Riley push-net
Single-beam echosounder	Seine
Split-beam sonar	Semi-pelagic net trawl
Sub-bottom profiler	Split-beam trawl
Synthetic Aperture Sonars [SASs]	Trammel bottom net
Corer	**Trap**
Box corer	Amphipod trap
Circular box corer	Fish trap
Corer	Modified crab pot
Craib corer	Potting equipment
Diver (+ corer)	Recruitment cages
Diver (+ pipe corer)	Traps
Diver (+ piston corer)	**Visual**
Gravity corer	360-degree camera
Gray O'Hare box corer	Benthic video sled
HAPS corer	Baited Remote Underwater Vehicle [BRUV]
Hessler-Sandia box corer	BRUV (+ stereo-video)
Modified Gray O'Hare box corer	Camera
Multicorer	Diver (+ photo)
Pipe corer	Diver (+ video)
Reineck box corer	Diver (+ visual)
Vibro corer	Drop camera

Dredge
Modified dredge
Modified scallop dredge
Pipe dredge
Triple-D dredge
Grab
Day grab
Diver (+ manual dig)
Double Van Veen grab
Ekman grab
Hamon grab
Mini-Hamon grab
Shipek grab
Smith-McIntyre grab
Ted Young-modified Van Veen grab
Van Veen grab
Hook and Line
Angling
Surface longline
Trolling lines
Vertical longline
Scrape Samples
Diver (+ scraper)
Free diver (+ scraper)
Scrape samples
Plates
Biofouling plates
Settlement plates
Structure substitute (mesocosm experiment)
HabCam bottom photos
Hybrid AUV
Lagrangian floating imaging platform
Mid-water video system
Mounted underwater cameras
Photo
Quadrats
Remotely operated vehicle [ROV]
ROV (+ stereo-video)
Sediment profile imaging [SPI]
SPI (+ Plan View)
SPIScan
Submersible
Time-lapse photography
Towed camera
Onshore transect survey
Onshore visual survey
Video
Video sled
Remote Sensing
Light Detection And Ranging [LiDAR]
Other
Clam rake
Diver (+ depth logger)
Diver (+ sampling)
Fluorometer
Net bags via diver collection
Niskin bottle + eDNA
Penetrometer

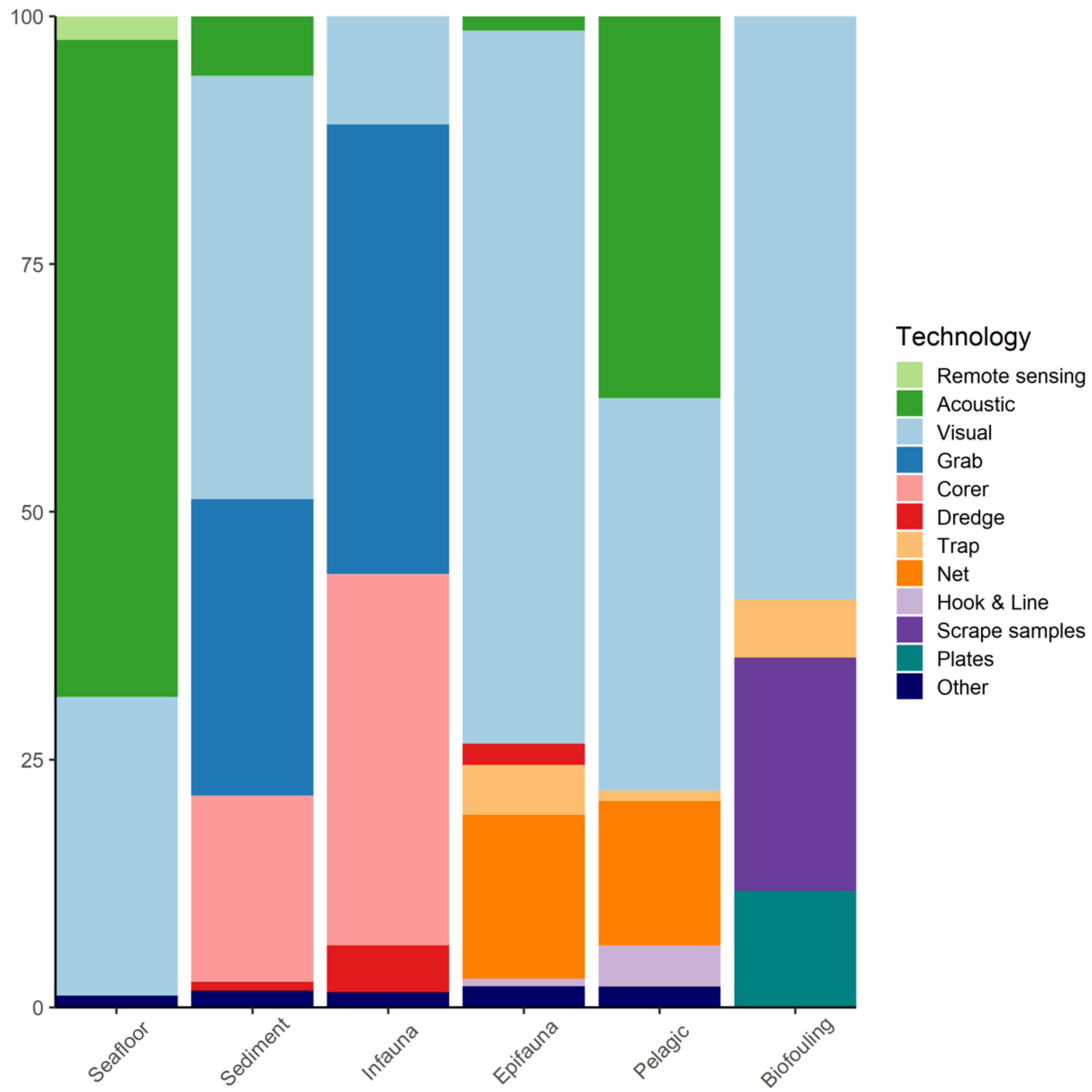


Figure 2. Proportions of the different technologies used for describing habitats and measuring changes in their characteristics.

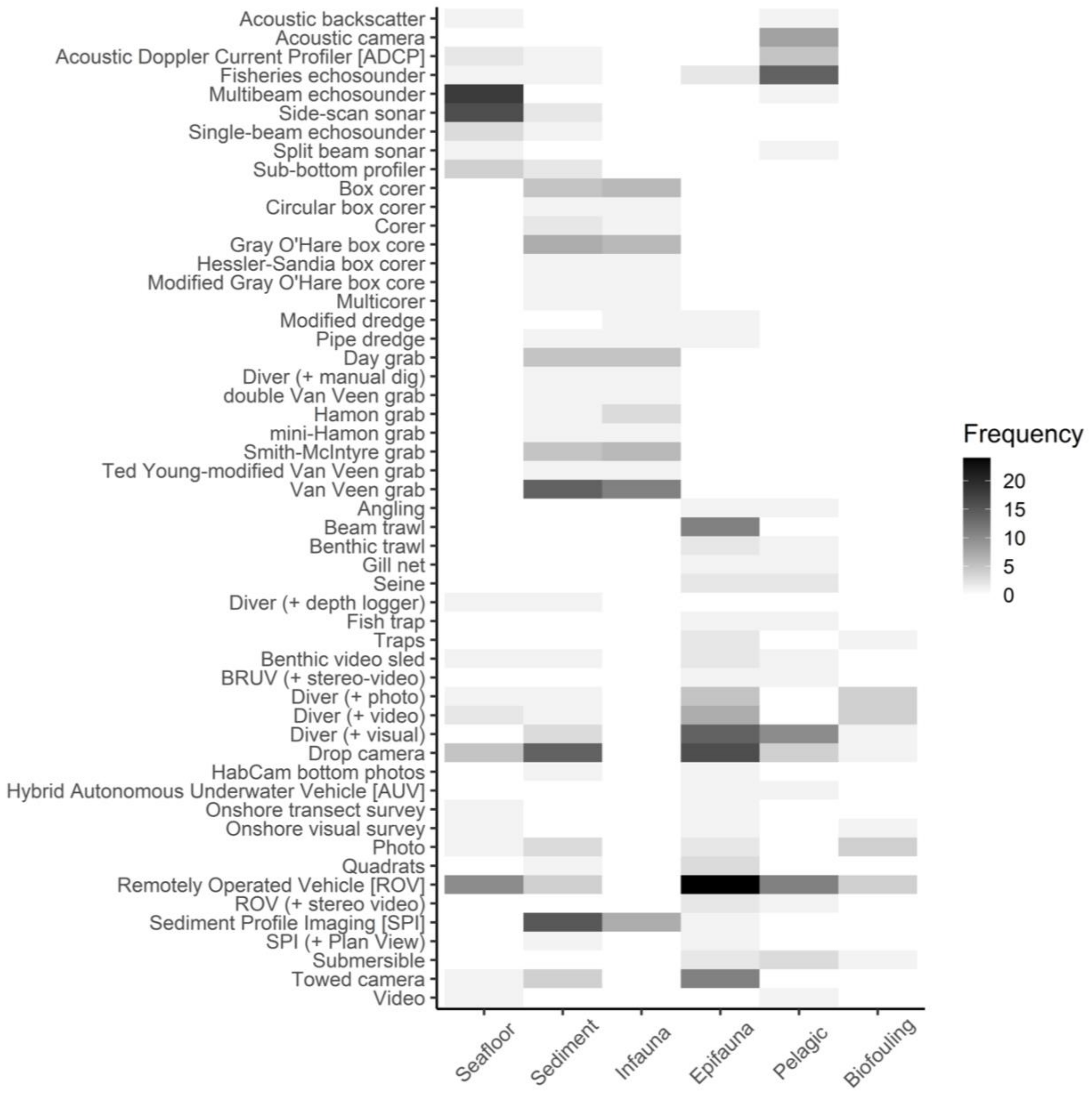


Figure 3. Heatmap showcasing the preponderance of sampling technologies across habitat categories; the darker the color, the more frequently used the technology. Only technologies that were used for two or more habitat categories are represented here.

Few reviewed documents explicitly stated the authors' reasons for choosing a specific technology over other available options, but we could often assess the motives from the characteristics of the technologies, or the description of the methodologies employed (Figure 4). Over 50% of the time, the technology was ubiquitous enough to handle the specificities of the sites monitored in the reviewed studies (e.g., MBESs, ROVs). The preference for ubiquitous technologies even reached 90% of the studies that surveyed seafloor characteristics. About 30% of the studies looking at pelagic communities used historically and/or geographically preferred technologies. Those were mainly various types of nets and trawls that have been used for decades (often centuries) for targeting particular species and/or environments (e.g., beach seine for sampling from shore). In roughly 25% of the studies assessing changes in epifauna and biofouling communities, and 20% of the documents describing sediment or pelagic habitats, the technologies employed were custom-made. Often, these technologies were drop or towed cameras and the frame and suite of sensors were specifically assembled by the teams conducting the surveys, or pots and traps were modified to target and keep all sizes of specific species. Lastly, opportunistic uses of a technology were less common, except for monitoring biofouling communities, and frequently corresponded to underwater video footage acquired during routine maintenance activities around oil and gas installations, pipelines, or cables, and provided to researchers for their studies (e.g., Love et al., 2019, Schutter et al., 2019, Todd et al., 2018). Observers on commercial or recreational fishing boats were also classified as opportunistic.

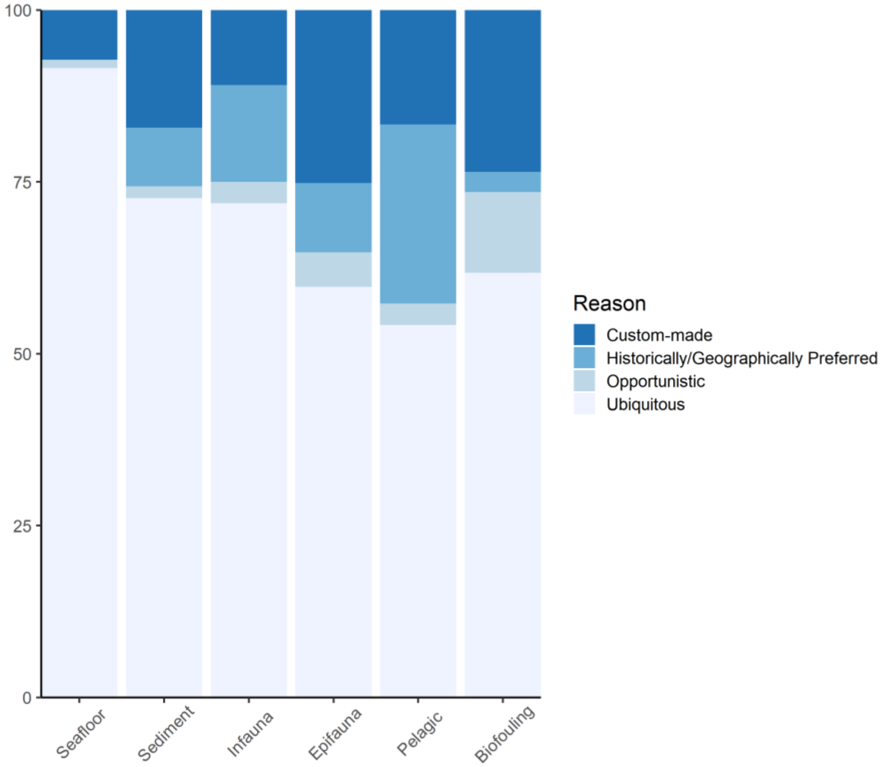


Figure 4 Proportions of each four general reasons for choosing a technology by habitat category: custom-made technology, historical and/or geographical preference for a type of technology, opportunistic use of a technology, or ubiquitous aspect of a technology.

A good proportion of the studies concentrated on the baseline characterization of five habitat categories (all but biofouling) without focusing on detecting changes or differences: over 50% when looking at seafloor characteristics; about 30% for sediment, infauna, and epifauna; and about 15% for pelagic (Figure 5). These baseline studies may have identified diverse habitats throughout their focus area but did not report the observed differences in assemblages or habitats, and especially did not assign habitat categories following specific classification methods. In addition, a limited number of baseline studies indicated the observation of differences within the sediment, infauna, and epifauna habitats that they surveyed. However, the majority of the remaining (non-baseline) studies for sediment, infauna, and epifauna, and about half for pelagic were able to detect changes or differences in habitats and communities. Most of the studies investigating biofouling communities identified changes or differences among samples and/or over time.

The technologies the most used in the studies that were able to detect changes in habitat were side-scan sonars for seafloor characteristics (used in 16 of 83 entries), SPI and Van Veen grabs for sediment (used in 15 and 14 of 117 entries, respectively), Van Veen grabs for infauna (used in 11 of 64 entries), ROVs and divers (equipped or not with imagery tools) for epifauna (used in 24 and 14 of 139 entries, respectively), fisheries echosounders and divers for pelagic communities (used in 14 and 10 of 96 entries, respectively), and scrape samples for biofouling (used in 5 of 34 entries).

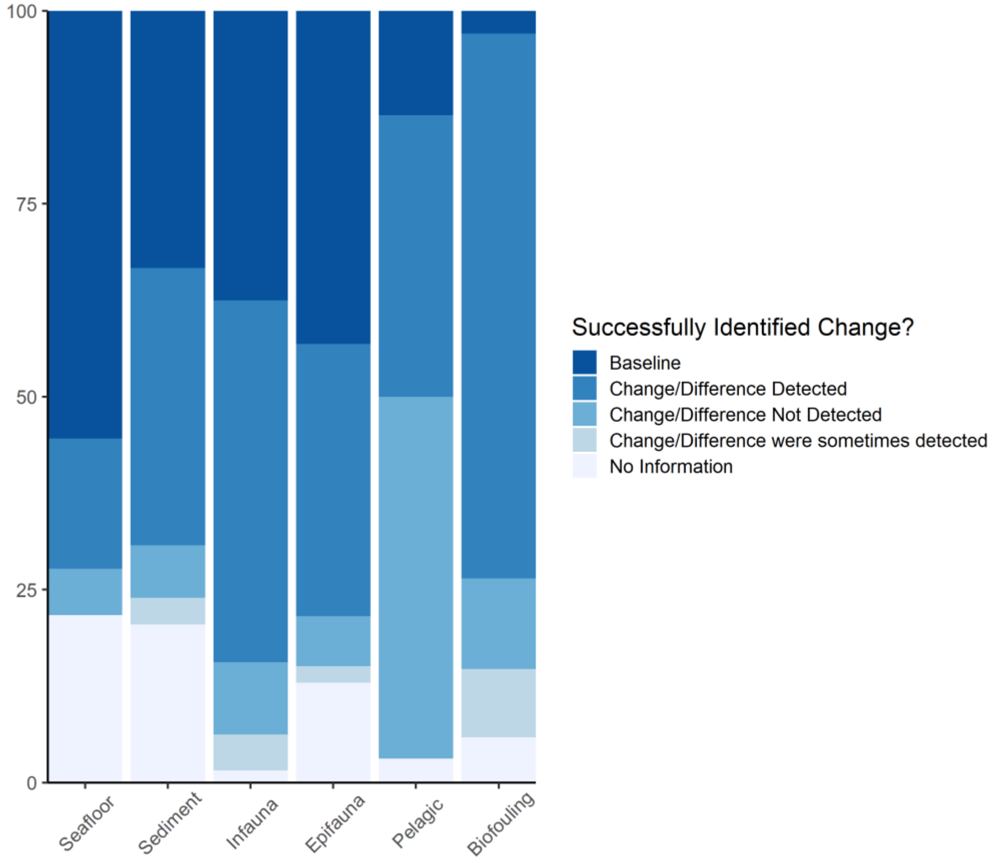


Figure 5. Success, within the reviewed studies, in detecting changes or differences in habitats, within the survey area or before/after an event susceptible to trigger changes.

While about half of the studies did not provide feedback on the sampling technologies they used, those that did varied between fully positive, fully negative, neutral, and a mix of each (Figure 6). The greatest proportions of positive feedback were for technologies used to survey seafloor characteristics, such as MBESs and side-scan sonars, and infauna communities (no dominant technology). Examples of feedback include: “Multi-frequency side-scan sonar and the introduction of color to the processed imagery has improved classification of the seabed as compared with single frequency data” (McIlvenny et al., 2016); “The Hamon grab provided point-sample information on fauna and sediment composition. These data allowed a quantitative analysis over the different areas and, to a degree, identified changes occurring within and in the near vicinity of the disposal site between 2002–2004” (Birchenough et al., 2006). On the other hand, the greatest proportions of negative feedback were for technologies used to survey sediment characteristics, such as SPI and Van Veen grabs, and pelagic communities, such as divers (equipped or not with imagery tools) and ROVs. Examples of feedback include: “Different sediments result in different degrees of penetration” (Rosenberg et al., 2009); “13 photos were invalidated due to the seabed surface being invisible as the prism had protruded too deep" (Tiano et al., 2020); "Fish behavior may be affected by the presence of divers" (Meyer-Gutbrod et al., 2019); "Real-time positioning is a major challenge for micro-ROVs (can be added for a substantial cost)" (Ajemian et al., 2015). Often, the feedback was related to a specific use for a particular goal (e.g., ROV tether too short to cover the entire survey area when deploying from a drilling platform; Gates et al., 2019), but sometimes it was more general, like sled and towed cameras are particularly sensitive to the rocking motion of swell at the surface (e.g., Broadhurst and Orme, 2014, Hemery et al., 2018), depth is a limit for sampling with scuba divers (e.g., Krone et al., 2013), or corers and grabs do not perform well in coarse sediments (e.g., Callaway, 2016).

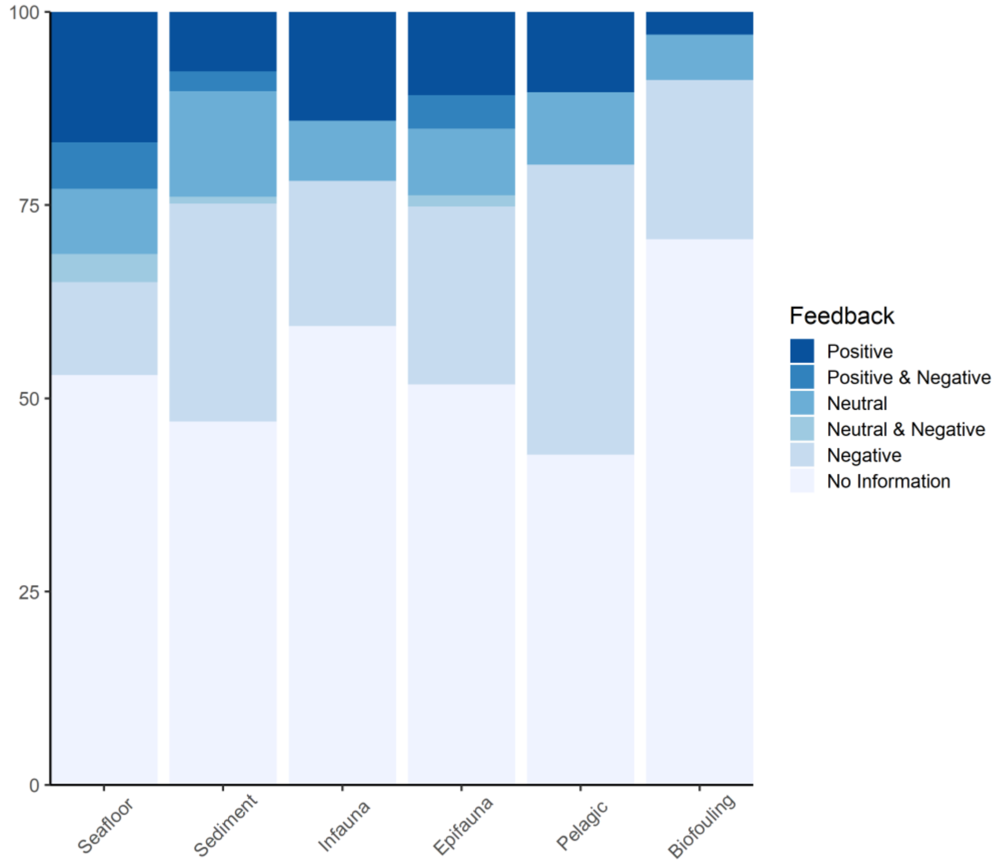


Figure 6. Proportion of positive, negative, or neutral feedback by the authors of the reviewed studies on the technologies used for surveying and monitoring the six categories of habitats. In many instances, the feedback could be classified as a combination of two or three options, when it was positive for some aspects of the work, negative for others, and neutral for yet others.

Table 4 summarizes the applicability to marine energy project sites of the most frequently used technologies for each of the six habitat categories, including noted limitations related to their use in high-energy environments, known unwanted impacts on species and/or habitats of interest, the cost range of the technologies themselves, and whether the software required for data analysis is proprietary or open source. All these technologies have been deployed in areas of high waves and/or high currents as found in places targeted for marine energy developments, but most are dependent on sea state and current velocity, and should be deployed when waves are small and during or close to slack tides for best performance.

Table 4. Applicability to marine energy project sites of the most frequently used technologies for each of the six habitat categories. Multiple technologies were used across several habitat categories.

Technology	Habitat Category	Used in High Wave	Used in High Current	Limitations	Unwanted Impacts	Cost[(a)]	Analysis Software
Acoustic camera	Pelagic	Yes	Yes	Water turbidity and entrained air bubbles were noted to disrupt data collection	None if frequencies used are beyond the hearing thresholds for sensitive organisms	$35,000 to $85,000	Manufacturer's proprietary software or third-party software
ADCP	Pelagic	Yes	Yes	Water turbidity and entrained air bubbles can disrupt data collection, as can the lack of particles in extremely clear water	None if frequencies used are beyond the hearing thresholds for sensitive organisms	$5,000 to $30,000	Manufacturer's proprietary software or third-party software
Beam trawl	Epifauna	Dependent on sea state	Yes	Limited capability on hard bottom (risks of net getting caught on rocks)	Trawl contact with seafloor may leave deep scars	$500 to $2,500	Any statistical analysis software
Box corer	Sediment Infauna	Dependent on sea state	Yes, but use is targeted for slack tides or lower flow conditions	Device weight needs to be sufficient to withstand currents and for adequate seafloor penetration; sediment characteristics will affect the ability of the technology to adequately collect samples	Bow wave may displace flocculent material and mobile fauna may disperse	$6,000 to $55,000	Any statistical analysis software
Day grab	Sediment Infauna	Dependent on sea state	Yes, but use is targeted for slack tides or lower flow conditions	Device weight needs to be sufficient to withstand currents and for adequate seafloor penetration; sediment characteristics will affect the ability of the technology to adequately collect samples	Destructive sampling method but limited footprint	$5,000 to $10,500	Any statistical analysis software
Diver (scuba or free)	Epifauna Pelagic Biofouling	Dependent on sea state	Yes, but use is targeted for slack tides or lower flow conditions	High waves and current can affect safety	Diver motion may affect animals' behavior	$500 to $4,500	Any image & statistical analysis software
Drop camera	Seafloor Sediment Epifauna	Dependent on sea state	Yes, but use is targeted for slack tides or	High waves and current can impact stability; high turbidity affects image quality	Associated lights may affect animals' behavior	$350 to $10,000	Any image & statistical analysis software

Technology	Habitat Category	Used in High Wave	Used in High Current	Limitations	Unwanted Impacts	Cost[(a)]	Analysis Software
			lower flow conditions				
Fisheries echosounder	Pelagic	Yes	Yes	Water turbidity and entrained air bubbles can disrupt data collection; individual fish are hard to discern when they move in schools	None if frequencies used are beyond the hearing thresholds for sensitive organisms	$38,000 to $300,000	Manufacturer's proprietary software or third-party software
Multibeam echosounder	Seafloor	Yes	Yes	Requires low sea states to produce higher quality data; can be used in conjunction with other devices for more accurate data collection	None if frequencies used are beyond the hearing thresholds for sensitive organisms	$100,000 to $450,000	Manufacturer's proprietary software or third-party software
Photo (out of water)	Biofouling	Not applicable	Not applicable	Requires structure to be pulled out of water	Biofouling communities are exposed to air	< $2,000	Any image & statistical analysis software
ROV	Seafloor Epifauna Pelagic Biofouling	Dependent on sea state	Yes, but use is targeted for slack tides or lower flow conditions	High waves and current can affect stability; high turbidity affects image quality	ROV motion and lights may affect animals' behavior	$3,000 to $6,000,000	Any image & statistical analysis software
Scrape Samples	Biofouling	Yes	Yes	High waves and currents can limit sample collection	Destructive sampling method but limited footprint	< $20	Any statistical analysis software
Sediment Profile Imaging	Sediment Infauna	Dependent on sea state	Yes, but use is targeted for slack tides or lower flow conditions	Image clarity affected by water turbidity; different sediment composition affects penetration depth and SPI may over-penetrate soft sediments	None	$5,000 to $90,000	Any image & statistical analysis software
Side-scan sonar	Seafloor	Yes	Yes	Requires low sea states to produce higher quality data, can be used in conjunction with other devices for more accurate data collection	None if frequencies used are beyond the hearing thresholds for sensitive organisms	$2,000 to $45,500	Manufacturer's proprietary software or third-party software
Smith-McIntyre grab	Infauna	Dependent on sea state	Yes, but use is targeted for slack tides or	Device weight needs to be sufficient to withstand currents and for adequate seafloor penetration; sediment characteristics will affect	Destructive sampling method but limited footprint	$9,000	Any statistical analysis software

Technology	Habitat Category	Used in High Wave	Used in High Current	Limitations	Unwanted Impacts	Cost[a]	Analysis Software
			lower flow conditions	the ability of the technology to adequately collect samples; may kite in deep water			
Sub-bottom profiler	Seafloor	Yes	Yes	Energy loss/disruption as it propagates through high-energy water column can affect received data signal	None if frequencies used are beyond the hearing thresholds for sensitive organisms	\$12,000 to \$160,000	Manufacturer's proprietary software or third-party software
Towed camera	Epifauna	Dependent on sea state	Yes, but use is targeted for slack tides or lower flow conditions	High waves and current can affect stability; high turbidity affects image quality	Sled motion and lights may scare away mobile animals; sled contact with seafloor may leave scars	\$300 to \$4,000	Any image & statistical analysis software
Van Veen grab	Sediment Infauna	Dependent on sea state	Yes, but use is targeted for slack tides or lower flow conditions	Device weight needs to be sufficient to withstand currents and for adequate seafloor penetration; sediment characteristics will affect the ability of the technology to adequately collect samples; high waves and currents can affect ability to get samples near an object or foundation	Destructive sampling method but limited footprint	\$1,400 to \$13,500	Any statistical analysis software

(a) Cost range estimates were based on publicly available information for instrument purchase, which can be significantly reduced through rental options, and do not include additional expenses related to various instrument accessories, vessels and crews, labor, maintenance, and other ancillary costs.

3.2 Overview of Most Common Sampling Designs and Statistical Analyses

3.2.1 Sampling Designs

The sampling designs employed by the reviewed studies varied greatly among technologies and habitats (Figure 7). Often, there was a primary sampling design and a secondary (e.g., BACI or CR as a primary, using transects). The transect was the predominant sampling design for surveying seafloor, epifauna, and pelagic habitats, followed by other (often a random design) and BACI/CR for epifauna and pelagic, which are sampling designs more suitable for use with echosounders, ROVs, or towed cameras. Unclassified stations were the main sampling design for both sediment and infauna characterization, followed by transect and some sort of stratified design (stratified stations and BACI/CR stratified) for sediment, and other design (often a random design) for infauna. These sampling designs are more suitable for use with corers, grab samplers, SPIs, or drop cameras. When specified, the sampling design for surveying biofouling communities was often random or opportunistic visual inspections or scrape samples, along with some stratified, gradient, or BACI/CR designs.

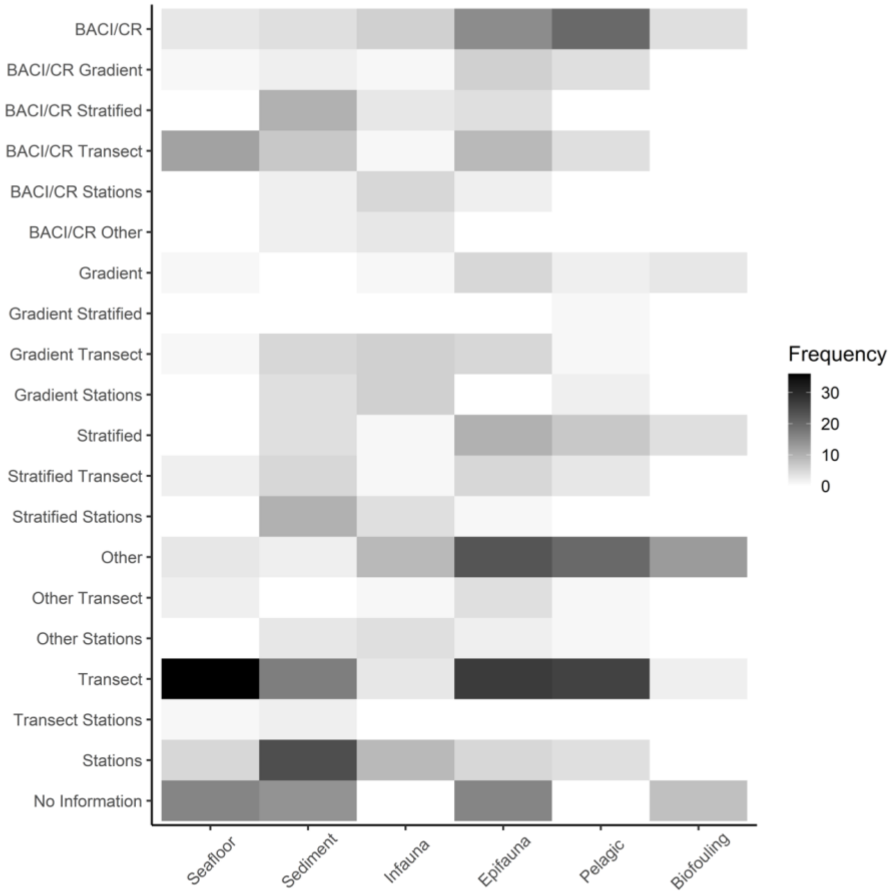


Figure 7. Heatmap showcasing the preponderance of sampling designs across habitat categories; the darker the color, the more frequently used the sampling design. When sampling designs are combined, the primary design is listed first and the secondary second. BACI/CR = before after control impact/control response.

3.2.2 Statistical Analyses

Paired with the abundant diversity of technologies identified in this review, a great variety of analyses and software was used to extract, process, and analyze the data after sampling (Table 5). Some of the software used were proprietary to specific instruments, but the most common ones were PRIMER (75 entries) and R (28 entries). Several studies used the biotic and abiotic data to generate habitat classifications like the Coastal and Marine Ecological Classification Standard (CMECS; e.g., in Cochrane et al., 2017 or HDR, 2018) or the JNCC's Marine Habitat Classification for Britain and Ireland (Connor et al., 2004; e.g., in CMACS, 2015 or Kregting et al., 2016). However, the most common analyses were univariate (e.g., analysis of variation [ANOVA]) or multivariate statistical analyses (e.g., (non-metric) multidimensional scaling [(n)MDS], principal component analysis [PCA], permutational analysis of multivariate dispersions [PERMANOVA], similarity percentages [SIMPER]) aimed at calculating and comparing biodiversity indices, characterizing faunal assemblages or sediment classes, or modeling the distribution of animals related to abiotic parameters (Table 5).

Table 5. Common analyses and software associated with the technology categories with the most applications across habitats.

Technology Category	Habitat	Most Common Analyses	Most Common Software
Acoustic	Epifauna & Pelagic	Generalized linear model, generalized additive model, ANOVA	Echoview Software, QPS Fledermaus Software, R, MatLab
Acoustic	Seafloor & Sediment	Benthic terrain modeler, digital elevation model	PRIMER, R (raster), HYPACK®/HYSWEEP®, CARIS HIPS & SIPS™, QPS Fledermaus Software, ArcGIS®/ArcVIEW®
Corer/Grab	Infauna & Sediment	ANOVA, Tukey's HSD post hoc, cluster, (n)MDS, DIVERSE, SIMPER, SIMPROF, ANOSIM, DISTLM, particle size analysis, PCA	PRIMER, R (vegan, random forest)
Net/Dredge	Epifauna, Infauna & Sediment	Particle size analysis, cluster, ANOVA, Tukey's HSD post hoc, nMDS/MDS, DIVERSE, SIMPER, SIMPROF, ANOSIM	PRIMER
Plate/Scrape/Visual	Biofouling, Epifauna & Pelagic	PCA, nMDS/MDS, PERMANOVA, PERMDISP, ANOSIM, ANOVA, SIMPER, generalized linear model, Mann-Whitney U-tests	PRIMER, SigmaPlot, SPSS, EventMeasure Stereo, VLC media player, ImageJ
Visual	Infauna (SPI imagery), Sediment & Seafloor	Categorized by indices, ANOVA, nMDS, DIVERSE, PCA, generalized linear model, SIMPROF, SIMPER, PERMDISP, PERMANOVA	Image Analyst, BIIGLE 2.0, MatLab, PRIMER, R, SigmaPlot

ANOVA = analysis of variance; ANOSIM = analysis of similarities; DISTLM = distance-based linear model; HSD = honestly significant distance; (n)MDS = (non-metric) multidimensional scaling; PCA = principal component analysis; PERMANOVA = permutational multivariate analysis of variance; PERMDISP = permutational analysis of multivariate dispersions; SIMPER = similarity percentages; SIMPROF = similarity profile.

3.2.2.1 Analyses of Physical Data

Because seafloor properties, like the nature of sediment or its rugosity and relief, may be affected by the installation and operation of marine energy devices, a thorough understanding of seafloor characteristics is essential to establish a baseline against which to assess changes. A diversity of analyses of physical data exists; the four most commonly used are described below.

- **Particle size analysis** is used to describe the physical characteristics of sedimentary environments. Manual methods of wet-sieving, dry-sieving, and pipetting are used for sorting coarse and fine material, which are then characterized by applying the Udden-Wentworth or Wentworth classification systems.[1] Additionally, more automated methods like laser diffraction are used for fine and superfine material (e.g., Beckman Coulter LS Particle Size Analyzer, Malvern Mastersizer 2000G, Multisizer Coulter Counter).
- The **Benthic terrain modeler** is a toolbox extension of ArcGIS Pro that enables users to process bathymetric data and characterize the structure of benthic environments. Users can define layers representative of seafloor structures. They can also classify biotopes by using the Bathymetric Position Index, or other measurable parameters such as rugosity and slope.
- **Digital elevation models** (DEMs) are created to visualize the seafloor using software such as Teledyne's CARIS HIPS and SIPS. The user creates a visual representation of the seafloor from both acoustic and lidar survey data. Biotopes are then established by delineating boundaries based on the surface topography visualized in the DEM.
- **CMECS** (Coastal and Marine Ecological Classification Standard) is a framework for standardizing coastal and marine variables using common terminologies garnered across local and global scales. CMECS is used to inventory observed resources to improve the understanding of distribution, availability, and size of marine populations, as well as to characterize the associated habitats. A reoccurring application of CMECS through this review was to classify epifaunal assemblages and describe the associated seafloor characteristics.

3.2.2.2 Univariate Analyses for Biological Data

Univariate statistical analyses are used to describe the biodiversity from benthic (infauna and epifauna), pelagic, and biofouling samples, and to test hypotheses about variables. Described below are three categories of univariate analyses most commonly used for biological data.

- **Diversity measurements** are calculated to quantify spatiotemporal variations in biodiversity and to establish baseline community composition. After taxa are identified, measurements of species diversity, richness, evenness, and dominance are quantified using indices such as Margalef's diversity index, Shannon-Wiener diversity index, Brillouin index, Simpson's Index, Pielou index.
- **ANOVA** (analysis of variance) applies an F-statistic to determine if there is a significant difference amount of variability in the means of sample groups. 1-way, 2+-way, and factorial ANOVAs can be applied to assess relationships between response variables, also called dependent variables (e.g., community diversity indices, biomass, density, catch-per-unit-effort [CPUE], sediment characteristics), and exploratory variables, also called independent variables (e.g., habitat groups or biotopes, depth, time [month, year, season], station, transect).

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[1] https://pubs.usgs.gov/of/2006/1195/htmldocs/images/chart.gif

- **Tukey's honestly significant difference (HSD) post hoc** is applied after a significant ANOVA test to explore the differences between sample groups. This method compares all possible group means, allowing for the identification of between-group differences. When pertaining to species diversity, this post hoc test allows for the identification of specific differences among exploratory variables such as time, depth, and sample group.

3.2.2.3 Multivariate Analyses for Biological Data

Multivariate statistical analyses are used to investigate the interactions between multiple response variables (e.g., diversity of species at several sites), which often do not meet the traditional statistical assumptions. Analyses most commonly used for the purpose of classification, ordination, and statistical test of hypotheses are described below.

- **Clusters** are used as a classification method to identify groups of similar data by computing the distances separating all combinations of the data points. A common application of cluster analysis is the exploration of community metrics (e.g., abundance, biomass, diversity) to determine whether they could be further classified into groups (e.g., of stations, transects, seasons) based on their (dis)similarities. This information can be further used to classify biotopes and to refine study designs.
- **MDS** (multidimensional scaling) and **nMDS** (non-metric MDS) are ordination methods used to determine relative (dis)similarities between groups of data and project them in a multidimensional space, typically 2- or 3-dimensions. (Dis)similarities are determined by applying an index, such as Bray-Curtis, Jaccard, or Sørensen, to a dataset. Ordination points that are closer together are more similar, allowing for a visual method of exploring data to identify groups within the dataset.
- **ANOSIM** and **SIMPROF** tests use (dis)similarity indices to determine the significance of ordination and cluster groups. ANOSIM (analysis of similarity) tests are a series of nonparametric tests that identify differences between predetermined groups. SIMPROF (similarity profile) is a permutation test used to determine whether groups that were not predefined prior to data analysis (i.e., groups generated from a cluster analysis) have structural (dis)similarities that are statistically significant. Neither the ANOSIM or SIMPROF tests provide information about what drives the group (dis)similarities, but **SIMPER** (similarity percentages) tests enable the identification of elements of the dataset that contribute to similarities within a group and differences between groups.
- **PERMANOVA** (permutational analysis of variance) is a nonparametric test that identifies similarity in groups through random data permutation, based on the selected (dis)similarity index. PERMANOVA generates a pseudo-F-test that is compared to a F-test derived from the actual data. It helps with data that tend to violate the assumption of normality (e.g., community data with an abundance of zero values). PERMANOVA is primarily used to assess variations in community structure amid exploratory variables (e.g., sites, depths, distances).
- **PCA** (principal components analysis) uses ordination to project points from a high-dimensional space to a linear plane that best captures the variability between points in their original space. This analysis uses eigenvalues to summarize the percent variance explained across the planes, or principal constituents, and the first few should most accurately represent the relationships between the sample points. By overlaying vectors representing environmental variables, PCA provides graphical opportunities for identifying potential correlations between the data points and the environmental variables.

- **Generalized linear models (GLMs)** and **generalized additive models (GAMs)** are models used in lieu of linear models due to their flexibility in modeling nonlinear data by including response variable distributions other than Gaussian distribution (e.g., Poisson, negative binomial) to define the mean and variance. GAMs differ from GLMs in that the linear predictors, or the exploratory variables, consist of additive nonparametric smoothing functions applied to each exploratory variable rather than an overall function applied to the full linear predictor. Both GLMs and GAMs are often applied to explore the relationships between ecological community data and environmental variables.

3.3 Existing Guidelines and Recommendations

None of the 12 existing guidelines for surveying and monitoring marine habitats that were reviewed here specifically target the U.S. marine energy industry. However, several aspects of the broader guidelines (e.g., ISO 16665 and ISO 19493; ISO, 2014, ISO, 2007 respectively) or those targeting other U.S. industries such as oil and gas (e.g., MMS' Notices to lessees (MMS, 2006, MMS, 2008, MMS, 2009a, MMS, 2009b) or renewable energy at large (e.g., BOEM's guidelines BOEM, 2019a, BOEM, 2019b, BOEM, 2020) can be applied to the specific cases of wave and tidal energy developments in U.S. waters. Table 6 summarizes the content of these guidelines, especially highlighting the targeted habitats and the recommended technologies, methods, sampling designs, and data analyses. Overall, 43 different technologies are recommended, and the most recurring ones are sediment grabs, video tools, and sub-bottom profilers. Entering Table 6 by targeted habitat, a reader can identify the technologies and methods recommended by each applicable guideline. However, the diversity of options remains abundant for each targeted habitat, and use of expert judgment is recommended when selecting technologies and methods based on the goals of a monitoring study, in addition to the habitats specifically targeted.

Table 7 provides recommendations for which technologies to use to survey benthic (epifauna and infauna) and demersal organisms at wave and tidal energy sites. These recommendations are based on a set of criteria related to the main general variables that would guide the selection of a technology: strength of currents, wave height, water depth, presence of obstacles in the water (e.g., marine energy devices, cables), and nature of the seabed. Local specificities and average weather conditions (e.g., wind, swell) also influence the technology selection during a project's planning process. Many technologies come in various sizes and shapes, and the best options to sustain high-energy environments may be the most adaptable ones, with the possibility to add weights to ballast in the water or on the seafloor, thrusters for extra propulsion, a frame to guide sampling after impact on the seafloor, etc. Reducing the dependence on a tether (e.g., autonomous underwater vehicle vs. ROV) will attenuate the effects from the swell in high wave conditions.

Table 6. Content summary of existing guidelines for surveying and monitoring marine habitats.

Source	Focus Industry	Targeted Habitats	Recommended Technologies	Recommended Methods	Recommended Sampling Design	Recommended Data Analyses
ISO 19493	Any industry developing in hard-substrate seafloor	Hard-substrate communities: supralittoral, eulittoral, and sublittoral hard substrate	Diving for visual inspection, cameras for photos or video, ROV, sonar	**Semi-quantitative surveys:** species recorded in terms of degree of coverage or number of individuals for large solitary animals **Quantitative surveys:** quadrats of a specific dimension defined for a systematic count of the flora/fauna cover	BACI, fixed, gradient, random, stratified random, systematic/grid	Diversity indices, dominance indices, multivariate analyses
ISO 16665	Any industry developing on soft-bottom substrate	Marine soft-bottom macrofauna	Corer, grab	Collect samples from a station to be processed for recording presence and biomass, then for storage	BACI, random/scattered, single spot (station), station network, stratified, transect	Sediment oxidation state, granulometry, carbon content; wet mass, dry mass, ash-free dry mass analyses; diversity indices, biotope classification
EPA 1998	Developments that need dredging	Areas targeted for discharge of dredged materials (water column and benthic habitats)	Bottom trawl, corer, discrete water sampler, grab, pump	Collect biota, sediment, and water samples **Tier I:** Evaluate existing information to list possible issues **Tier II:** Measure and model contaminants, theoretical bioaccumulation	Periodic reference area for both dredging site and disposal site, periodic reference point, reference area, reference point	Chemical analyses for contaminants in water and in flora and/or fauna tissue; physical analyses: grain size, specific gravity, total solids

Source	Focus Industry	Targeted Habitats	Recommended Technologies	Recommended Methods	Recommended Sampling Design	Recommended Data Analyses
				Tier III: Generic bioassay for toxicity and bioaccumulation tests **Tier IV:** Case-specific bioassay		
MMS 2006	Oil and gas	Leases in the Pacific outer continental shelf region	Deep penetration seismic profiler, medium-penetration seismic profiler, high-resolution multibeam, magnetometer, shallow-penetration sub-bottom profiler, side-scan sonar	Geotechnical analysis of foundations soils underlying the proposed platform sites and pipeline route, high-resolution geophysical surveys	Site-specific survey 1000 m radius around the platform or 100 m beyond furthest anticipated anchor location, and 600 m radius of the axis of the proposed pipeline route or 100 m beyond anticipated anchor points, whichever are greater	Geotechnical/data analysis of soil samples, interpreted geologic structure of stratigraphic cross-sections for platform site, maps
MMS 2008	Oil, gas and sulphur leases	Gulf of Mexico offshore continental shelf, shallow hazards program	Depth sounder, magnetometer, side-scan sonar, shallow-penetration sub-bottom profiler, medium-penetration sub-bottom profiler, medium-penetration seismic profiler, three-dimensional seismic reflection surveys. Corer, divers, ROV, submersible.	State-of-the-art instruments; minimizes interference between instruments; digital records at one sample per second at least	Depends on the survey type. In general, survey lines are spaced with a maximum of 300 m aided with crosslines across the lease area and the nearby areas where changes are expected to happen	Geotechnical/data analysis to map the lease area and proposed construction layout
MMS 2009a	Oil, gas and sulphur	Gulf of Mexico offshore continental shelf, biologically sensitive features and areas, depth: <300 m	Cameras (color still photography and video simultaneously)	Operate with surface monitor and recorder, record differential GPS positioning and water depth, minimum of 100 photos	Survey along defined transects within and around the lease block, with additional focus on areas with live-bottom features to cover the entire feature area	Produce seafloor maps with bathymetric contours, outline of potentially sensitive biological features and other potential obstructions relative to the proposed platform
BOEM 2019a	Renewable energy	Atlantic outer continental shelf − benthic habitat	**Community composition:** Hamon grab (hard bottom), Van Veen grab (soft sediment), benthic sled,	**Community composition:** follow EPA NCCA methods (e.g., 0.04	**Community composition:** two years of seasonal surveys, at least one sample per 1−2 km^2 within a proposed area,	Present tabular and geospatial datasets

Source	Focus Industry	Targeted Habitats	Recommended Technologies	Recommended Methods	Recommended Sampling Design	Recommended Data Analyses
			cameras for videos and photos, SPI **Sediment scour and/or deposition:** multibeam or interferometric bathymetry (with backscatter data), SPI	m^2 grab, 0.5 mm sieve) **Sediment scour and/or deposition:** mosaic providing 100% coverage, tow sonar at 10−20% range, resolution able to detect features 0.5−1 m in diameter	control sites identified for monitoring post- construction **Sediment scour and/or deposition:** baseline survey, should cover 100% of the area, one sample per 1−2 km along proposed line, or one sample per 1−2 km^2 within proposed area	
BOEM 2019b	Renewable energy	Atlantic outer continental shelf − fisheries	Beam trawl, benthic imagery, benthic sled, gillnet or trammel net, otter trawl, Hamon grab (hard bottom), Van Veen grab (soft sediment), ventless trap	**Otter Trawl**: tow at 2.9−3.3 knots, no more than 20 min, sample all fish species, record weight and length, minimum of 30 trawls per survey period **Gillnet, trammel net, beam trawl:** 9 ft beam trawl with 1 in. knotless liner, may include stomach content **Ventless trap:** sample weight and length of species caught, gear and techniques to mirror those of commercial fishing **Molluscan and shellfish:** follow EPA NCCA methods (e.g., 0.04 m^2 grab, 0.5 mm sieve)	**Otter Trawl:** BACI with random stratified surveys (10 sites <0.5 km, 10 sites 0.5−2.5 km, 10 control sites), 2 years of surveys with one per season **Gillnet, trammel net, beam trawl:** stratified by depth and habitat type, minimum of three locations within affected area and three reference locations <1 km away, 2 years for 6 days in spring and fall for gillnet or trammel net, 2 years seasonally for beam trawl **Ventless Trap:** random stratified BACI with multiple controls, sites at varying distances based on habitat type and depth, 2 years of seasonal surveys **Molluscan and shellfish:** two years of seasonal surveys, at least one sample per 1−2 km^2 within a proposed area, control sites identified for monitoring post- construction	ANOVA on abundance, species diversity, size and weight distribution, multivariate analysis of catch/community composition, MDS, cluster analysis, prey items from stomach content identified to lowest taxonomic level, counted, and weighed

Source	Focus Industry	Targeted Habitats	Recommended Technologies	Recommended Methods	Recommended Sampling Design	Recommended Data Analyses
BOEM 2020	Renewable energy	Seafloor and sub-seafloor	Corer, CTD sensors, grab, LIDAR, side-scan sonar, sub-bottom profilers (high-frequency CHIRP systems, medium-penetration seismic systems), velocity probe, vessel-mounted acoustic positioning system	State-of-the-art instruments, minimize interference between instruments; digital records at one sample per second at least	Series of regularly spaced and parallel track lines with tie-lines running perpendicular, grid oriented with respect to bathymetry, geologic structure, cable corridor, and proposed locations, provide coverage of the entire area that could be physically disturbed	Classification and determination of geotechnical properties (e.g., grain size distribution, compressibility, shear strength)
CEFAS 2002	Developments that need aggregate extraction/ dredging	Benthic habitats	**Quantitative methods:** Hamon grab, Day grab, Shipek grab, Van Veen grab, corers **Qualitative and semi-quantitative methods:** trawls, New Haven scallop dredge, Rallier-du-Baty dredge, anchor dredge, video and still photography, ROVs, camera sledge **Remote acoustic methods:** Single- and multibeam echosounders, seismic profiling, side-scan sonar	Estimate grab sample volume for validity, separate benthic infauna from sediment with 0.5 mm mesh sieve, record specific and accurate information about the technologies used, including site conditions to be considered for processing data	Grid, random grid, stratified random grid, depending on the findings from pilot survey; baseline surveys can target single sampling events in many sites within the project area; monitoring surveys can focus on areas where change is predicted to occur, using transects or BACI designs	Biomass, species analyses, population dynamics, ANOVA, seafloor mapping, particle size analysis
CEFAS 2011	Offshore renewable energy	Benthic, pelagic, intertidal, physical and sedimentary process	ADCP, acoustic survey, corer, CTD, digital image scanning sonar, dredge, echosounder, grab, multibeam sonar, ROV, trawl, underwater photography, sediment traps, sub-bottom profiler	Sediment sieved through a 0.5 mm sieve, organisms identified to species level	BACI, single sample station, systematic grid if homogeneous seabed; stratified random sampling if heterogeneous seabed; lower, mid, and upper shore levels along three transects running perpendicular to the shore	Biotope maps, seabed maps, organism population dynamics
Davies 2001	Any industry	Benthic Habitat	Echosounder, grab, side-scan sonar, SPI, towed camera, video and still photography	SPI: penetrate sediment to a minimum of two-thirds the height of face plate but not above	Collect samples from along track lines based on the need of the project and available time and resources without sacrificing data quality. SPI: three replicate images at required stations along transects.	Seafloor mapping: classification (supervised or unsupervised), point-to-area interpolation, scatterplots variogram, quality control for ground-truthing

Source	Focus Industry	Targeted Habitats	Recommended Technologies	Recommended Methods	Recommended Sampling Design	Recommended Data Analyses
					Grab: random, stratified random, systematic grid sampling	

ADCP = Acoustic Doppler Current Profiler; ANOVA = analysis of variance; BACI = before after control impact; BOEM = Bureau of Ocean Energy Management; CEFAS = Centre for Environment Fisheries and Aquaculture Science; CTD = conductivity temperature depth; EPA NCCA = U.S. Environmental Protection Agency's National Coastal Condition Assessment; ISO = International Organization for Standardization; LIDAR = light detection and ranging; MDS = multidimensional scaling; MMS = Mineral Management Service; ROV = remotely operated vehicle; SPI = sediment profile imagery.

Table 7. Technology recommendations for surveying epibenthic and demersal organisms (light grey lower matrix) and infauna organisms (dark grey upper matrix) at wave and tidal energy sites.

Infauna Epifauna	Strong Currents	Mild Currents	High Waves	Low/No Waves	Deeper 30 m	Shallower 30 m	Obstruc-tions	Free Passage	Coarse Seabed	Soft Seabed
Strong currents			Dredge	Dredge, heavy core, heavy grab	Dredge, heavy core, heavy grab	Dredge, heavy core, heavy grab	Dredge	Heavy core, heavy grab	Dredge	Heavy core, heavy grab
Mild currents			Dredge	Any corer, any grab, dredge, SPI	Any corer, any grab, dredge, SPI	Any corer, any grab, diver, dredge, SPI	Diver, dredge	Any corer, any grab, diver, dredge, SPI	Day grab, dredge, Van Veen grab	Any corer, any grab, diver, SPI
High waves	Hook & line	Fisheries echosounder, hook & line, trawl			Dredge	Dredge	Dredge	Dredge	Dredge	-
Low/no waves	Drop camera, fisheries echosounder, heavy ROV, trawl	Any ROV, divers, drop camera, fisheries echosounder, seine, towed camera, trawl			Any corer, any grab, dredge, SPI	Any corer, any grab, diver, dredge, SPI	Diver, dredge	Any corer, any grab, diver, dredge, SPI	Day grab, dredge, Van Veen grab	Any corer, any grab, diver, SPI
Deeper 30 m	Drop camera, fisheries	Any ROV, drop camera,	Fisheries echosound	Any ROV, drop camera,			Dredge	Any corer, any grab,	Day grab, dredge,	Any corer, any grab, SPI

Infauna Epifauna	Strong Currents	Mild Currents	High Waves	Low/No Waves	Deeper 30 m	Shallower 30 m	Obstruc-tions	Free Passage	Coarse Seabed	Soft Seabed
	echosounder, heavy ROV, trawl	fisheries echosounder, towed camera, trawl	er, hook & line, trawl	fisheries echosounder, towed camera, trawl				dredge, SPI	Van Veen grab	
Shallower 30 m	Drop camera, fisheries echosounder, heavy ROV, trawl	Any ROV, diver, drop camera, fisheries echosounder, seine, towed camera, trawl	Hook & line, trawl	Any ROV, diver, drop camera, fisheries echosounder, seine, towed camera, trawl			Diver, dredge	Any corer, any grab, diver, dredge, SPI	Day grab, dredge, Van Veen grab	Any corer, any grab, diver, SPI
Obstruc-tions	Drop camera	Diver, drop camera	Hook & line	Diver, drop camera	Drop camera	Diver, drop camera			Diver	Diver, SPI
Free passage	Drop camera, fisheries echosounder, heavy ROV, trawl	Any ROV, diver, drop camera, fisheries echosounder, seine, towed camera, trawl	Fisheries echosounder, trawl	Any ROV, diver, drop camera, fisheries echosounder, seine, towed camera, trawl	Any ROV, dredge, drop camera, fisheries echosounder, trap, trawl	Any ROV, diver, drop camera, dredge, fisheries echosounder, trap, trawl			Day grab, dredge, Van Veen grab	Any corer, any grab, dredge, diver, SPI
Coarse seabed	Dredge, drop camera, fisheries echosounder, heavy ROV	Any ROV, diver, dredge, drop camera, fisheries echosounder, towed camera	Dredge, fisheries echosounder, hook & line	Any ROV, diver, dredge, drop camera, fisheries echosounder, towed camera	Any ROV, dredge, drop camera, trap	Any ROV, diver, dredge, drop camera, trap	Any ROV, diver, drop camera, trap	Any ROV, diver, dredge, drop camera, towed camera, trawl		
Soft seabed	Drop camera, fisheries echosounder, heavy ROV, trawl	Any ROV, diver, drop camera, fisheries echosounder, seine, towed	Fisheries echosounder, trawl	Any ROV, diver, drop camera, fisheries echosounder, seine, towed	Any ROV, dredge, drop camera, fisheries echosounder, trawl	Any ROV, camera sled, diver, dredge, drop camera, fisheries	Any ROV, diver, drop camera, traps	Any ROV, camera sled, diver, dredge, drop camera, fisheries		

Infauna Epifauna	Strong Currents	Mild Currents	High Waves	Low/No Waves	Deeper 30 m	Shallower 30 m	Obstruc-tions	Free Passage	Coarse Seabed	Soft Seabed
		camera, trawl		camera, trawl		echosounder, seine, towed camera, trawl		echosounder, seine, towed camera, trawl		

ROV = remotely operated vehicle; SPI = sediment profile imagery.

4.0 Discussion

As one would expect with such a broad research field, the diversity of technologies available for characterizing and measuring changes in benthic and pelagic habitats is considerable, making the development of recommendations for technologies and sampling methods that fulfill the monitoring needs around marine energy project sites challenging. As was often emphasized in the feedback from the authors of the documents reviewed here, many technologies are susceptible to excessive hydrodynamic energy, which is true in many marine environments but especially at sites favorable to marine energy development that are targeted because of their strong tidal currents and high wave profiles. For example, a study noted that the box trawl they were using was limited to flow velocities below 1.8 m.s-1 (Horne et al., 2013), while another commented on the interference on their sonar data due to the entrained air in strong tidal currents (ORPC, 2014). Strong currents were also an issue for maintaining ROVs, towed cameras, and even scuba divers at a constant height above the seafloor and along straight transects (Broadhurst and Orme, 2014, Foubister, 2005, Greene, 2015). Swell conditions affected the quality of the data obtained by tethered instruments such as ROVs and towed cameras by creating vertical motion that could, sometimes, not be controlled (Bender and Sundberg, 2018, Hemery et al., 2018). Heavier technologies seemed to be less affected than those of a lighter build (Fields et al., 2019). Heavy swells and currents also tend to resuspend the sediment and alter the visibility, limiting the use of video and still imagery (Greene, 2015, Pearce et al., 2014, Van Hoey et al., 2014). In some areas, the currents are so fierce that they have flushed away the thinner sediments, thereby affecting the ability to use corers or grabs to collect sediment and infauna samples (Callaway, 2016). Despite the diversity of corers and grabs used in the reviewed studies, our examination did not highlight any technology more suitable than others when it comes to sampling coarse sediments and infauna living therein. Nevertheless, if their use is timed properly regarding slack tides and storm swell, all the technologies identified in the present literature review have been and/or would be applicable to marine energy development sites. In addition to the upfront cost of an instrument, an important factor to keep in mind when selecting a technology for marine energy sites is its reliability and durability in harsh conditions, so that the necessary sampling can be obtained without too many trials that add costly vessel and labor times to a survey (Holte and Buhl-Mortensen, 2020).

Nets and trawls are often used in baseline or pre-installation site characterization surveys to describe benthic and/or pelagic communities or for ground-truthing results from acoustic surveys (Guida et al., 2017, DP Energy Marine, 2013, ORPC, 2014). The diversity of nets and trawls available to marine biologists directly originates from the technologies that fishermen around the world have used and perfected for centuries. Some nets or trawls may be more effective than others depending on the habitats and species targeted. For instance, beam trawls can sample harder, coarser seafloor habitats than otter trawls, and gillnets are more size-selective than trammel nets (BOEM, 2019b). However, because of the risk of getting these fishing apparatuses caught in marine energy devices, cables, or mooring lines, they are rarely used in post-installation surveys, except for beam trawls that can be built relatively small and sometimes used within the footprint of a project (BOEM, 2019b).

Overall, video and still imagery, and visual surveys in general, seem to be the most common method used for characterizing surface sediments, epifauna, pelagic, and biofouling communities. These technologies are highly adaptable; often deployed as a dropdown system, buoy, platform, or float at different levels of the water column; mounted on ROVs, sleds, or submarines; or held by divers. Depending on the characteristics of a marine energy project site or goals of a study, one technology may be better adapted than another. For instance, Kregting et al. (Kregting et al., 2016) used a drop camera rather than scuba divers because of cost considerations, while O'Carroll et al. (O'Carroll et al., 2017) used divers equipped with video cameras to survey the seafloor at the foot of a tidal turbine because a drop camera or ROV could not get close enough. Drop cameras are great tools for collecting standardized images of the seafloor and benthic communities (e.g., Kregting et al., 2016, Pearce et al., 2014), but they are difficult to implement when looking forward at a specific target, such as when assessing colonization and reef effects around moorings and foundations. Using a 360-degree camera would assure that the target is in the field of view, as long as water turbidity allows for good visibility (Pattison et al., 2020). Divers are usually more suitable in dense kelp fields or when surveying close to or underneath artificial structures (e.g., Page et al., 1999, Thuringer and Reidy, 2006), but both divers and underwater vehicles are known to potentially affect the behavior of marine animals during surveys (e.g., Spanier et al., 1994, Stoner et al., 2008). Imagery technologies mounted on robotics or drop frames have the advantage of achieving greater depths with longer bottom times than diver surveys (Cruz-Marrero et al., 2019, Sheehan et al., 2020, Taylor et al., 2016). Drop, sled, or towed cameras are often highly customizable; some are equipped with multiple cameras facing different angles and with additional instruments such as a conductivity-temperature-depth sensor (e.g., Hemery et al., 2018), while others are built to endure strong currents and navigate rugged terrains (e.g., DP Energy Marine, 2013, Foster-Smith & Foster-Smith, 2012).

While using cameras to collect visual data is a relatively straightforward technique that has proven to be an effective method of classifying marine communities and habitat characteristics, the analysis of image and video data can be complex and time-consuming. Data collection is ultimately limited by the storage capacity of the technology and the individual capabilities of the video equipment (e.g., number of frames collected per second of video). In addition, it can result in a tremendous amount of data collected. Pre-processing of images or segments of video often requires the selection of footage that is of high enough quality to enable accurate characterizations. These are sometimes selected at predetermined intervals (e.g., every 15 seconds), but are at other times selected based on the clearest video segment available (Šaškov et al., 2015, Taormina et al., 2020). In very specific situations, images may be selected using software designed to automate data analysis (e.g., BisQue online image analysis, MotionMeerkat), but the software still rely on verification by an expert to guarantee the accuracy of the algorithms. Still images and video footage may also require image enhancements like a color correction to improve image quality (Guida et al., 2017), or stitching to provide a seamless mosaic for analysis (Pattison et al., 2020, Šaškov et al., 2015). Post-processing of the images or videos involves both manual and automated methods of annotating the images; however, software designed to automatize data analysis (e.g., BisQue online image analysis, CoralNet, Idrisi Selva 17, MotionMeerkat) was applied in very particular situations and relied, here too, on an accuracy review by an expert (Šaškov et al., 2015, Taormina et al., 2020). The most common image analysis method used in post-processing was the point-contact method, where a grid overlay was superimposed over the image and images were analyzed at each juncture (Taormina et al., 2020, Page et al., 2019, Sempere-Valverde et al., 2018). Species identifications and characterization of habitats may require the input of multiple experts, each specializing in a unique discipline (e.g., invertebrates, fish, sediments, geology).

Often, technologies are used in pairs (simultaneously or not), either to add a layer of data collection or to ground-truth the results obtained with another instrument. For example, corers, grabs, and drop cameras are common technologies for ground-truthing; side-scan sonar and multibeam echosounder data are used when mapping seafloor and sediment characteristics (e.g., Pearce et al., 2014); trawls can be used to ground-truth demersal fish communities described using hydroacoustic methods (e.g., Soldal et al., 2002); scuba diver and/or beam trawl surveys have been used to ground-truth epifaunal assemblages characterized from data collected by ROVs, towed cameras, or video sleds (e.g., Spencer et al., 2005); and environmental DNA samples can be collected to ground-truth pelagic, benthic, biofouling and even infauna communities (e.g., Mauffrey et al., 2021). Ground-truthing using an independent technology is particularly important when environmental conditions make sampling challenging. As an alternative to using two truly independent technologies that would require extra vessel and labor costs, modifying an existing instrument to pair it with a second technology may prove sufficient. For instance, adding a video camera to a beam trawl is a common way to obtain images of both sessile and mobile epifauna and demersal fauna that are not well sampled with a trawl, like sea pens or other sessile organisms able to quickly retract into the sediment, or fast-moving fishes and invertebrates fleeing the approaching trawl (e.g., OSU and NNMREC, 2012). Others have modified sediment grabs by mounting a camera in a waterproof housing to the side of the grab and doubling it as a drop camera to obtain still or video imagery of the sediment surface and epifauna (e.g., Birchenough et al., 2006, Verdant Power, 2006). Similarly, some SPIs come equipped with a plan view camera, which greatly improves the identification and enumeration of epifauna compared to what is visible solely on the prism image (Integral Consulting, 2017, Revelas et al., 2020).

The choice of sampling designs and statistical analyses may be as important as (if not more important than) the technologies for identifying and measuring changes in habitats (ISO, 2007, ISO, 2014). Sampling designs like BACI that involve a comparison of prior- and post-disturbance states, or comparisons of affected and control sites, are broadly used for assessing impacts but need to rely on good baseline or reference data (Smokorowski and Randall, 2017). Yet, if changes in habitats caused by marine energy devices are to be identified and measured, baseline and reference data need to be obtained prior to site disturbance, stored as raw data and, as much as possible, made available publicly for future comparisons with post-disturbance surveys (Callaway, 2016). Local fishermen and fisheries managers can provide a good understanding of the distribution, abundance, and spatiotemporal trends of commercially fished species and the habitats critical to these species. In some cases, this knowledge can be leveraged as baseline information to design studies. Gradient designs are suitable options that do not require baseline or historical data, in the sense that the sampling measures how effects decrease with increasing distance from the source of disturbance, thereby providing a spatial understanding of the impact (Methratta and Dardick, 2019, Punzo et al., 2015). A before-after-gradient design adds a temporal scale, especially if the sampling is repeated over multiple seasons and years (Bailey et al., 2014, Ellis and Schneider, 1997). When available, seafloor baseline assessments are often used to inform stratified and gradient sampling designs, identifying different substrata where sampling needs to happen in order to fully characterize the various biotopes (e.g., Aquatera Ltd., 2015, Argyll Tidal Limited, 2013, SEAI, 2011).

Once data were collected, parameters assessed to characterize infauna, epifauna, pelagic, and biofouling communities in the studies reviewed here were highly diverse, including measurements of diversity (e.g., Shannon-Wiener’s, Shannon-Weaver’s, Chao’s, Simpson’s), abundance, biomass, species richness, species evenness, and percent cover, aligned with the various recommendations available in the different guideline documents (Table 6). Various multivariate statistical analyses were then used to identify differences in assemblages and/or spatiotemporal changes in habitats, such as of classifications, ordinations, and statistical tests of hypotheses. Depending on the objectives of a study, these parameters were further converted into biodiversity or habitat quality indices (e.g., the AZTI Marine Biotic index by Umehara et al., 2019, Benthic Habitat Quality index by Rosenberg et al., 2009, or Bottom Association index by Degraer et al., 2019). Multivariate analyses using the PRIMER software was the statistical technique most consistently applied to address spatiotemporal associations between community parameters and habitat characteristics, but R is gaining traction because of its versatility, customizability, and affordability. The diversity of packages in R (e.g., *nlme, ecodist, mgcv, vegan, ggplot2*, *random forest*) enable users to apply a wide variety of statistical tools (e.g., linear and nonlinear modeling, parametric and nonparametric analyses, probability, clustering, neural networks), and this platform also provides for the ability to produce and customize visualization tools like maps, tables, and graphs.

5.0 Conclusions

In conclusion, the high diversity of marine habitats and technologies already used to survey them preclude recommending a specific set of technologies for characterizing changes in benthic and pelagic habitats caused by marine energy devices (Figure 8). However, technologies and sampling methods that are adapted and designed for working efficiently in energetic environments should be favored, alongside sampling designs and statistical analyses that are carefully thought out to identify differences in faunal assemblages and spatiotemporal changes in habitats. Because several national and international guidelines for sampling and monitoring benthic and pelagic habitats around offshore activities already exist, relying on these existing guidelines is recommended when selecting suitable monitoring technologies, sampling designs, and sets of data analyses. More importantly for monitoring reports and publications is the need to thoroughly describe the reasons why a specific technology was selected, the methods employed to implement the technology in the field, the sampling design followed to collect data, the data processing and analyzing steps, and any benefits or drawbacks the technology provided to the study. Publicly sharing this information with the marine energy community will help progress toward more transparency and consistency in data collection, and enable the transferability of data and results among projects to fulfill environmental permitting requirements and lower the costs associated with baseline characterizations and post-installation monitoring surveys (Copping et al., 2020).

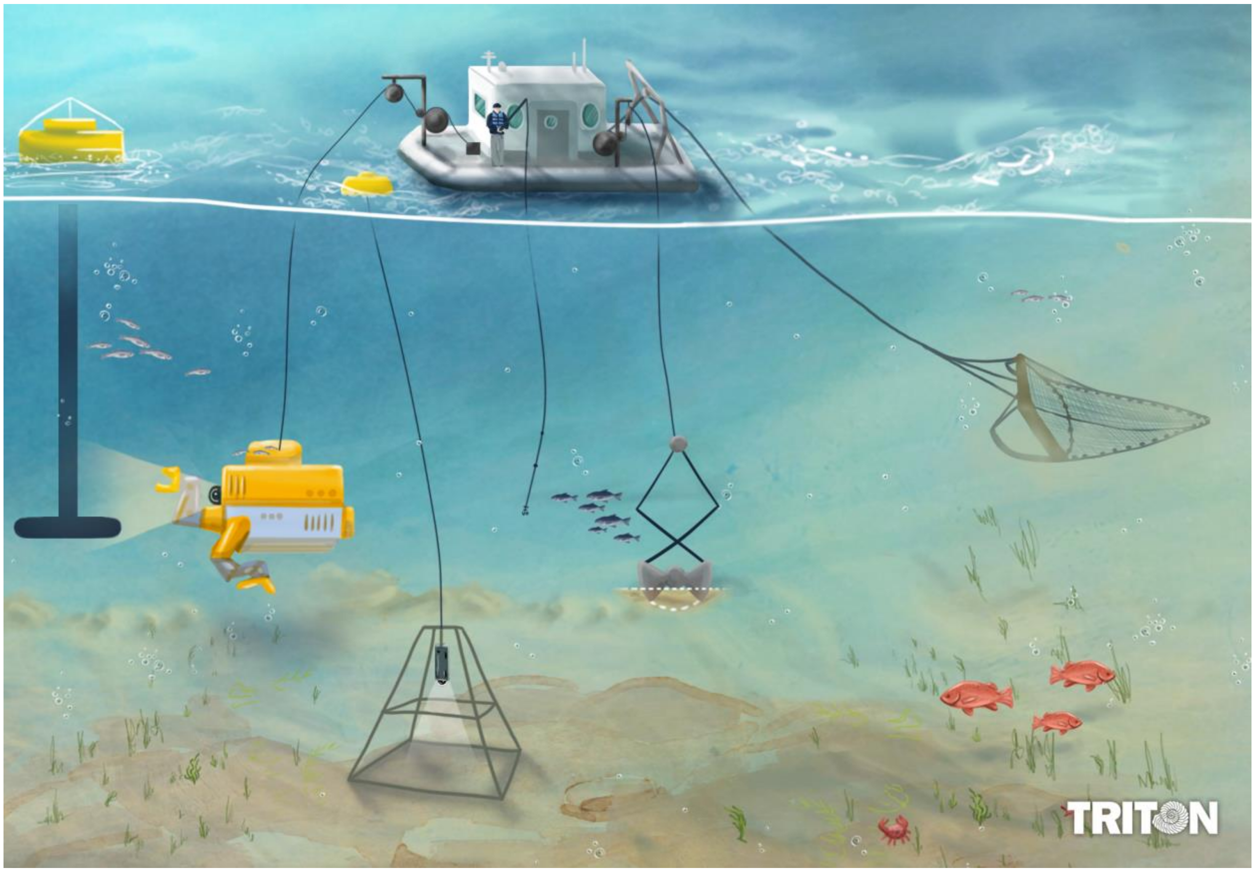

Figure 8. Example of technologies suitable for monitoring changes in benthic and pelagic habitats around marine energy devices. (Illustration by Stephanie King, PNNL)

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Appendix A

Reference Library

This reference library compiles the citations of all the documents used for the Triton Field Trials − Changes in Habitat literature review. The present reference library lists all the documents assessed for the literature review, as a centralized place to find the relevant information. All references were entered in EndNote, citations were extracted and are listed below.

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