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What's in My Toolkit? A Review of Technologies for Assessing Changes in Habitats Caused by Marine Energy Development

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Abstract: Marine energy devices are installed in highly dynamic environments and have the potential to affect the 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, and 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. 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. Technologies and sampling methods that are designed for working 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.

Keywords: biofouling; epifauna; habitat; infauna; marine energy; pelagic; sampling; seafloor; sediment; technologies

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1. Introduction

In numerous countries around the world, regulatory authorities require that potential impacts on the marine environment are assessed prior to industrial development at sea, which includes activities such as offshore drilling, dredging, or installing marine energy infrastructure. For example, European countries are held by the European Water Framework Directive [1], Habitat Directive [2], and Marine Strategy Framework Directive [3] to monitor the status of the ecological quality of freshwater and saltwater bodies and the various habitats they host, and to maintain the sustainable use of these water bodies. In the United States (U.S.), water quality is regulated by the Clean Water Act [4] and associated acts, while habitats and species of special concern are regulated by various policies such as the Endangered Species Act [5], Fish and Wildlife Coordination Act [6], and Magnuson–Stevens Fishery Conservation and Management Act [7]. 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 the spatiotemporal coverage to identify changes [8,9]. 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 [10,11]. 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 [12,13], which needs to be taken into account when designing and interpreting the results of surveys.

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 [14]), with some technologies being 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 perfected acoustic and optical technologies [8,15,16]. Acoustic techniques for characterizing seafloor and sediment properties often require ground-truthing with physical sampling or optical imaging technologies, especially when monitoring physical disturbances due to anthropogenic activities at sea [17]. Choosing the right technology depends on the goal of the study and the habitat and depth targeted, but also on a trade-off between sample size, number of replicates, and field costs [11].

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 the standardization of monitoring surveys for soft-bottom macrofauna (ISO 16665 [18]) and hard-substrate communities (ISO 19493 [19]) 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 [20] and on sampling designs for environmental data collection [21], the Bureau of Ocean Energy Management (BOEM, formerly the 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 report requirements [22], shallow hazards [23], biologically sensitive underwater features and areas [24], deep-water benthic communities [25], benthic habitat surveys [26], fisheries related to renewable energy development [27], and geophysical, geotechnical, and geohazard guidelines [28]. In the United Kingdom, the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) has established guidelines for benthic studies at dredging sites [29] and data acquisition to support marine energy projects [30], 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 [31].

Despite these guidelines and manuals, identifying habitat changes resulting from human activities such as marine energy development has proven to be a challenging task, particularly due to 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, which makes it difficult to compare protocols and results and transfer lessons learned from one project to another [32,33]. 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 [33,34]. 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., [35]). Innovative methods and technologies may sometimes be required, however, the consistency of the data and results and the affordability of new technologies remain to be assessed [36,37].

The goal of the present literature review is to provide parties involved in surveying and monitoring the environmental effects of marine energy development, and in particular, wave and tidal energy projects, 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. 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, but also at offshore wind farms, oil and gas offshore sites, and other marine industries around the world over the last 20 years. The aim of this review was 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 what habitats to survey and what constitutes a change can sometimes be challenging. For the purpose of 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 [38], we considered changes in seafloor and sediment characteristics, benthic and pelagic communities, and biofouling assemblages.

2. Materials and Methods

2.1. Literature Review

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; accessed on 31 March 2021 [39]), 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 [40,41]) 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, with a main focus 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; accessed on 31 March 2021) using 15 sets of keywords about marine energy, analogous industries, monitoring technologies, and habitats as well as various combinations of these sets to narrow down the results. 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.

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	Note about whether the data obtained can be used for modeling (as dependent or independent variables).
Notes	Any additional notes upon reviewing documents.

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) was synthesized per 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 per habitat category.

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.

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 [18,19,21]. 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. 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, but when they did, the feedback 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 the frequencies of entries. As much as possible, results are presented and discussed in the following sections by habitat category.

3. 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 the seafloor, 117 entries to sediment, 64 to infauna, 139 to epifauna, 96 to pelagic, and 34 to biofouling.

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 1). Visual was the most diverse technology class, including surveys with divers, remotely operated vehicles (ROVs), and drop or towed cameras, among others. Not all technologies were employed within each habitat category and some technologies were more commonly used than others (Figures 1 and 2). 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 EdgeTech and Klein for side-scan sonars. 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 such as drop camera 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 ROV. 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 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

Table 3. *Cont.*

Acoustic	Net and Trawl
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)	Midwater 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 [SAS]	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 cage
Diver (+ pipe corer)	Trap
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	HabCam bottom photos
Modified dredge	Hybrid AUV
Modified scallop dredge	Lagrangian floating imaging platform
Pipe dredge	Midwater video system
Triple-D dredge	Mounted underwater cameras
Grab	Photo
Day grab	Quadrats
Diver (+ manual dig)	Remotely operated vehicle [ROV]
Double Van Veen grab	ROV (+ stereo-video)
Ekman grab	Sediment profile imaging [SPI]
Hamon grab	SPI (+ plan view)
Mini-Hamon grab	SPIScan
Shipek grab	Submersible
Smith–McIntyre grab	Time-lapse photography
Ted Young-modified Van Veen grab	Towed camera
Van Veen grab	Onshore transect survey
Hook & Line	Onshore visual survey
Angling	Video
Surface longline	Video sled
Trolling line	**Remote Sensing**
Vertical longline	Light Detection and Ranging [LiDAR]

Table 3. *Cont.*

Acoustic	**Net and Trawl**
Scrape Samples	**Other**
Diver (+ scraper) Free diver (+ scraper) Scrape sample	Clam rake Diver (+ depth logger) Diver (+ sampling)
Plates	Fluorometer
Biofouling plate Settlement plate Structure substitute (mesocosm experiment)	Net bag via diver collection Niskin bottle + eDNA Penetrometer

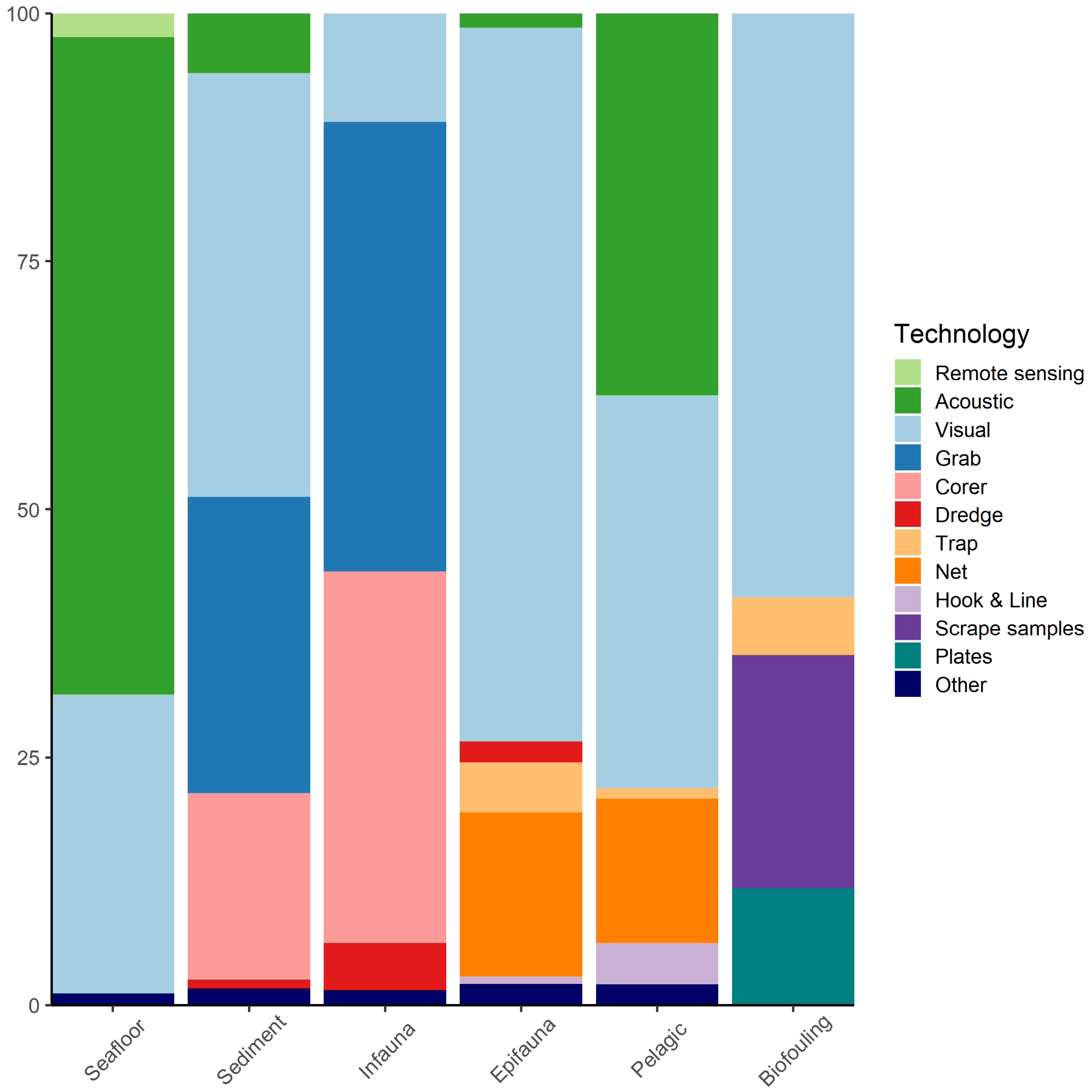

Figure 1. Proportions of the different technologies used for describing habitats and measuring changes in their characteristics.

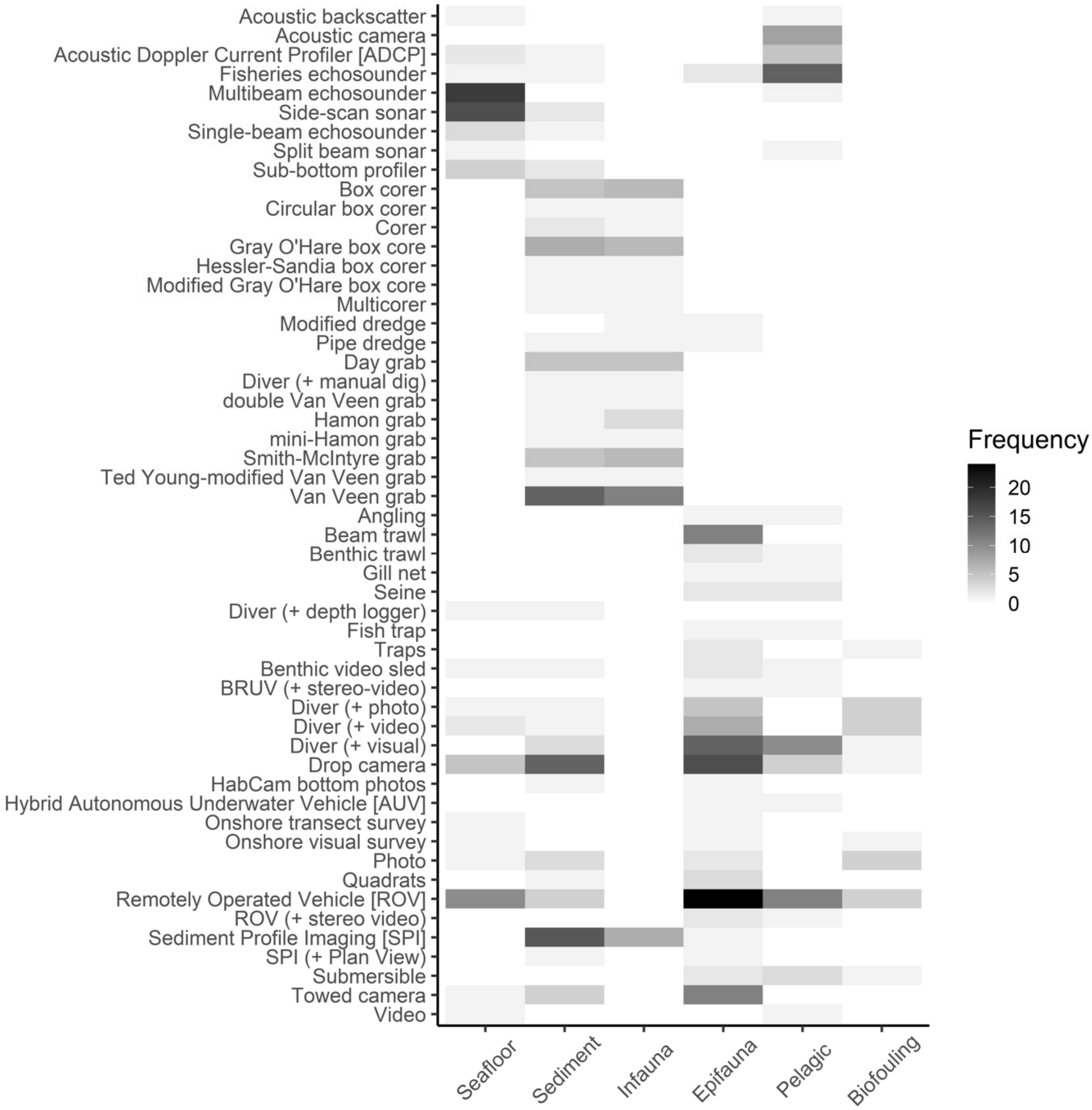

Figure 2. Heatmap showcasing the preponderance of sampling technologies across habitat categories; the darker the color, the more frequently used the technology. Only technologies that were used for two or more habitat categories are represented here.

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 3). 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. These 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 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., [42–44]). Observers on commercial or recreational fishing boats were also classified as opportunistic.

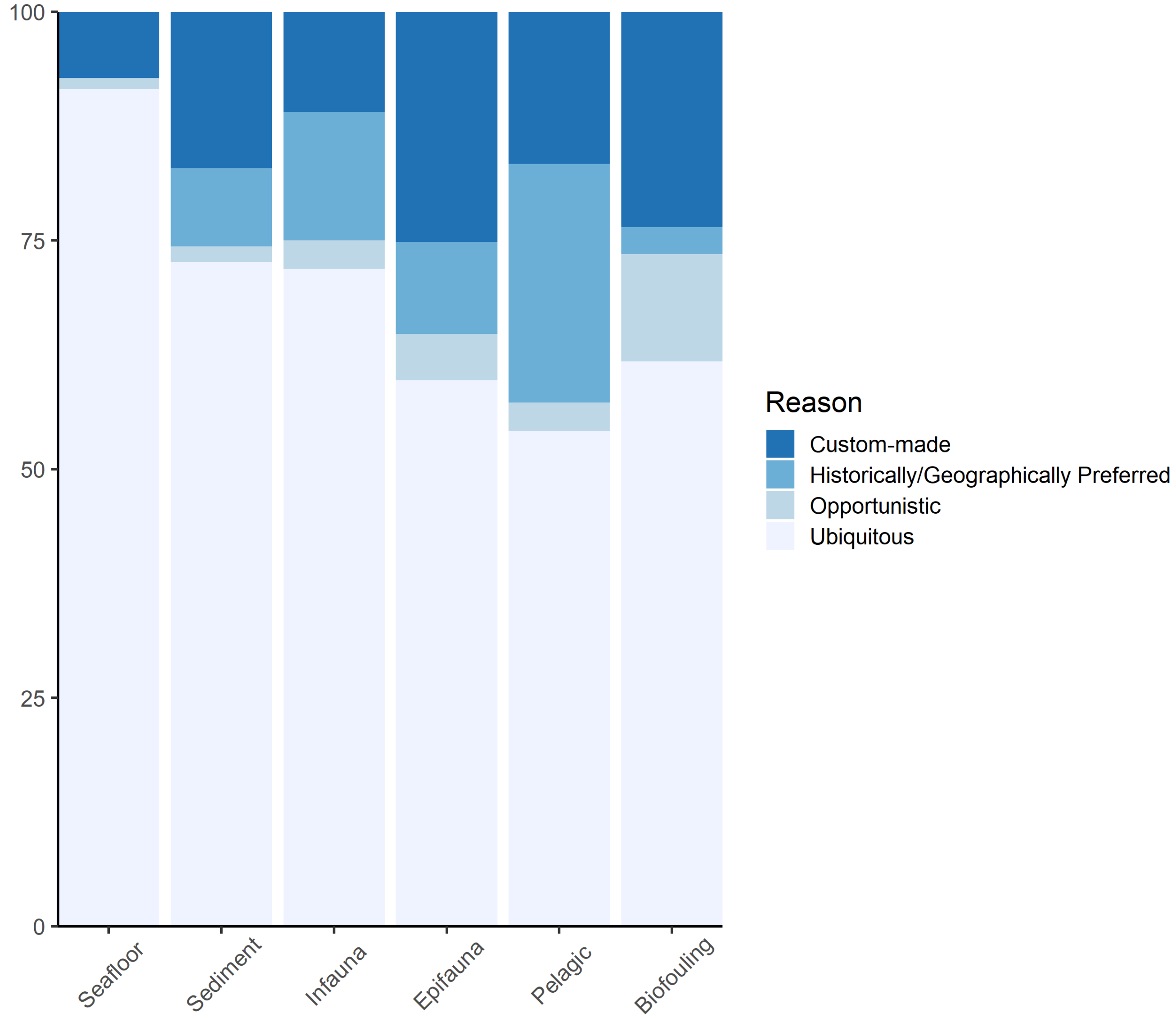

Figure 3. Proportions of each four general reasons for choosing a technology per habitat category: custom-made technology, historical and/or geographical preference for a type of technology, opportunistic use of a technology, or ubiquitous aspect of a technology.

The sampling designs employed by the reviewed studies varied greatly among technologies and habitats (Figure 4). 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 the 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 (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.

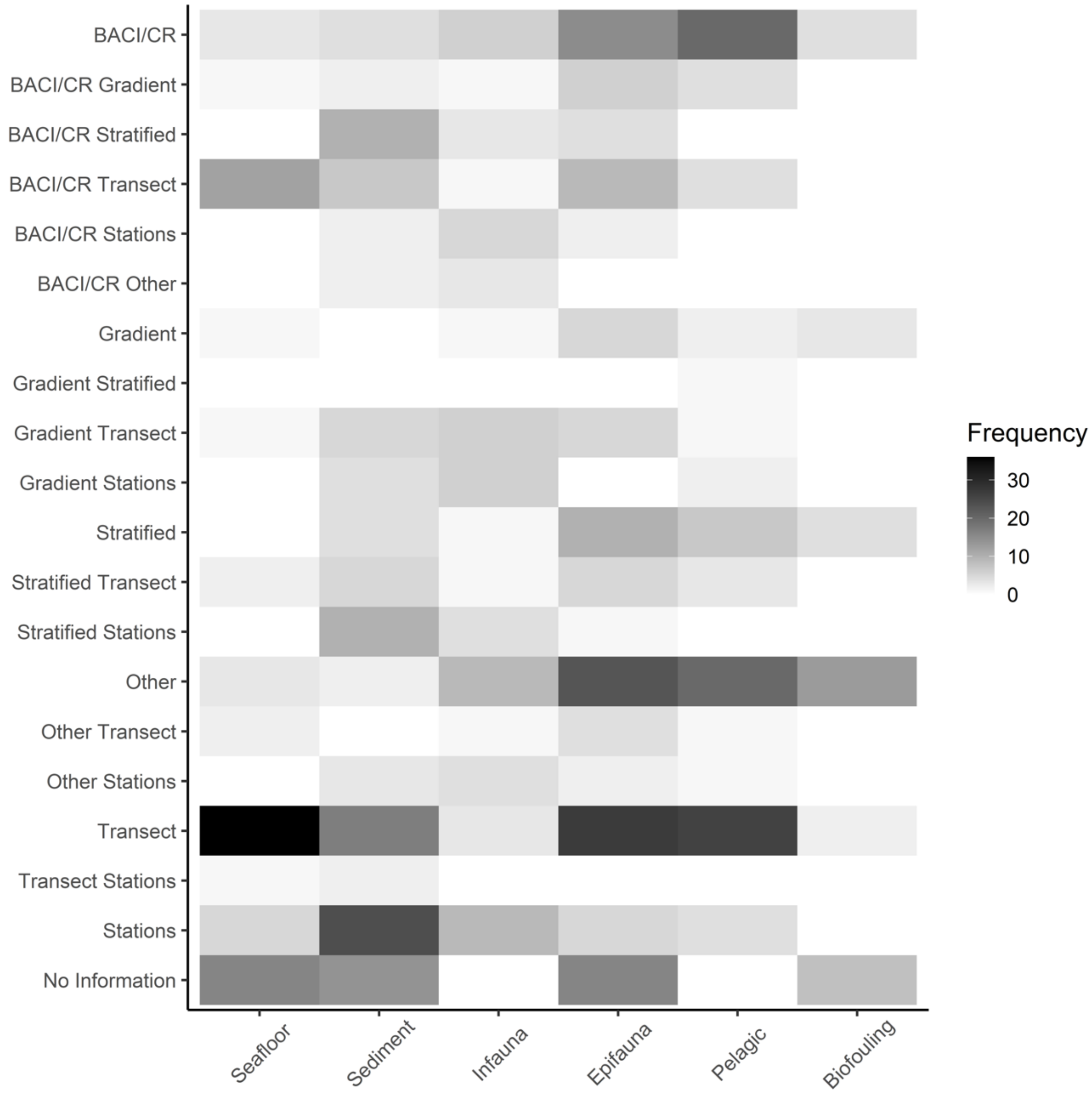

Figure 4. Heatmap showcasing the preponderance of sampling designs across habitat categories; the darker the color, the more frequently used the sampling design. When sampling designs are combined, the primary design is listed first and the secondary second. BACI/CR = before after control impact/control response.

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

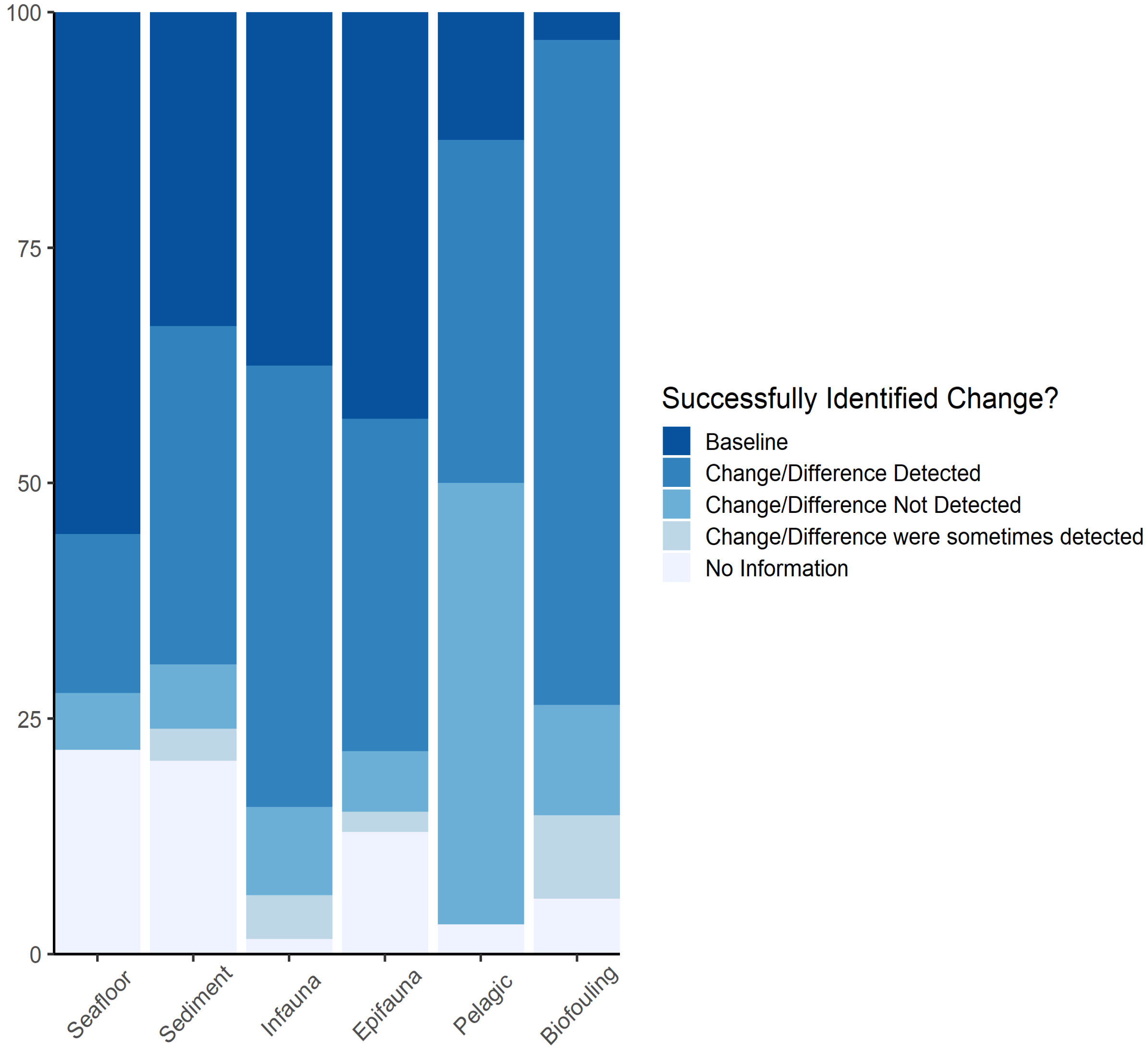

Figure 5. Success, within the reviewed studies, in detecting changes or differences in habitats, within the survey area or before/after an event susceptible to trigger changes.

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 proportion of positive feedback was for technologies used to survey seafloor characteristics such as MBESs and side-scan sonars, as well as 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" [45]; and "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" [17]. On the other hand, the greatest proportion of negative feedback was 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" [46]; "13 photos were invalidated due to the seabed surface being invisible as the prism had protruded too deep" [47]; "Fish behavior may be affected by the presence of divers" [48]; and "Real-time positioning is a major challenge for micro-ROVs (can be added for a substantial cost)" [49]. Often, the feedback was relative 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 [50]), but sometimes it was more general such as sled and towed cameras are particularly sensitive to the rocking motion of swell at the surface (e.g., [51,52]), depth is a limit for sampling with scuba divers (e.g., [53]), or corers and grabs do not perform well in coarse sediments (e.g., [12]).

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 4). 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 such as the Coastal and Marine Ecological Classification Standard (CMECS; e.g., in [54] or [55]) or the JNCC's Marine Habitat Classification for Britain and Ireland ([56]; e.g., in [57] or [58]). However, the most common analyses were univariate (e.g., ANOVA) or multivariate statistical analyses (e.g., (n)MDS, PCA, PERMANOVA, 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 4).

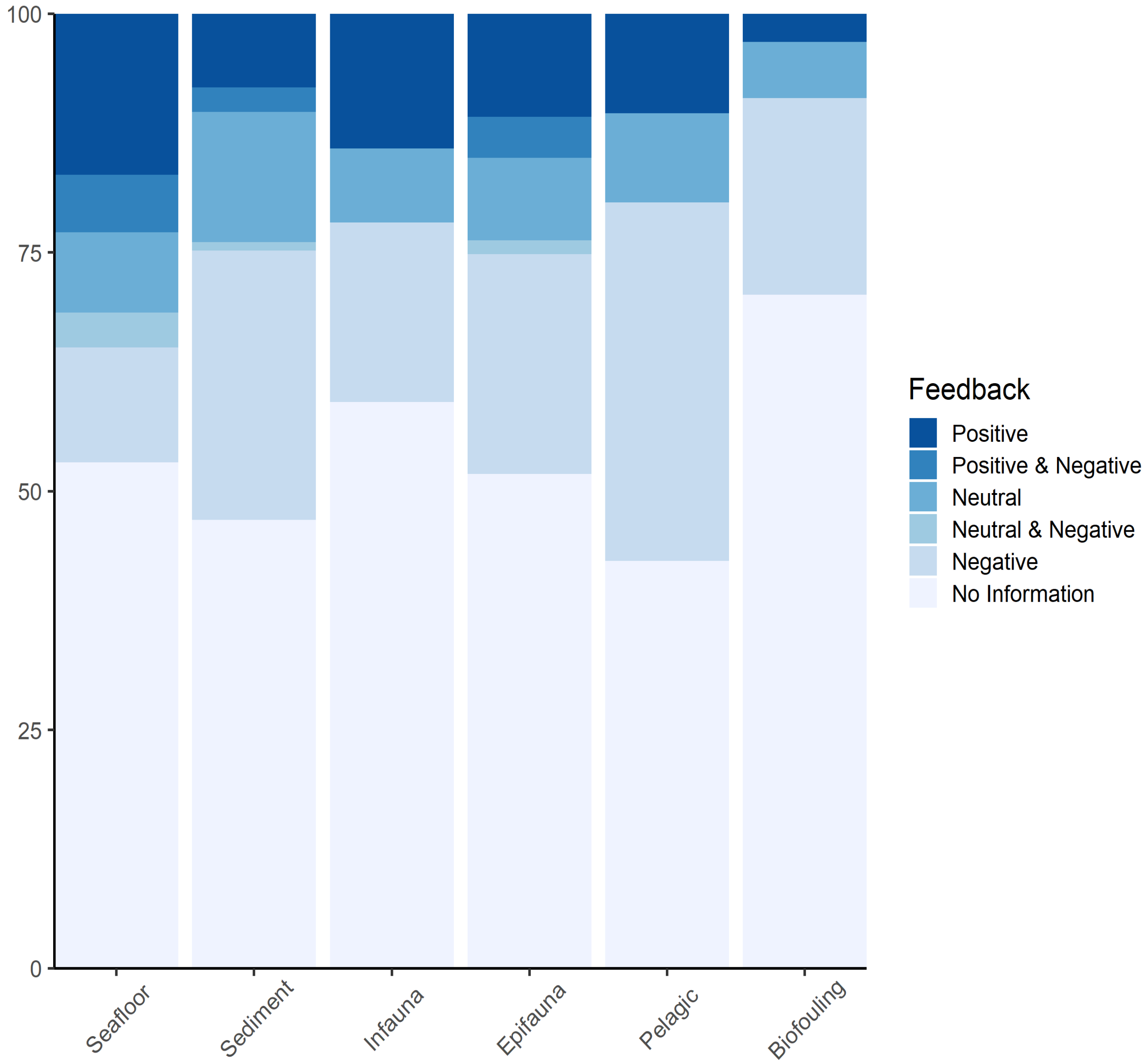

Figure 6. Proportion of positive, negative, or neutral feedback from the authors of the reviewed studies on the technologies used for surveying and monitoring the six categories of habitats. In many instances, the feedback could be classified as a combination of two or three options, when it was positive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

Table 4. Common analyses and software associated with the technology categories that had the most applications across habitats.

Habitat	Technology Category	Most Common Analyses	Most Common Software
Seafloor	Acoustic	Benthic terrain modeler, digital elevation model	R (raster), HYPACK®/HYSWEEP®, CARIS HIPS & SIPS™, QPS Fledermaus Software, ArcGIS®/ArcVIEW®
	Visual	Categorized by indices, PCA, generalized linear model	Image Analyst, BIIGLE 2.0, MATLAB, R, SigmaPlot

Table 4. *Cont.*

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

ANOVA = analysis of variance; ANOSIM = analysis of similarities; DISTLM = distance-based linear model; HSD = honest 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.

4. 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 $m \cdot s^{-1}$ [59], while another commented on the interference on their sonar data due to the entrained air in strong tidal currents [60]. 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 [36,51,61]. 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 [52,62]. Heavier technologies seemed to be less affected than those of lighter build [63]. Heavy swells and currents also tend to resuspend the sediment and alter the visibility, limiting the use of video and still imagery [36,64,65]. 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 [12]. 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 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 ship and labor times to a survey [11].

Table 5 summarizes the applicability to marine energy project sites of the most frequently used technologies for each of the six habitat categories, including noted limitations on the use in high-energy environments, known unwanted impacts on species and/or habitats of interest, cost range of the technologies themselves, and whether the software required for data analysis are proprietary or open source. Table 6 provides recommendations on 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 5. 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 *	Analysis Software
Acoustic camera	Pelagic	Yes	Yes	Water turbidity and entrained air bubbles were noted to disrupt data	None if frequencies used are out of 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, as well as lack of particles in extremely clear water.	None if frequencies used are out of hearing thresholds for sensitive organisms	$5000 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 $2500	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	$6000 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	None	$5000 to $10,500	Any statistical analysis software

Table 5. *Cont.*

Technology	Habitat Category	Used in High Wave	Used in High Current	Limitations	Unwanted Impacts	Cost *	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 impact safety	Diver motion may affect animals' behavior	$500 to $4500	Any image & statistical analysis software
Drop camera	Seafloor Sediment Epifauna	Dependent on sea state	Yes, but use is targeted for slack tides or lower flow conditions.	High waves and current can impact stability; high turbidity impact image quality	Associated lights may affect animals' behavior	$350 to $15,000	Any image & statistical analysis software
Fisheries echosounder	Pelagic	Yes	Yes	Water turbidity and entrained air bubbles can disrupt data; individual fish are hard to discern when they move in schools	None if frequencies used are out of 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	None if frequencies used are out of 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	Require structure to be pulled out of water	Biofouling communities are exposed to air	<$2000	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 impact stability; high turbidity impact image quality	ROV motion and lights may affect animals' behavior	$3000 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

Table 5. *Cont.*

Technology	Habitat Category	Used in High Wave	Used in High Current	Limitations	Unwanted Impacts	Cost *	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	$5000 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	None if frequencies used are out of hearing thresholds for sensitive organisms	$2000 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 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; may kite in deep water	None	$9000	Any statistical analysis software
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 out of 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 impact stability; high turbidity impact image quality	Sled motion and lights may scare away mobile animals; sled contact with seafloor may leave scars	$300 to $4000	Any image & statistical analysis software

Table 5. *Cont.*

Technology	Habitat Category	Used in High Wave	Used in High Current	Limitations	Unwanted Impacts	Cost *	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 impact ability to get samples near an object or foundation.	None	$1400 to $13,500	Any statistical analysis software

* Cost range estimates were based on publicly available information and multiple quotes 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.

Table 6. 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	Obstructions	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	-

Table 6. *Cont.*

Infauna Epifauna	Strong Currents	Mild Currents	High Waves	Low/No Waves	Deeper 30 m	Shallower 30 m	Obstructions	Free Passage	Coarse Seabed	Soft Seabed
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 echosounder, heavy ROV, trawl	Any ROV, drop camera, fisheries echosounder, towed camera, trawl	Fisheries echosounder, hook & line, trawl	Any ROV, drop camera, fisheries echosounder, towed camera, trawl			Dredge	Any corer, any grab, dredge, SPI	Day grab, dredge, Van Veen grab	Any corer, any grab, SPI
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
Obstructions	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

Table 6. *Cont.*

Infauna Epifauna	Strong Currents	Mild Currents	High Waves	Low/No Waves	Deeper 30 m	Shallower 30 m	Obstructions	Free Passage	Coarse Seabed	Soft Seabed
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 camera, trawl	Fisheries echosounder, trawl	Any ROV, diver, drop camera, fisheries echosounder, seine, towed camera, trawl	Any ROV, dredge, drop camera, fisheries echosounder, trawl	Any ROV, camera sled, diver, dredge, drop camera, fisheries echosounder, seine, towed camera, trawl	Any ROV, diver, drop camera, traps	Any ROV, camera sled, diver, dredge, drop camera, fisheries echosounder, seine, towed camera, trawl		

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

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. [58] used a drop camera rather than scuba divers because of cost considerations, while O'Carroll et al. [66] 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., [58,64]), but are difficult to implement when looking forward at a specific target, for example, to assess colonization and the reef effect 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 [67]. Divers are usually more suitable in dense kelp fields or close to/underneath artificial structures (e.g., [68,69]), but both divers and underwater vehicles are known to potentially affect the behavior of marine animals during surveys (e.g., [70,71]). Imagery technologies mounted on robotics or drop frames have the advantage of achieving greater depths with longer bottom times than diver surveys [72–74]. Drop, sled, or towed cameras are often highly customizable; some are equipped with multiple cameras facing different angles and with other instruments such as a conductivity–temperature–depth sensor (e.g., [52]), while others are built to endure strong currents and navigate rugged terrains (e.g., [75,76]).

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. Corers, grabs, and drop cameras are common technologies for ground-truthing side-scan sonar and multibeam echosounder data when mapping seafloor and sediment characteristics (e.g., [64]); trawls can be used to ground-truth demersal fish communities described using hydroacoustic methods (e.g., [77]); and 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., [78]). 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 ship 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 such as 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., [79]). 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., [17,80]). Similarly, some SPIs come equipped with a plan view camera, which greatly improves the identification and enumeration of epifauna compared to what is visible on the prism image only [81,82].

However, 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 [18,19]. Sampling designs such as BACI that involve a comparison of prior- and post-disturbance states, or between affected and control sites are broadly used for assessing impacts, but need to rely on good baseline or reference data [83]. However, 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 [12]. Gradient designs are other 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 [84,85]. A before-after-gradient design adds a temporal scale, especially if the sampling is repeated over multiple seasons and years [86,87]. When available, seafloor baseline assessments are often used to inform stratified and gradient sampling designs, identifying different substrata where sampling needs to take place in order to characterize the various biotopes (e.g., [88–90]). Once data were collected, parameters assessed to characterize infauna, epifauna, pelagic, and biofouling communities in the studies here reviewed 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. Various multivariate statistical analyses were then used to identify differences in assemblages and/or spatiotemporal changes in habitats. Depending on the objectives of a study, these parameters were further converted into biodiversity or habitat quality indices (e.g., AZTI Marine Biotic index in Umehara et al. [91], Benthic Habitat Quality index in Rosenberg et al. [46], or Bottom Association index in Degraer et al. [92]).

5. 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. However, technologies and sampling methods that are adaptable and designed for working efficiently in energetic environments should be favored, alongside sampling designs and statistical analyses 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.

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Appendix A

Appendix A compiles the citations of all 259 documents used for the present literature review, listed in alphabetical order.

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