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Differentiating and defining 'exposed' and 'offshore' aquaculture and implications for aquaculture operation, management, costs, and policy

Edited by
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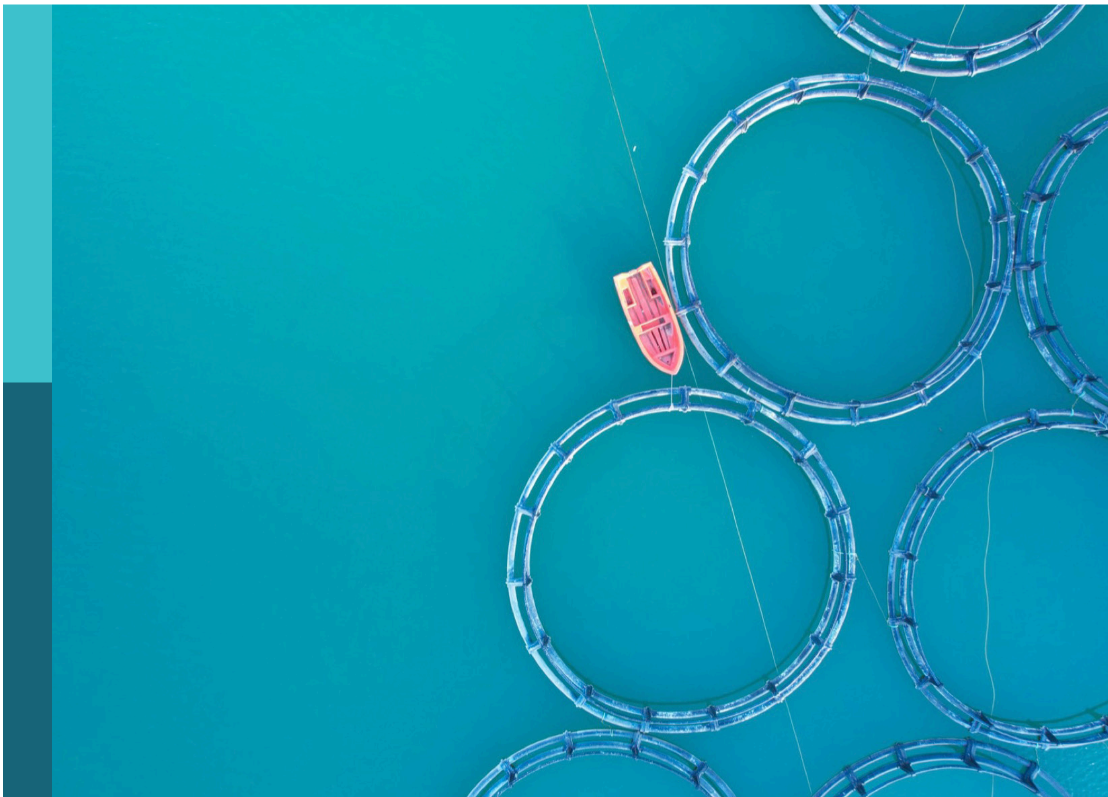

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Differentiating and defining 'exposed' and 'offshore' aquaculture and implications for aquaculture operation, management, costs, and policy

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Editorial: Differentiating and defining "exposed" and "offshore" aquaculture and implications for aquaculture operation, management, costs, and policy

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Editorial on the Research Topic
Differentiating and defining "exposed" and "offshore" aquaculture and implications for aquaculture operation, management, costs, and policy

The following work is the result of contributions from 44 experts from 10 countries, led by the Working Group for Open Ocean Aquaculture (WGOOA) under the umbrella of the International Council for the Exploration of the Sea (ICES), Copenhagen, Denmark. This Research Topic covers the following topics in this sequence:

(1) Introduction to the conceptual problem and definition of the term "offshore"; (2) account of the "offshore" definition in national and international laws including the United Nations Convention on the Law of the Sea (UNCLOS) (Rozwadowski, 2004) and the Oslo and Paris Convention for the Protection of the Marine Environment of the North-East Atlantic) (OSPAR Convention, 1992); (3) presentation of current aquaculture operations that are offshore and/or exposed; (4) development of indices as assessment tools to describe the exposure of an aquaculture farm; (5) application of these indices in aquaculture with a view to site, species, and technology selection, operation, and maintenance (O&M); (6) considerations regarding the costs of expanding aquaculture from protected to more exposed sites; (7) influence of these definitions under socio-economic aspects; and (8) a conclusion with an outlook of necessary research areas to enable expansion of aquaculture activities into "offshore" and "exposed" water bodies.

Four additional publications from non-ICES member scientists are included here as these scientific contributions fit thematically into this Research Topic and expand on important topics. Gonzales et al. explore the opportunities for co-location of aquaculture and clean energy operations. Carroza-Meza et al. make recommendations on the management and regulation of offshore aquaculture to encourage industry growth. Gagnon and Gagnon review the status of off-bottom mariculture of extractive species in exposed environments.

1 Description of the Research Topic and introduction to the compilation of publications

Farmers, engineers, scientists of various disciplines, as well as insurers, lawyers, NGO workers, and others involved in marine aquaculture often use the term "offshore" when the farm is located in a region where the height of waves and the velocity of currents become a challenge for the technology used, the cultured organism, and O&M. However, what exactly does "offshore" mean as opposed to "open ocean" and how do these terms differ from "exposed"? Other site descriptions such as "nearshore" or "inshore" are also used, as well as "coastal" or "Exclusive Economic Zone (EEZ)" aquaculture and "farming the deep blue". All of these terms have only a vague description and do not seem to be clearly defined or perhaps even well understood.

In general understanding, the term "offshore" refers to activities or objects that are located far from the coastline, i.e., something typically located in the open ocean or under harsh oceanic conditions. However, how does the specific meaning of "offshore" differentiate itself from the term "open ocean", which is generally understood as a body of water that can, but not necessarily has to be, very far from the coastline and likely requires a certain depth of water and is subject to strong currents and high waves. It becomes even more complicated if this type of site description were also understood to include the construction of aquaculture facilities or structures in the open sea, which are located beyond the continental shelf. This is exactly where the term "EEZ aquaculture" has been used. For if the site is only far enough from the coast and is already outside the territorial sea, i.e., in a zone that is 3 or up to 12 nautical miles from the coast, depending on the country, one could speak of the EEZ. So, these three terms alone vary greatly in the context in which they are used and could be explained collectively as "farming the deep blue". However, this term of "farming the deep blue" has also been established for the required increase in production that could be operated in the open sea, i.e., not necessarily far away and not at all needing to be exposed to the inclement environmental conditions, which we considered in the explanation of the "open ocean aquaculture term". Further, because aquaculture facilities that are close to the coast, traditionally described as "nearshore", can be subjected to strong currents and high waves as well, it can be confused with the above as an "open ocean parameter", and then further confused as it can also be characterized as "exposed". Therefore, "exposed" conditions can exist just in front of the mainland or an island, within inlets, and thus, be anything but "offshore" or in the "open ocean". Whether this type of aquaculture can then also be described as "inshore" is unclear, because "inshore" is supposedly a part of "nearshore", but closer to the coast than the term "nearshore" actually means. So "nearshore aquaculture" could also be understood as coastal aquaculture, because the terms "inshore" and "nearshore" would be synonyms in this instance.

This jumble of terms, further complicated by perspective (Figure 1), all have no clear definition and are therefore used arbitrarily and must be distinguishable from each other. In particular, the terms "offshore aquaculture" and "exposed aquaculture" need a clear definition as current developments and ongoing search for locations to increase aquaculture production will have to turn to distant and environmentally challenging areas to avoid competition for space with other stakeholders close to the coast.

The following publications will investigate and discuss the terms "offshore" and "exposed" with the associated changes in the aquaculture sector and society (see also Table 1). While Buck et al. identify the difficulties in understanding and applying different terms in characterizing a location of an aquaculture farm, Markus

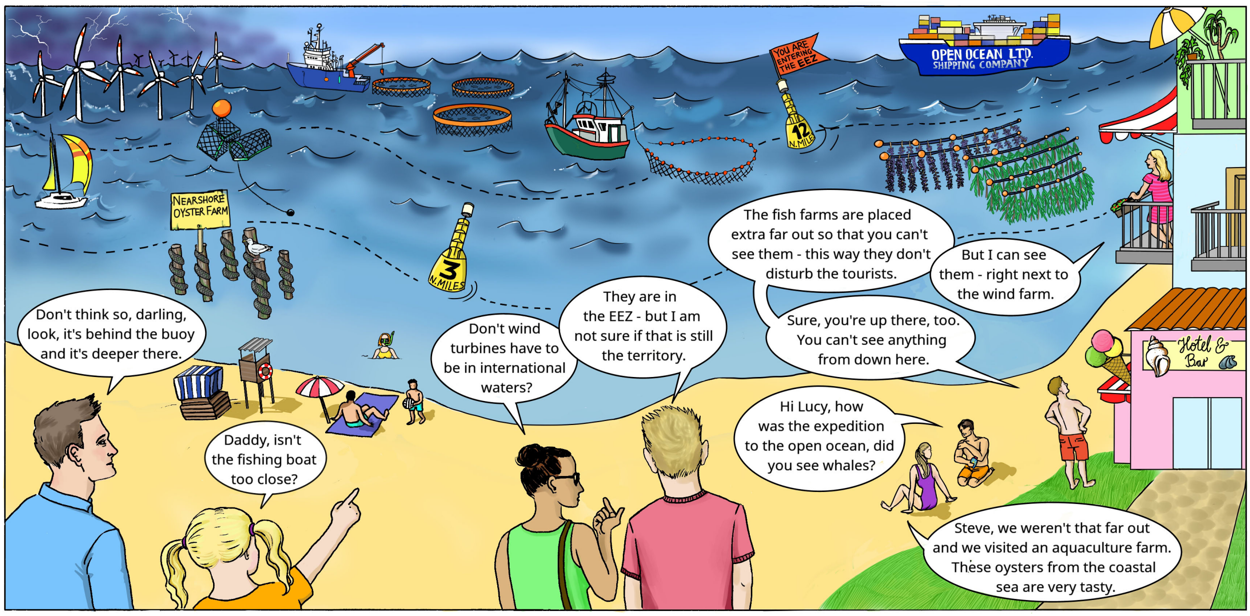

FIGURE 1
Aquaculture far away: "I understand it even when I don't see it." There are many different terms for describing the location of an aquaculture facility, and the distinctions between them are confusing. [Image: Buck/Holzé (AWI)].

TABLE 1 Publications in this Research Topic with the different topics discussed.

	No.	Topic and title	Authors
ICES	1	Clarification of the "Offshore-Exposed" issue	Buck et al.
	2	Legal framework	Markus
	3	Current status of exposed and offshore aquaculture	Heasman et al.
	4	Development of an index to describe the exposure of an aquaculture farm	Lojek et al.
	5	Application of how this index affects biology, technology, and O&M of aquaculture farms	Heasman et al.
	6	Distinct effects of distance from shore or exposure on the cost of large-scale seaweed production	Dewhurst et al.
	7	Description of what role this development has from a socio-economic perspective	Krause et al.
	8	The conclusion in the totality of all approaches and application for different user groups	Sclodnick et al.
Non – ICES	9	Synthesis of multinational marine aquaculture and clean energy co-location	Gonzales et al.
	10	Recommendations for facilitating offshore aquaculture: lessons from international experience	Carroza-Meza et al.
	11	Status of off-bottom mariculture in wave-exposed environments. Part 1. Global inventory of extractive species commercial farms in temperate waters	Gagnon
	12	Status of off-bottom mariculture in wave-exposed environments. Part 2. Comparative loading and motion of longline designs currently used in exposed commercial farms	Gagnon

addresses the term "offshore" and its use and meaning in the context of the Law of the Sea. Heasman et al. provide an updated review on exposed and offshore aquaculture worldwide. The exposure index presented in Lojek et al. lay out a methodology for classifying sites based on different wave and current parameters (significant wave height, extreme current speed, etc.). Sites can then be characterized using an exposure index. Industry participants will have a much better understanding of what that site is like, how it differs to other sites they are familiar with, and what challenges they encounter. Heasman et al. describe the challenges of operating a farm that is spatially far from shore, applying two of the indicative indices to known aquaculture sites. Dewhurst et al. use the example of macroalgae aquaculture to determine additional costs when aquaculture is carried out in exposed or distant marine areas. Krause et al. analyze the challenges of offshore aquaculture to society, while Sclodnick et al. provide a concluding evaluation followed by an outlook.

Author contributions

BB: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. KH: Writing – original draft, Writing – review & editing. TS: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Resolving the term "offshore aquaculture" by decoupling "exposed" and "distance from the coast"

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The terms "offshore" and "open ocean" have been used to describe aquaculture sites that are further from the coast or in higher energy environments. Neither term has been clearly defined in the scientific literature nor in a legal context, and the terms are often used interchangeably. These and other related terms (for example "exposed", "high-energy") variously refer to aspects of a site such as the geographic distance from shore or infrastructure, the level of exposure to large waves and strong currents, the geographic fetch, the water depth, or some combination of these parameters. The ICES Working Group (ICES, 2024) on Open Ocean Aquaculture (WGOOA) therefore identified a need to define the terminology to reduce ambiguity for these types of aquaculture sites or more precisely, to: (1) promote a common understanding and avoid misuse for different classifications; (2) enable regulators to identify the characteristics of a marine site; (3) allow farmers to be able to assess or quantitatively compare sites for development; (4) equip developers and producers to identify operational parameters in which the equipment and vessels will need to operate; (5) provide insurers and investors with the terminology to consistently assess risk and premiums; and (6) circumvent the emergence of narratives that root in different cognitive interpretations of the terminology in public discourse. This paper describes the evolution of the use of the term "offshore aquaculture" and define the most relevant parameters to shift to a more definitive and robust term "exposed aquaculture" that can inherently relay clearer information. Adoption of this more definitive definition of "exposed" will allow the user to define a site with more than just distance from shore. Key differences and the importance of these terms are discussed that affect various interest groups. Follow-up articles in this compilation from scientific members of the WGOOA as well as other scientists outside ICES are incorporated that develop a set of definitions and a rigorous exposure index.

KEYWORDS

offshore aquaculture, exposed aquaculture, definition of aquaculture locations, terminology, aquaculture location parameters

1 Introduction

Aquaculture production in estuarine and coastal habitats has grown substantially over the past 3-4 decades (FAO, 2022), and environmental sustainability has improved (Naylor et al., 2021), and the importance of aquaculture's contributions to Sustainable Development Goals (SDGs) emphasized (Troell et al., 2023). At the same time, coastal and marine industries of other sectors have also grown (Buck et al., 2004; Wilding et al., 2018; Weitzman et al., 2019). Traditional activities such as shipping (commercial and naval), fishing, mining for oil, gas, and minerals, or tourism have expanded, and new types of activities have emerged (such as different types of renewable energy, etc.) (Kleingärtner, 2018) in this zone referred to as "offshore". Hence, Smith (2000) has aptly coined this overall development as the "industrialization of the world ocean" and others have referred to it as the marine urbanization (Dafforn et al., 2015) and the "blue acceleration" (Jouffray et al., 2020). These developments have increased competition for space and resources, primarily in less energetic inshore and nearshore waters. In many cases this has led to increased stakeholder conflicts and limited the expansion of marine aquaculture (Holm et al., 2017).

Increased conflicts nearshore have led to the search for sites that will allow for the expansion of aquaculture operations that will increase production by permitting larger sites with more distance between them that will decrease conflicts. For the last 40 years there has been an active scientific and policy forum to a move of marine aquaculture away from the nearshore habitat to more exposed and distant ocean areas. In most of these efforts, the quest to find new concepts for more robust designs and equipment enabled aquaculture to develop in areas with fewer user conflicts. Efforts have not always been fully successful since every site is complex, having different geographic, topographic, physical, geological, chemical, biological, and oceanographic parameters. Nearly all marine aquaculture to date has been concentrated in "sheltered" and/or "nearshore" areas due to the lower hydrodynamic energy in these waters with lower investment capital and operational costs. Aquaculture operations located in such areas require less investment in robust technology and worker safety, generate lower insurance costs, are easier to manage logistically by not requiring expensive wave energy robust service vessels.

Aquaculture farmers, scientists, administrators and policymakers often operate with concepts such as "onshore", "inshore", "nearshore", "offshore", or "open ocean", to name a few of numerous terms. Such concepts have been interchangeably used to characterize different types of aquaculture sites referring to farms' location in relation to the shoreline, aspects of a site such as the geographic distance from shore, exposure to waves and currents, geographic fetch, water depth, or some combination of these parameters. But the industry's efforts to continue expanding beyond sheltered, nearshore sites have revealed that such concepts and terms are neither very precise nor do they provide clear information about the site's environmental, technical, economic, and social conditions for aquaculture operations. As a result, too often these concepts are used arbitrarily depending on sectoral perspectives of, for example, scientists, conservationists, fisheries, lawyers, ocean engineers, to name a few. This particularly holds true with regard to the term "offshore" (Froehlich et al., 2017; Morro et al., 2021). Currently, "offshore aquaculture" is predominantly used to describe any farm that could be exposed to strong currents, high waves, and other unfavorable environmental conditions. It is argued here that the present uses of the term "offshore" conflate distance from a coastline with the degree of exposure to adverse environmental, logistical, or other conditions. Distance from the coast has minimal relevance with regard to the equipment or species required, or suited to, the site. Consequently, for the adequate description of aquaculture site conditions to identify suitable aquaculture sites, a more precise terminology is needed to support governments policymakers, administrators, scientists, farmers and other stakeholders in the planning and execution of aquaculture operations.

Outside of the aquaculture fraternity the use of the term "offshore" can cause confusion and uncertainty. First, a generic concept such as "offshore" is difficult to distinguish from other vague concepts such as 'inshore', 'nearshore', 'open ocean', 'sheltered' or 'exposed', forcing stakeholders to clarify the description of an area in each case. Second, most of these terms do not correspond to legal terms defined in international treaties or national laws. To make matters worse, these terms are often used and interpreted inconsistently by both lawyers and scientists. For example, while Dua (2023) would argue that 'onshore' operations include activities or assets located within a country's borders, lawyers would argue that 'within a country's borders' would also include 'territorial waters' as defined by international law, which can extend up to 12 nautical miles (nm) into the sea.

2 Objectives and research requirements

In order to clarify more precisely, we, as members of the ICES "Working Group on Open Ocean Aquaculture" (ICES, 2024), are appointed to scientifically define the terminology of "offshore aquaculture" and "exposed aquaculture" more precisely. The main objectives are to: (1) discuss the understanding, terminology, and linguistic use of the term "offshore" in comparison to the other terms, (2) examine the different published definitions of the terms, and (3) recommend a new term for this kind of aquaculture. Results of this work will better classify aquaculture operations that take place in various zones of the ocean (distant and/or exposed) and clarify the definitions to interest groups of different levels of expertise and origins (farmers and fishermen, scientists, regulators, NGOs, insurers etc.). We aim to develop an ontology for "offshore" and "exposed" aquaculture, encompassing a representation, formal naming, and definition of the categories, properties and relations between the concepts, data and entities that substantiate all domains of discourse (Buttigieg et al., 2013; Arp et al., 2015, 2016).

We argue that a clear interpretation of the terminology will yield the following new advantages to (1) promote a common understanding and avoid misuse of arbitrary classifications which can lead to misinterpretation and confusion among different actors, such as NGOs, licensers, and government agencies; (2) enable regulators to identify the characteristics of a marine aquaculture site; (3) allow farmers to assess or quantitatively compare sites for development; (4) enable developers, equipment suppliers, and producers to identify operational parameters in which the equipment and vessels must operate; (5) provide insurers and investors with the terminology to consistently assess risk and premiums; and (6) circumvent the emergence of narratives that root in different cognitive interpretations of the terminology in public discourse arenas.

3 Illustrating the importance to develop generic geographic terms and quantitative criteria

The urgency as to why such a definition is required has been established however two questions remain to be addressed:: "For whom?" and "Which parameters are needed to clearly differentiate new descriptions from current uses of the term "offshore?" For example, Farmer A is located at an exposed, nearshore site with up to 6 meters (m) significant wave heights, while Farmer B is located at a further distance from the coast but in shallower waters, sheltered and with lower wave heights (Table 1). Farmer A invests in robust design and engineering to survive the strong forces of waves and currents. Farmer B has more of a focus on logistics, smart operational features, and the design and engineering needed to overcome issues related to accessibility of the remote farm. Both farmers see their concepts as challenges, although these are fundamentally different development scenarios. Nevertheless, the two farmers have one aspect in common; they are categorized as being part of "offshore aquaculture". Conversely, if these two farmers engage within, for example policy and licensing procedures, they may warrant very different sets of approval/support conditions under the same "offshore" terminology. This current term's ambiguity causes potential conflicts and disruptions in the communication processes that hamper advancements in the development.

In contrast to the term "offshore", the term "exposed" aquaculture refers to the energetic characteristics of aquaculture sites. Exposed locations are generally understood to be "unprotected" or "not-sheltered" and experience high hydrodynamic energies induced by waves, currents, and winds. Consequently, "exposed" areas can be understood relatively in contrast to "sheltered" areas, as the site has an increased level of

TABLE 1 Representation of the different perceptions of the two farmers "A" and "B".

	Conditions at the farm site (wave height)	Distance from harbor	Investment
Farmer A	Exposed (up to 6 m)	Nearshore	High due to robust system design
Farmer B	Sheltered (low wave height)	Far	Moderate due to existing infrastructure of the shelf, but has to invest in remote operation and in longer travel times[1]

1 = includes additional work hours of personnel.

energy and exposure as it becomes less sheltered. In addition, exposed sites may also be far from land. Thus, the combination of the degree of exposure and the distance from the coast is an important feature. However, what does the term "nearshore" then mean? – and when is a site considered "sheltered"? The explanation to-date is relatively simple and may appear intuitive, but is in fact very complex. Our rationale to explain this type of aquaculture is that all aquaculture that is not "exposed" is "sheltered"; and that all aquaculture that is not "offshore" is "nearshore". One cannot describe terms by listing what they do not mean; i.e., only mentioning its antonym. To provide a basic understanding of how different aquaculture sites can vary in two of these main characteristics, distance to shore and energy of the site, four regions, which are not mutually exclusive, are presented in Figure 1, which show how both degree of energy and the distance from shore describes the characteristics of a site: (1) sheltered (protected), (2) exposed, (3) near to land (nearshore), and (4) far from land (offshore).

We develop an analytical approach that de-emphasizes aspects such as distance from shore that focuses and collates the most influential factors when assessing farmer activities. Therefore use the energy levels at farm sites as a proxy for the degree of exposure of aquaculture installations.

4 The evolution of the definition and interpretation of the term "offshore"

Semantically, the term offshore consists of two elements. The word "off" usually indicates a certain degree of separation between different entities ("away from", "removed from", "separated", "not at" etc.). The term "shore", on the other hand, is most commonly used to describe an area of land that stretches along the edge of a body of water. Merely joining together such relatively straightforward terms, however, does not allow for an objective definition of a specific area at sea. Based on a literal interpretation alone, the exact location, i.e., the geographical line where the shore begins and ends, as well as the distance between that line and a chosen geographical point at sea, lying "off" the "shore", remains open to interpretation. Accordingly, the term "offshore" has been used traditionally in combination with an action or an installation, which was clearly distant from the shore, but at some undefined distance. Similarly, the content of the term "offshore" was also sometimes shaped by legal/regulatory distinctions of a specific country, i.e., federally managed waters opposed to state managed. Intuitively, "offshore" suggested something that was "far away". At the beginning of the 20th century, the term "offshore" was also introduced in the economic realm to describe the relocation of financial assets to other national jurisdictions, i.e., some of the Caribbean Island nations (Suss et al., 2002; Gravelle, 2009; Ogle, 2017). Due to the fact that some of these sites are remote islands used by institutions thousands of kilometers away, the term "offshore" acquired the semantic characteristic to describe something very far away – meaning, out of one's reach or out of sight.

As time progressed, the term "offshore" was also used for the technically rooted exploration and exploitation of marine resources by other economic sectors, for example offshore drilling (Cruz and Krausmann, 2008), offshore oil & gas (Drumond et al., 2018), and offshore hydrocarbons (Makogon, 2010), as well as for other operations, such as offshore servers, offshore wind etc (Blanco, 2009). In particular, the offshore oil industry, with large-scale

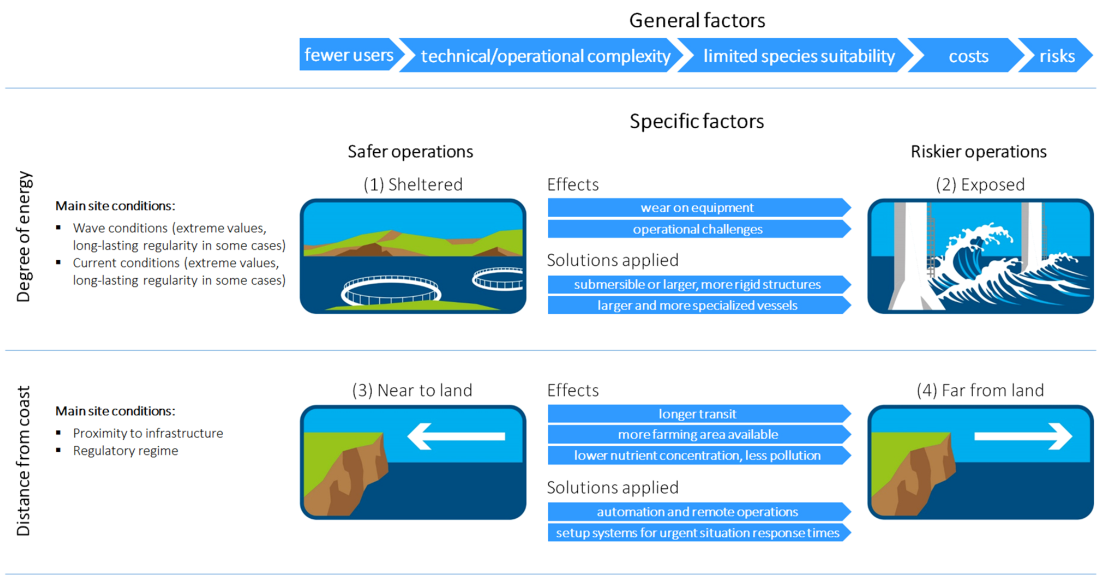

FIGURE 1
Comparison of "sheltered" vs. "exposed" (top) as well as "near to land" vs. "far from land" (bottom) environments along with a selected collection of general and specific descriptions of each.

structures far out at sea, operating at any time of the day or night, armed against all forces of the ocean, with many accessible only by helicopters, emphasizes how inaccessible offshore infrastructures are. However, the basic understanding remains the same, i.e., that all of these operations take place in locations that are geographically distant from the shoreline. Therefore, the main reason for perceiving the term "offshore" with a distance from the coast or an imaginary place far away is due to terminology that is triggered by other offshore undertakings unrelated to aquaculture. This is reflected in the usage of the word "offshore" as a primary or secondary term in published literature.

The Google N-gram Viewer platform is an online search engine that determines the occurrence of any search term based on an annual count of n-grams in printed sources. Using these n-grams, we want to determine in which causal context the term 'offshore' has been used in recent decades. Data shown in Figure 2 are based on Michel et al. 2010 for the period from 1970 until 2019. N-grams with the term "offshore" in combination with another term ("offshore" + "X"), such as offshore wind, offshore aquaculture, offshore bank, offshore gas, as well as other combinations are shown. An N-gram is the result of breaking down a text into individual words or fragments, such as word combinations and counted in frequencies (Bohannon, 2010; Michel et al., 2010; Russell, 2011; Lin et al., 2012). There may be some inaccuracy in the Google N-gram Viewer data, especially since words from books are only counted if there are more than 40 entries. Nevertheless, one aspect of the data set is unmistakable: at the beginning of the 1970s, all activities that took place in geographically remote regions were frequently associated with the term "offshore". For example, the use of the term "offshoring" began in earnest in the 1970s (Metters and Verma, 2008). After a dry spell of about 30 years, the term suddenly became prominent, frequently used to describe the spinoffs of many businesses and company combinations to other countries, typically to leverage cost advantages such as lower labor costs, favorable economic conditions, or tax benefits. There is no question that this term implies "distance". Therefore, the semantic understanding of that term was shaped many years before the combination "offshore" and "aquaculture" was used.

5 Present definitions

Present definitions of "offshore" aquaculture and related terms use various combinations of distance from shore, fetch, wave conditions, and water depth.

The term "offshore" is used differently in different sectors. Most wind farm operators, associate distance with the term "offshore" (Böttcher, 2013). In the US, however, "offshore" wind generally encompasses any wind turbine that is not on land (Madsen and Krogsgaard, 2017). It becomes even more confusing in risk and safety groups, who declare that all areas that are "off" the shore are "offshore", i.e., any amount of separation from the coastline (SOMOS, 2018). Similarly, in international law the term "offshore" does not indicate a specific distance from the shore (Markus, in press). Sailors also like to use the term offshore for those areas where there are severe weather conditions. In US aquaculture, the term "offshore" is often used for areas located outside of state-controlled waters which generally extend to 3 nm. All in all, in the public mind, the term is afflicted with many different confusing definitions. Several distance-based boundaries have legal implications, but none is equated to the term "offshore". The exclusive economic zone (EEZ) is defined in international law as "an area beyond and adjacent to the territorial sea" which may extend up to 200 nm from a coastal states' baseline. The territorial sea may extend up to a limit of 12 nm, i.e. it may cover smaller areas (sometimes reaching 2, 6, or 9 nm into the sea, depending on a country's claims in this regard, e.g., Cicin-Sain et al., 2001). Hansen (1974) summarized the results of a project funded by the US NOAA Sea Grant in 1970 to exploit the oceans away from the coast and defined "Open Ocean Mariculture" as being conducted in unprotected areas, whether near to or far from the shoreline. For offshore kelp farms, Cannon (1980) focused on distance and space; with regard to the US, he defined its EEZ as offshore, i.e., beyond the 3 nm zone and extending outwards to 200 nm. Twu et al. (1986) described "offshore aquaculture" conducted along the southern coast of Korea where, during the winter monsoon, waves could reach a significant wave height of 3 m and wave periods of about 10 s. During summer the entire Korean coastline is found to be

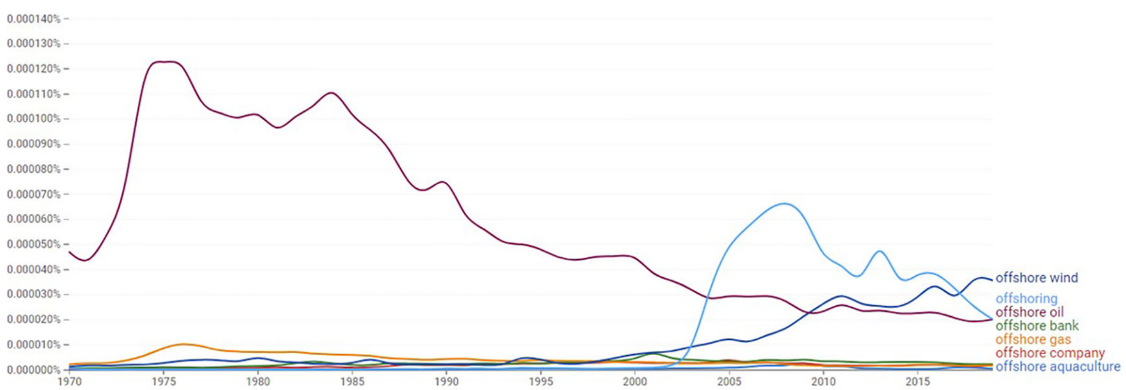

FIGURE 2
Frequency of N-grams in our everyday language used in combination with the word "offshore" in published literature between 1970 and 2019, based on Michel et al. (2010).

vulnerable to typhoon-generated waves of up to 10 m. Muir and Basurco (2000) chose a minimum distance of 2 km from the coast and a depth of 50 m, as well as reduced access due to bad weather conditions (high waves) and the need to incorporate some kind of remote operations such as automatic feeding, remote monitoring, etc. Since the mid-1980s, research on aquaculture in exposed and often distant waters, particularly in the US, increased. Results were communicated to users and other interested parties in a series of four US-based conferences on open ocean aquaculture (Polk, 1996; Hesley, 1997; Stickney, 1998; Bridger and Costa-Pierce, 2003). The first major gathering in Europe took place in Cork (Ireland) in 2004 and was followed by other conferences organised by the European Aquaculture Society (EAS) and workshops (Rosenthal et al., 2012a, b), and a series of events (the Offshore Mariculture Conference by Mercator Media).

The conference in Cork gave rise to a definition based on a four-tier classification system. It equally focused on distance and a lack of shelter but was adapted primarily to the coast of Ireland A modified site classification system originating from the Norwegian Aquaculture Site Classification Scheme and ranging from class 1 (sheltered) to class 4 (offshore), based solely on a site's significant wave weight (Ryan, 2004). Definitions that followed accepted Ryan's definition with additional parameters, such as Drumm (2010) who developed requirements for equipment and servicing vessels to survive and operate in severe sea conditions. HR (2011) used the EEZ to define "offshore". Lovatelli et al. (2013) identified a minimum distance of 2 km (approx. 1.1 nm) from shore and a depth of 50 m and deeper. Bak et al. (2020) defined sites as offshore when located >3nm from the shore regardless of local water depth, while nearshore was defined as <3nm distant from shore, being sheltered in <50m depth and exposed >50m depth. Buck and Langan (2017) and Buck et al. (2018) defined the term "EEZ-Aquaculture" to distinguish it from "coastal aquaculture". These were all valuable attempts at a better explanation and preliminary definition of the terms, but these works still reflect the need to find a more suitable definition, since none of the available definitions provides a clear-cut and holistic view on the multidimensional question of "offshore" terminology. However, despite recent and ongoing developments (EU-funding, development of robust technologies in Norway and elsewhere, conferences on "open ocean aquaculture"), the term "offshore aquaculture" remains unclear. In Table 2, further terms are described, which should serve to complete the common terms related to the location of a farm in the sea. Figure 3 underpins this overview. The need and time are now to define aquaculture in exposed, hostile, and highly energetic environments in greater scientific detail, aiming at multidimensional descriptors that enable state-of-the-art definitions for complex siting questions.

6 Distinction between "offshore" and "exposed", and its relevant parameters

The resulting challenge is how to compile a uniform set of scientific standards from these rather incomplete and legally non-binding definitions. Whether a legally binding definition can develop from this sooner or later cannot be predicted in the current state. This can only be decided once the terminology has been implemented and is therefore not part of this publication. An often-used classification to describe the conditions of a location are its geophysical and oceanographic characteristics and their parameters. Identifying these is complex as different clusters of parameters need to be considered. There are many publications on the parameterization of the term "offshore" or "exposed" aquaculture. Froehlich et al. (2017) examined a wide range of peer-reviewed and grey literature; they made a structured parameter list based on the number of mentioned parameters. But their classification was not unique as additional parameters were identified previously by Hansen (1974), Cannon (1980), Twu et al. (1986), Ryan et al. (2005), Drumm (2010), Lovatelli et al. (2013), Buck and Langan (2017), and Buck et al. (2018).

Figure 4 provides, in six groups, parameters that we have synthesized, and commonly agreed upon in the published literature as suitable descriptors of the offshore character of sites used for aquaculture operations. Parameters are grouped into (1) oceanographic data, (2) descriptors of water column, (3) operation and location parameters, (4) technology, (5) licensing and qualification, and (6) other relevant descriptors. The grouped parameters are weighted or correlated, discussed in depth, and also provide a basis for the additional works presented in this special issue.

Important questions relate to what importance should be given to the different parameters in Figure 4 and which of these are the most crucial for the diverse types of species and farming systems (for example of fish, crustaceans, bivalves, or macroalgae) at a given site. Engineers developing technologies could identify different parameters than those chosen from farmers, insurance companies, lawyers/regulators, or other stakeholders. However, in order to organize a classification, it is necessary to identify different target groups that are active in either "offshore" and/or "exposed" aquaculture. Hence, in order to produce a classification of "exposed aquaculture", the perspectives of different aquaculture related stakeholder groups must be integrated, requiring a multi-actor approach.

There is a plethora of parameters which pertain to the distinction of both "offshore/nearshore" and "exposed/protected" (Figures 1, 4), but these are not intrinsic to a definition. Parameters show trends across these two continuums, but the implications of these trends may vary depending on target culture species, which is important to understand for planning and management. For example, open ocean sites typically have a higher capacity to assimilate nutrients, which can allow for higher stocking densities in cage farming and larger biomasses without significantly increasing the impact on the environment in terms of fed aquaculture (Welch et al., 2019), but may imply different challenges in terms of management of the ecological carrying capacity for extractive species (Filgueira et al., 2015; Smaal and van Duren, 2019). It is therefore preferable to regulate production densities at sheltered and exposed locations differently to maximize the value of the resource. For example, Fujita et al. (2023) point out how SalMar's Ocean Farm 1 plans to measure the effects of their offshore farm on the benthic environment using hyperspectral imaging, a technique that has not been necessary for commercial nearshore farms.

TABLE 2 Further definitions of terms in addition to "offshore" and "exposed", which serve to complete the common terminology in connection with the location of an aquaculture operation in the sea.

Term	Description
Coastal Aquaculture (antonym: EEZ-A[1])	"Coastal aquaculture" describes operations in the coastal sea, usually referred to as the "territorial sea". These areas can range from the coastline to the adjacent EEZ, but mostly refers to nearshore environments. Coastal aquaculture therefore covers a broad area, as it includes all areas where inshore and nearshore aquaculture takes place and, in rather rare cases, offshore aquaculture. Nevertheless, a distinction is generally made between the two terms, namely that "coastal aquaculture" is carried out close to the coast and "offshore aquaculture" in open sea areas further away from the coast.
Inshore Aquaculture antonym: OA[1], OOA[1]	The exact distance that "inshore" is from the coastline can vary considerably and depends on various factors. These vary greatly depending on the user and how "inshore" is used in context. In principle, there is no set distance that is generally considered to be "inshore" as this depends on the particular activity or area of interest. Generally speaking, "inshore" refers to waters that are relatively close to the coast, often not deep, as opposed to "offshore" which describes areas more distant from the coast. However, to be clear about the antonym "offshore", "inshore" should definitely be in the territorial sea and at a short distance from the coastline, as certain parameters stand out in proximity to the coast: (1) control of environmental conditions can be carried out more easily, (2) which leads to a simpler O&M, (3) due to the short distance, the sailing to the farm is of shorter duration, which (4) results in lower costs, and (5) the investment in a more stable technology can be lower, as the weather and wave/current conditions are usually less challenging compared to offshore locations. Often, however, too many farms are built in favorable inshore locations, which in turn exceed the ecological carrying capacity. Inshore activities take place within the coastal sea.
Nearshore Aquaculture antonym: OA, OOA	"Nearshore", like "inshore", refers to operations that take place in waters in the immediate vicinity of the coast. In the context of aquaculture, "nearshore" thus refers to farming activities in water close to the coast, which may be shallower and closer to shore. Again, there is no clear distance to the coastline that can be defined as "nearshore", and this in turn depends on the type of activity. The terms "inshore" and "nearshore" are therefore often used interchangeably but can have slightly different meanings depending on the context. However, there may be some differences: While "inshore aquaculture" can refer specifically to waters that are very close to shore, possibly in shallow bays, estuaries or intertidal zones, "nearshore aquaculture" would encompass a slightly wider spatial area and refer to waters that are relatively close to shore, but not necessarily as narrowly defined as "inshore". The same applies to water depth, as "inshore" is often defined as having a shallower water depth. "Nearshore" could therefore refer to waters that may be slightly deeper but are still close to the coast. It is important to note that these terms can be interpreted differently in different regions and contexts. In many cases, they are used as interchangeable terms to generally refer to the proximity of aquaculture activities to the coast. Nevertheless, "nearshore" aquaculture would arguably be located behind "inshore" aquaculture when viewed from the coastline, possibly with some overlap. As shown in Figure 3, "nearshore" activities take place within the territorial sea.
Foreshore Aquaculture (antonym: OA, OOA, EEZ-A)	The term "foreshore" refers to the part of a sea and shore area that lies between the high and low tide line, i.e. the eulittoral zone in the classic sense. Aquaculture is thus practiced in this zone, which is exposed to the tides (for example some oyster farms and pile cultures for mussels). "Foreshore" activities take place within the coastal sea (see Figure 3).
Onshore (antonym: any other term defined here)	"Onshore aquaculture" is synonymous with land-based aquaculture and refers to any farm that is located on land or within a fairly small water body (i.e. ponds, but not lakes). This includes indoor farms (RAS[1], pRAS[1], or flowthrough) or outdoor farms (ponds or raceways). The size of waterbody that would differentiate onshore aquaculture from production in a lake or other enclose water body is outside the scope of this article.
OOA (antonym: inshore, coastal, nearshore aquaculture)	"Open Ocean Aquaculture" (OOA) refers to the farming of aquatic species that takes place in open oceans, as opposed to traditional methods that are carried out near the coast or in protected marine water bodies. Very often, these areas are deeper than those in the in- or nearshore. OOA aims to utilize the space beyond coastlines to enable the production of marine organisms with high biomass yields. In contrast to coastal aquaculture facilities, where environmental impacts and space constraints can play a role, open ocean aquaculture potentially offers more space for the cultivation of the farmed species organisms. There are challenges and concerns associated with OOA, including environmental impacts, potential effects on wildlife populations, seabed pollution and social acceptability issues. The terms "open ocean aquaculture" and "offshore aquaculture" are often used interchangeably, but may have slight differences depending on the specific context. In general, both refer to aquaculture in open waters, far from the coast, however, there are some differences: From a spatial perspective OOA emphasizes farming in the open oceans, in most cases very far from the coast and beyond the 12 nm zone. The term "offshore aquaculture" refers to a shorter distance from the coast, which we believe should be set at 3 nm. This means that, in some countries, "offshore aquaculture" can take place in the territorial sea, beyond the 3 nm mark and up to 12 nm. Regarding the depth, OOA specifically targets farming in deep waters characteristic of open oceans, while "offshore aquaculture" can be conducted in both, relatively shallow or deeper areas.
EEZ-A (antonym: coastal aquaculture)	EEZ aquaculture" describes aquaculture activities in the exclusive economic zone. In countries where the EEZ begins 12 nm seawards from the baseline close to coasts, efforts to practice aquaculture are more in the research status. A special type of aquaculture here is the combination of offshore wind farms (OWF) and aquaculture, which is known as "multi-use". In those countries, for example the USA, where the EEZ lies either 3 or 9 nm off the coasts (baselines), there are already commercially operated aquaculture farms.
Sheltered (antonym: exposed aquaculture)	"Sheltered aquaculture" refers to aquaculture activities that take place in protected or sheltered water bodies. These environments offer natural or artificial protection from the effects of strong currents, high waves, tidal influences or other extreme environmental conditions. Shelter can be provided by location (bays, lagoons, etc.), by natural structures (islands, reefs, etc.) or by artificial structures (piers, harbors, etc.). Often the term "protected" is used as a synonym, but this leads to misunderstandings, as "protected aquaculture" can also mean (1) that special measures are taken to protect the environment from the potential impacts of aquaculture, and (2) that aquaculture activities are protected by special laws or regulations to ensure that they are operated sustainably and have no negative impact on the environment or other interests. To avoid this uncertainty, aquaculture that is protected by its location should be labelled exclusively as "Sheltered Aquaculture". These activities take place predominantly in the coastal sea.

[1]EEZ-A, Exclusive economic zone aquaculture; OA, Offshore Aquaculture; OOA, Open Ocean Aquaculture; RAS, Recirculating Aquaculture System; pRAS, partial Recirculating Aquaculture System.

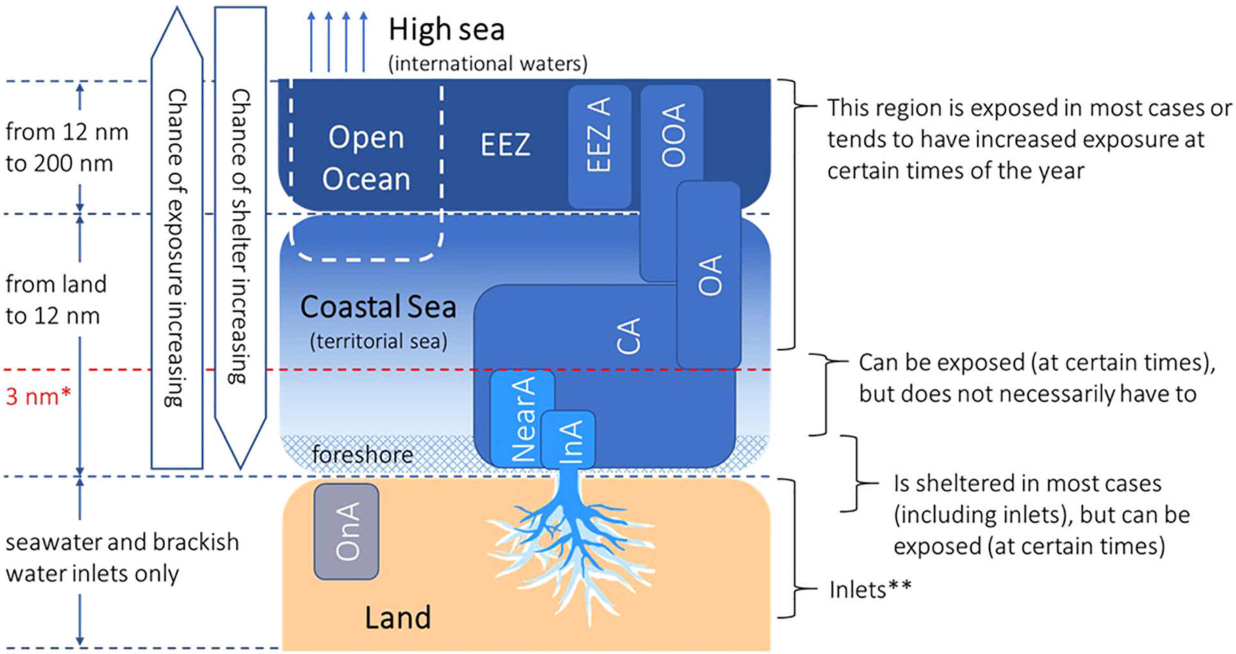

FIGURE 3
Illustration of the different aquaculture terms that have to do with a location description. * = red dotted line shows where the offshore area starts towards the open ocean; ** = by "Inlet" is meant any kind of body of water as an arm of the sea inland, such as fjords, bays, estuaries, lagoons, etc.; CA, Coastal Aquaculture; EEZ, Exclusive Economic Zone; EEZ A, EEZ Aquaculture; InA, Inshore Aquaculture; NearA, Nearshore Aquaculture; OA, Offshore Aquaculture; OnA, Onshore Aquaculture; OOA, Open Ocean Aquaculture.

Establishing definitions that allow for the clear partitioning of sites as one category or another also enables the analysis of trends in other parameters across the spectrum of site types. Parameters that describe the water column with reference to species suitability, such as oxygen (particularly important for fish), chlorophyll (secondary site quality characteristic for filter feeders, such as mussels and oysters), nutrient concentrations (relevant for macroalgae) or temperature (all species), are essential in the context of site selection criteria studies for the evaluation of the biological production potential and must never be neglected. Nevertheless, these parameters are not the typical barriers to practicing aquaculture in relation to "offshore" or "exposed" environments (even though we know that nutrient concentrations, for example, can decrease with distance from the coast to the open ocean in many marine bodies of the world, e.g., Cravo et al., 2003; Aziz et al., 2019). Similarly, "other factors" (see Part 6 in Figure 4) should not be underestimated, as fouling (Bannister et al., 2019; IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships, 2020), predators (Freeman, 1996), or conflicts (Buck et al., 2004; Hipel et al., 2018) with other users are known to have a significant effect on the success of aquaculture operations in nearshore and/or protected areas. Additionally, the concept of synergies in terms of multi-use (for example, offshore wind farms [OWF] and aquaculture) of areas is of increasing interest globally (Buck and Langan, 2017) and, in particular, low-trophic aquaculture (LTA) in OWF can make a significant contribution to achieving the Sustainable Development Goals of the United Nations (Maar et al., 2023; Troell et al., 2023).

Similarly, other parameters in Figure 4 all have their specific importance for the success of a commercial aquaculture farm, but are more general than specific to offshore or exposed areas. In the first instance, a site is defined according to the most important parameters (depth, wave height, current velocity) that will determine how it is farmed, distance from shore and energy environment (i.e., classified as "offshore/nearshore" and "exposed/sheltered"). It is important to characterize and describe the site according to all the other parameters afterwards, as they will still impact the suitability of the site and the species and equipment chosen to farm there.

This work has surfaced and is agreed upon amongst a substantial number of authors from various disciplines, the two parameters "wave" and "current" in all their facets (height, frequency, velocity, direction). It is therefore necessary to work out a way to use these parameters as a basis to discuss a definition of the terms. Although it is known that the depth of a site will have a significant effect on the expression of the wave (Lojek et al., Heasman et al., in press), we consider the depth as a secondary effect in this publication, as the wave data itself is sufficient to describe the degree of exposure of the site.

7 Discussion

Members of the ICES Open Ocean Aquaculture Group (WGOOA; ICES, 2024) have defined a terminology to distinguish "offshore aquaculture" from "exposed aquaculture" more precisely by developing an index that better describes the degree of exposure (see Lojek et al., in press). We suggest that the definition of "offshore" versus "nearshore" and "exposed" versus "sheltered" be defined exclusively according to the distance from shore based on visibility and the wave and current conditions respectively, creating discrete categories for

(1)	No.	Parameter	Effect mode
Oceanographic data	1.1	current velocity	direct
	1.2	wave action	direct
	1.3	wave variation	direct
	1.4	wave period	direct
	1.5	wave direction	direct
	1.6	wind speed / fetch	direct
	1.7	depth of seabed and farm position in the water column	direct
	1.8	degree of exposure	consequence

(2)	No.	Parameter	Effect mode
Water column	2.1	oxygen	indirect
	2.2	pH	indirect
	2.3	temperature	indirect
	2.4	salinity	indirect
	2.5	plankton	indirect
	2.6	nutrients	indirect
	2.7	sediment load	indirect

(3)	No.	Parameter	Effect mode
Technology	3.1	system design	consequence
	3.2	technical complexity	consequence
	3.3	wear on equipment	consequence
	3.4	materials used	consequence
	3.5	ecosystem-friendly material	consequence
	3.6	life expectancy of material	consequence
	3.7	buoyancy type	consequence
	3.8	mooring	consequence
	3.9	submersible modes	consequence

(4)	No.	Parameter	Effect mode
Opeartion & location	4.1	smart operations	consequence
	4.2	larger/specialized vessels	consequence
	4.3	remote monitoring	consequence
	4.4	distance and transit time	none
	4.5	farm size	none
	4.6	multi-use of offshore sites	none
	4.7	IMTA	none

(5)	No.	Parameter	Effect mode
Licensing & qualification	5.1	health & safety training	consequence
	5.2	specialized diving operations and requirements	consequence
	5.3	emergency preparedness	consequence
	5.4	special qualification for personnel	consequence
	5.5	offshore certification of vessel, personnel, equipment	consequence

(6)	No.	Parameter	Effect mode
Other factors	6.1	predators	indirect
	6.2	pathogens	indirect
	6.3	carrying capacity	consequence
	6.4	biofouling	consequence
	6.5	species choice	consequence
	6.6	nutrition/feed	consequence
	6.7	stakeholder/user conflicts	consequence
	6.8	pollutants/contaminations	indirect
	6.9	visibility from shore	consequence
	6.10	costs	consequence

FIGURE 4
Parameters/factors that will impact performance and characteristics of aquaculture carried out in "exposed" and/or "offshore" waters. Parameters were extracted from the common literature (e.g. Hansen, 1974; Cannon, 1980; Twu et al., 1986; Ryan et al., 2005; Drumm, 2010; Lovatelli et al., 2013; Buck and Langan, 2017; Froehlich et al., 2017; Buck et al., 2018) and coincide with the authors' experience of carrying out aquaculture in exposed and/or remote locations.

each term. We establish clear site descriptions as an "exposed-offshore site", and an "exposed-nearshore site". Other adjectives describing different parameters (such as temperate or oligotrophic, high/low saline or eutrophic, etc.) would only be applied during specific discussions evaluating the site.

As part of a more accurate description on exposure, the physical attributes can now be associated with engineering (structural requirements, robustness of equipment, vessel design, technology); logistics (requirements to operate in that physical environment); biology (potential cultivated species at the site); health and safety (improved requirements, vessel/equipment design and automation); operations and management (vessel size, site access and visit frequency, seeding and harvest windows); social and environmental license (acceptability associated with the site); economics (cost of engineering, logistics and production relative to species yield and value) and policy and regulation (all the above) are more tangible.

Finally, we want to clarify the question of what should be understood by the term "offshore aquaculture". How can the term be defined, and what does this mean for current and future aquaculture?

In addition to all these facets, there is always the idea that the distance a service vessel has to travel from the port to the aquaculture operation should be considered in the "offshore" definition. After all, long travel distances play a significant role in the economic feasibility of an aquaculture enterprise, which are influenced by high costs incurred by staff, fuel, etc. Thus, long distance travel routes to the farm site may also be due to designated shipping routes, where vessels rarely reach a destination via the bird's-eye route, but take longer due to other navigational barriers such as shoals, rocks, nature conservation areas, intensively used commercial shipping routes, etc. An aquaculture enterprise can be 500 m off the coast but many nautical miles from the nearest port "offshore"? Here we need to understand an essential difference between "long travel time" and "offshore", because "offshore" is precisely "off the shore", i.e., for example a few kilometers perpendicular to the coastline, and should not be confused with "off-port", i.e., several kilometers away from the port. So how do we classify, for example a shellfish operation far from the harbor, which is in fact only 500 m off the coast, and, how do we distinguish it from those that exist, for example, several nautical miles towards the "open ocean"? In this case, we would call the site that is 500 m away from the coast "inshore", "near the coast" or "nearshore", because only the distance to the port is the cost driver here, not the distance to the sea. Here, the 500 m specifies the degree to which the farm is offshore, not the distance to the harbor. One exception to this guiding principle is proximity to small islands that do not provide any meaningful operational advantage. A site that is far from the mainland but near to some small, uninhabited islands, or where these islands have no influence on operations (landing of products, crew changes, bunkering, etc.) could still be considered offshore.

A definition that would make the most sense for us to apply is a farm that is operated out of sight - and from our point of view this farm is "offshore". Of course, this kind of approach depends on many factors, namely how high the farm's superstructure is, for example a mussel backbone vs. Ocean Farm 1 (Buck et al., 2018) or the height of the person standing on the beach and looking towards the sea, because stature certainly conditions how far a person can see - especially if, opposite a calm sea, a wave now integrates, which can block the view. A range could be given based on an average human height of 159 to 170 cm and an average height of aquaculture facilities (100 cm), so the calculated distance for a facility out of sight would be approximately 3 nm, based on an observer standing at sea level at the edge of the coast (see Figure 3). This definition does not employ a highly technical approach as is taken with the "exposure" definition, but this is appropriate for "offshore" since it is already in use by a larger number of different stakeholders and has a less direct impact on farm operations, equipment choice, and economics. If the term "offshore" is used it should refer to the distance only, unrelated to the requirements of an aquaculture site and/or the exposure of that specific site. Further, the effort to measure and communicate the precise distance of a farm from shore is not excessive (for example Farmer A can describe their farm as "an exposed farm that is for example 8 nm from shore"). As such, a precise and consistent use of the term is less necessary, yet still provides value to a maturing industry that needs to partition and discuss its sub-sectors.

The 3 nm distance is also used in many legislative contexts. It is consistent with the historical limit of territorial seas under which many countries recognized control up to 3 nm from the baseline from the 1600s until the 1958 Geneva Convention on the Territorial Sea and the Contiguous Zone (Swarztrauber, 1970). This 3 nm limit still separates state and federal waters in the USA, where waters beyond this limit are legally the "Outer Continental Shelf" (BOEM, 1953).

8 Conclusions and recommendations

The previously used definitions or characterizations of "offshore" or "open ocean" aquaculture have been unable to be established as generally accepted definitions. While some terms were established to demonstrate a particular point at sea or create a framework for analysis, they were never intended nor adequate for widespread adoption (Lovatelli et al., 2013; Morro et al., 2021). Therefore, the question arises how this newly proposed terminology will be adopted by the various user groups (farmers, scientists, engineers, insurers, NGOs, etc.; see Section 2) or, at best, be accepted. The need for a clearly defined terminology stems from those user groups, as a precise universally accepted, standardized definition has been unresolved for decades and consequently terms have been used somewhat arbitrary (Buck and Langan, 2017; Froehlich et al., 2017).

We present a strict definition of "exposed" aquaculture primarily focused on the physical attributes of a site and the parameters of "depth", "waves", and "currents" in all their facets are considered to be the principal considerations. The effects of all other factors characterizing a site (see Figure 4) are considered subordinate to these oceanographic parameters. Thus, this work advocates that the terms "exposed/sheltered" can be defined in such a way that discussion about the nature of the site in question is unambiguous. In contrast, such understanding enables the terms "offshore/nearshore" to be utilized more accurately to simply describe a farm's distance from shore. Consequently, an "offshore" site with a certain degree of exposure, must be described using both terms: i.e., a site that is far from the coast and additionally exposed to harsh weather conditions is an "exposed offshore" site. In conclusion, although we maintain that "offshore" is a continuum, which can be quantified, we recommend that whenever a specific threshold must be defined, a distance of 3 nm from shore (not port) should be used (Figure 3).

The establishment of specific definitions for these terms, particularly to distinguish "exposed aquaculture" from "offshore aquaculture", comes at an appropriate and crucial time in industry development, as there are several open ocean farms operating in different regions of the world today. Though, the continuous implementation of term dissemination can only be achieved through an ongoing dialogue and a common roadmap orientated towards stakeholder/user groups and has to (1) go far beyond scientific publications, (2) support and awaken an understanding for the introduction of this terminology, and (3) use and disseminate the defined terms correctly at different levels (ICES, FAO, NGOs, peer-reviewed and grey literature, research projects and reports, company catalogues, technical and conferences papers, and many more).

Our vision for where and how the industry will continue to develop is well established, based on a substantial amount of real-world experience, and reflects empirical data that is oceanographic, operational, and financial in nature. Significant growth is anticipated in most of these regions which will need to be supported by focused R&D efforts (and funding opportunities), regulatory environments that encourage such growth, and interactions between various stakeholders which can be facilitated by specific and well-defined terminology. We hope that these definitions and the discussion presented in the Special Edition will be useful in progressing the collective understanding of aquaculture in exposed sites, the environments that this industry sub-sector operates in, and the challenges and opportunities created.

Finally, the question arises as to how this new terminology, as we understand and propose it, will reach the various user groups (farmers, scientists, engineers, insurers, NGOs, etc.; see Section 2) and, at best, be accepted. It is important that the user groups understand the motivation behind the steps we have taken, as this is the only way that the terms will become part of the general linguistic usage of these user groups in the future.

Firstly, it should be emphasized that the need to give the terms a clear definition stems from these user groups themselves. The question of a precise universally accepted, standardized definition has been unresolved for decades and the use of the terms has been somewhat arbitrary for just as long (Buck and Langan, 2017; Froehlich et al., 2017).

Nevertheless, there needs to be a common roadmap for how the user groups (1) learn about these efforts (not every user reads scientific publications), (2) support the understanding of this terminology, and (3) use and disseminate the defined terms correctly at different levels (ICES, FAO, NGOs, journals and grey literature, research projects, reports, company catalogues, technical papers and conferences, and many more) in the future.

The solution can only lie in the continuous implementation of term dissemination, and acceptance can only be achieved through an ongoing dialogue at the above-mentioned levels. The process will certainly take a few more years, but the foundation has been laid and will be disseminated, at least among the authors of this article.

The authors understand if some stakeholders find it difficult to accept or apply this terminology. Many farmers farm and do not go into the clarification of terms. Costs may also be incurred if, for example, print media has to be changed or advertising adapted. Nevertheless, we want to encourage the industry to develop an understanding of why terminology is important (see Section 2). Understanding comes first; direct implementation can follow.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

BB: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Writing – original draft, Writing – review & editing. HB: Writing – original draft, Writing – review & editing. AB: Writing – original draft, Writing – review & editing. MC: Writing – original draft, Writing – review & editing. BC-P: Writing – original draft, Writing – review & editing. TD: Writing – original draft, Writing – review & editing. JF: Writing – original draft, Writing – review & editing. HM: Writing – original draft, Writing – review & editing. DF: Writing – original draft, Writing – review & editing. NG: Writing – original draft, Writing – review & editing. JH: Writing – original draft, Writing – review & editing. WI: Writing – original draft, Writing – review & editing. GK: Writing – original draft, Writing – review & editing. TM: Writing – original draft, Writing – review & editing. NP: Writing – original draft, Writing – review & editing. TS: Writing – original draft, Writing – review & editing. BS: Writing – original draft, Writing – review & editing. ÅS: Writing – original draft, Writing – review & editing. MT: Writing – original draft, Writing – review & editing. DW: Writing – original draft, Writing – review & editing. SV: Writing – original draft, Writing – review & editing. KH: Writing – original draft, Writing – review & editing.

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Conflict of interest

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Synthesis of multinational marine aquaculture and clean energy co-location

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Marine co-location, i.e., multiple fixed ocean activities operating in the same place and at the same time, can maximize the space- and resource-use efficiency in crowded seascapes. While interest grows, commercial use is nascent and the collective benefits or limitations of co-locating aquatic food and clean energy remains scattered throughout the literature. In this study, we synthesize multinational findings of co-location scientific publications (N = 102) to better understand the patterns and knowledge gaps at the co-located ocean food-energy nexus. We track and compare food (aquaculture) and energy (tidal, offshore wind, and wave) co-located ocean activities, noting the focus (e.g., ecological), motivation (e.g., impact/risk), and assessment type (e.g., modeling), as well as nine key metrics of interest (depth, distance from shore, aquaculture yield, etc.), mainly for aquaculture co-location. We found the number of annual co-location publications increased over time and space but are largely concentrated in the North Sea (n = 39). We also found about half of publications include aquaculture, one-third of publications report at least one metric – reporting aquaculture yield was particularly rare (n = 1) – and few studies focused on impact/risk (n = 7). However, conducting a targeted *post-hoc* evaluation of North Sea gray literature (N = 61), due to this region's importance in the field, showed more coverage of impacts/risk (e.g., liability) and similar attention to aquaculture. Of the scientific papers that did report metrics, the ranges of depth and distance exceeded those reported for standalone sectors, indicating co-location could be facilitating a "push" of ocean activities into farther offshore and/or deeper exposed waters. Ultimately, while aquaculture is commonly cited in the co-location literature, the shortage of metrics, like aquaculture yield, and possible impact/risk evaluations – though gray literature can provide critical insights – emphasizes the need for knowledge sharing and modeling to address and explore the uncertainty, especially for co-located aquaculture production. This study provides a needed snapshot of marine co-location, particularly in emerging regions, highlighting gaps in understanding aquaculture-energy potential in the oceans.

KEYWORDS

co-location, offshore aquaculture, marine spatial planning, renewable energy, multi-use

1 Introduction

Globally, there is a growing need for ocean space for the expansion of renewable energy and aquatic food production (McCauley et al., 2015; Lester et al., 2018a; Jouffray et al., 2020; FAO, 2022; GWEC, 2023). However, marine waters are already congested with competing and often opposing sectors, challenging new and/or less prioritized sectors to “fit in” (Tiller et al., 2013; Bull and Love, 2019). The emergence of ocean-based clean energy and seafood sectors could usher in a new era of sustainable and synergistic marine use and management (Lester et al., 2018b; LiVecchi et al., 2019). On the other hand, poor planning of this transition could lead to a breakdown of ocean industries, cascading environmental threats, and the displacement of jobs, both locally and globally (Halpern et al., 2008; Lester et al., 2013; O’Hara et al., 2021). For busy seascapes to sustainably maintain or expand a “blue economy” (Smith-Godfrey, 2016), research must be conducted to shed light on how the various ocean sectors interact, highlighting areas of synergy and discord.

Aquaculture is increasing in significance on the global food stage, now exceeding wild capture fisheries in total volume (Costello et al., 2020; FAO, 2022). However, how to make space in the ocean for marine aquaculture – along with other ocean sectors – is becoming a more widespread question (Sanchez-Jerez et al., 2016; Gentry et al., 2017; Lester et al., 2018a; Couture et al., 2021). Offshore or more exposed aquaculture presents an opportunity to expand aquaculture farther into ocean waters, while also potentially reducing impacts, such as water quality issues and disease (Holmer et al., 2008; Price et al., 2015; Froehlich et al., 2017). Here “offshore” is specifically distance based (i.e., far from shore), which differs from “exposed” or “open ocean”, which can experience high energy conditions (e.g., large waves and/or strong currents) but are still close to shore (see Buck et al., 2024 for definition details). Regardless, aquaculture farther from shore has struggled to establish itself in many regions, such as the United States (Lester et al., 2018b; Fujita et al., 2023) – a large seafood consuming, but low aquaculture producing country (FAO, 2022). As a result, some research has aimed to create solutions to help make space for farming in the oceans (e.g., Sanchez-Jerez et al., 2016; Gentry et al., 2017; Lester et al., 2018a) that allows for aquaculture expansion, while minimizing effects on the marine environment and existing ocean stakeholders.

Co-location of ocean activities has the potential to be a tool that increases the value of a region while reducing trade-offs to stakeholders and the environment by using ocean space more efficiently. Historically, investigations into synergies between ocean sectors have taken different forms. Several studies have been conducted that investigated the relationship and potential opportunities for synergy between fisheries and marine energy (de Groot et al., 2014; Stelzenmüller et al., 2016; Kyvelou and Ierapetritis, 2020). Some relatively recent research on co-location of marine energy and aquaculture systems has been explored (O’Donncha et al., 2017; Di Tullio et al., 2018; Weiss et al., 2018), including potential environmental risks (Benjamins et al., 2020; Demmer et al., 2022). While research into the benefits and tradeoffs associated with co-locating ocean activities is increasing, there is a lack of consistency on how best to define “co-location” (Schupp et al., 2019), which creates uncertainty in management processes, as well as a potential lack of comparative environmental metrics. As aquaculture begins to expand farther from shore and potentially alongside other sectors, a deeper accounting of the current pace and status of the science can help inform knowledge gaps and next steps. Importantly, a more holistic evaluation of existing studies may provide a useful lens to assess the coverage of the standing literature.

Integrating aquaculture around other existing and developing ocean activities requires an accounting of multiple human and ecological dimensions. An ecosystem-based approach to aquaculture (EAA) is an existing planning framework designed to position aquaculture more compatibly within its surrounding ecosystem and reduce competition for space in the ocean, calling for the explicit consideration of ecological, social, and governance aspects of development (Soto et al., 2008; Byron and Costa-Pierce, 2013). Notably, EAA aims to balance competing needs and stakeholders, while also protecting the marine environment that supports them. While there are often obstacles to employing EAA (Brugère et al., 2019), understanding the upper and lower limits of aquaculture in a particular site can be useful in developing long-term and sustainable aquaculture systems. To determine limits, carrying capacities can be evaluated through four dimensions of aquaculture development: physical, production, ecological, and social (McKindsey et al., 2006; Ross et al., 2013). Assessing measures of physical carrying capacity (e.g. depth, distance from shore) are used to inform initial siting potential of a given location. This is typically the first step of any development, aquaculture or otherwise (Ross et al., 2013; Froehlich et al., 2017; Lester et al., 2018a; Morris et al., 2021; Garavelli et al., 2022). Similarly, evaluation of production (e.g., yield), social (e.g., public perception) and ecological (e.g., impact) carrying capacity measures provide guidance for aquaculture development under EAA (McKindsey et al., 2006; Ross et al., 2013). Notably, this approach emphasizes reducing aquaculture impact across all aspects, including underscoring the importance of equity. Ultimately, these dimensions offer an informative structure to assess the breadth and depth of co-location science through an aquaculture lens. Recently, Guyot-Téphany et al. (2024) assessed ocean multi-use – which we argue is a broader definition within which co-location resides (see *Methods* for our definition) – over the past two decades, comparing the studies to those of multiple-use marine protected areas and marine spatial planning (MSP). Although informative, a quantitative synthesis of co-location from an EAA perspective is missing from the literature – particularly the metrics that inform the four carrying capacities.

This study aims to provide a current snapshot of the standing marine co-location literature, especially as it relates to ocean-based aquaculture. The quantitative review is aimed at providing a comprehensive understanding of the research knowledge and gaps – including motivations, methods, and numeric values (Table 1) – as well as potential benefits and limitations to future co-location development. Importantly, we draw on broad EAA themes, exploring regional comparisons and quantifiable measures, including depth and distance to shore and how they compare to the respective standalone industries (i.e., without co-location). We also

TABLE 1 Lists the categories and measures that were extracted from publications.

Category	Measure	Definition	Example
Focus*	Ecology	Topics addressing the structure, dynamics, and functions of the ecosystem.	O'Donncha et al., 2017; Serpetti et al., 2021
	Governance	Focusing on permitting, regulations, or policy information.	Stuiver et al., 2016; Bocci et al., 2019
	Socioeconomic	Discussing financial, perception, or behavioral data.	Wever et al., 2015; Sie et al., 2018
Motivation	Horizon Scanning	Identifying early signs of opportunity and potential future development.	Lacroix and Pioch, 2011; Green et al., 2019
	Industry Development	Evaluation of techniques that could optimize industry and system output.	Shawon et al., 2013; Lagasco et al., 2019
	Impact/Risk	Measures and discusses environmental responses and social issues that could result from development of co-located systems.	Onea and Rusu, 2015; Banach et al., 2020
Assessment Type	Review	Compiles and reports findings of other published literature.	Buck et al., 2008; Schupp et al., 2019
	Model	Conceptual, statistical, and process-based modeling.	Benassai et al., 2014; Gimpel et al., 2015
	Pilot/Testing	Creates and reports observational and lab-based data.	Buhagiar et al., 2019; Konispoliatis et al., 2021

* Indicates a category that is cross-cutting, meaning that a publication could apply to more than one measure.

provide a more in-depth assessment of the specific marine aquaculture co-location metrics and trends. Finally, we identify key research opportunities needed to advance the field.

2 Methods

Literature on co-location was compiled by conducting a search of the following five terms: "offshore co-location", "marine co-location", "marine multi-use", "marine renewable energy", "offshore co-management". The initial literature search was conducted in February 2021 and a secondary search was conducted in February 2023, both using the Web of Science (WOS) search engine. We defined co-location in this scenario as "two or more ocean activities occurring in the same place and at the same time" (Schupp et al., 2019), and more specifically those that are largely stationary with built infrastructure, i.e., excludes shipping, wild capture fisheries, etc. However, many papers included in this corpus were published prior to this definition. Therefore, we refer to many publications as being "co-location", even though they might use a somewhat different terminology (e.g., multi-use, co-siting). Included publications were limited to those published between the years 2000 and 2022 because we observed no publications that fit our definition of co-location were published prior to 2000. The initial search yielded 2,308 publications, which were filtered to only include those containing key factors of co-location, as defined for this study. Any papers that were limited to discussion of only engineering parameters of specific infrastructure were not included. This search only included papers written in English, which will bias our results towards English-speaking regions and audiences. Further, only papers discussing marine environments were considered for this analysis. A vast majority (98%) of the literature returned in the initial search did not meet these criteria.

The filtering process yielded a smaller corpus of 102 papers. Every paper was read in its entirety to understand the full context. Selected publications were sorted into three categories, by their focus: ecology (n = 47), governance (n = 38), and socio-economics (n = 59), based on the category definitions in Table 1. These categories reflect the broader themes of sustainability and the EAA framework previously described (Ross et al., 2013). Given the interdisciplinary nature of the field, it was common for papers to encompass more than one category and thus the same paper could be placed into multiple categories. Therefore, the summation of each category per year will not equal the total publications in that year. We also documented the motivation (i.e., horizon scanning, industry development, and impact/risk) and assessment type (i.e., review, model-based, or pilot/testing) to discern the stage of development globally. Comparisons were made between categories over time to determine trends in publications of co-location research, particularly any gaps. The data were natural-log transformed and a linear model was fit to examine the relationship between the average publication rate of co-location literature over time.

We also sorted papers into which specific activity was evaluated in each paper (aquaculture = 50, tidal energy = 23, wave energy = 58, wind energy = 89, or other = 39) to identify trends in which activities are most commonly co-located. We define "activity" in this study as being any human-led action in marine waters in a co-location context. The "other" activity designation was assigned to publications that discussed co-location beyond the four primary activities of this study, such as solar energy or desalination. Again, this distinction was crosscutting and publications were often assigned to multiple activity categories. Fisheries co-occurring with energy or aquaculture were not considered as "co-location" in this study. While we see fisheries as an important sector to include in assessments of multi-sector ocean planning, this study was centered on understanding co-location as a tool in sustainable ocean development. Therefore, we did not include fisheries activities in this particular study due to (1) it being a well-established, incumbent industry (Pauly, 2008) and, thus, falling outside of our definition of "development" and (2) the transitory nature of wild capture fishing sets it apart from more permanent, stationary fixtures being developed in ocean spaces, such as aquaculture and energy systems, which are the focus of this study.

For publications that were location or regionally specific, the Large Marine Ecosystem (LME) where the study was focused was recorded. The LME scale was selected because it allowed for grouping of trends across different ocean areas. Regional comparisons helped identify where certain locations were more commonly referenced in co-location literature. We also extracted a series of measures from each publication, depending on which category they were assigned (Table 1). Metrics included in each focus category were identified based on their availability in the literature and relevancy to the ocean activities being addressed in this study. We also compared some of the most commonly reported metrics (distance and depth) in the co-location articles to review-based publications that report on the same metrics, but for the standalone sectors (e.g., aquaculture not co-located). This comparison helps capture how co-location fits into single sector development. In particular, how co-location may be constraining or pushing the respective sectors' "normal" operational limits.

Finally, an aquaculture-specific analysis was conducted to understand how co-location of activities might help or hinder aquaculture expansion, specifically. The publications that fell into this category did so because they explicitly listed aquaculture as being a sector that either is being co-located or could potentially be co-located with another ocean sector. Where possible, the following additional metrics were recorded from publications, due to their relevance to aquaculture infrastructure and species growth: depth (m), distance to shore (km), current velocity (m/s), significant wave height (m), sea surface temperature (C), chlorophyll-a concentration (mg/m^3), species/taxa, production (tons/year), and yield (production/area). Metrics were recorded as representative as possible. In many instances, studies reported a general range, in which case the maximum and minimum values were recorded in addition to the average value of that range. In other cases, only a single value was reported.

The metrics chosen for this study were due to their importance in aquaculture suitability based on the four carrying capacities within the EAA framework (McKindsey et al., 2006; Ross et al., 2013; Buck et al., 2024). Depth and distance can be restricted based on cost or technological limitation. The measures are also pertinent to impacts on the benthos, with greater distance and depth typically reducing impacts (Froehlich et al., 2017). Similarly, wave height and current can prove too strong or weak, balancing infrastructure capacity and environmental interactions, respectively. Sea surface temperature, chlorophyll-a, and taxa are particularly critical from a biological perspective and are basic forms of information necessary to determine aquaculture suitability. Lastly, and relatedly, yield provides a unifying measure of productivity over space, time, and taxa (Fong et al., 2024; Kebede et al., 2024). In addition, we did a qualitative review of these papers, highlighting common themes among them, including mentions of disease, contamination, and regulation, informed by the standing aquaculture literature (Galparsoro et al., 2020). We also highlight studies that report on the most extreme cases and critically assess the robustness of that research.

3 Results

3.1 Publication trends

The publication of co-location literature has increased over time, with only a slight emphasis of the articles being socioeconomic focused more recently (Figure 1A). Co-location research historically had a low publication rate from 2000 to 2013 (2 publications per year), after which publication rate steadily increased until 2017 (14 publications per year) (Figure 1A). In fact, this period of growth (2013–2017) tripled the rate of annual publication before plateauing during the years 2018–2022 (10–14 papers per year) ($R^2adj = 0.84$). Socioeconomic papers accounted for 58% of the studies, while governance (37%) and ecology (46%) were slightly less. Of note, almost half of the socioeconomic papers (41%) evaluated social dimensions, such as social perception (e.g., Wever et al., 2015; Jhan et al., 2022), which can be a dominant factor in determining the capacity for development in some regions (e.g., Byron and Costa-Pierce, 2013). But in general, over time all categories reflected relatively similar patterns, which is a somewhat promising trend from an EAA perspective because it suggests that knowledge is being garnered across the suite of aquaculture carrying capacities (Figure 1B).

Although broader ecosystem themes were relatively equivalent, study motivation differed substantially, with "Horizon Scanning" (50%) and "Industry Development" (43%) dominating the literature, and very little attention given to "Impact/Risk" (7%) (Figure 1C). Of the publications that did contain analyses, most were model-based ($n = 58$) or reviews ($n = 38$), but very few were in-water pilot or testing studies ($n = 6$). Of the impact/risk papers, two suggested a framework or approach for assessing risk in co-located systems (Macadré et al., 2014; Van Hoof et al., 2020), citing risk as a potential obstacle to the expansion of co-located and multi-use systems. Some of the main risks to consider being damage, liability, and lack of safety standards. Others discussed impact and risk to the environment (Onea and Rusu, 2015; Benjamins et al., 2020; Serpetti et al. (2021). Serpetti et al. (2021) in particular presented a model that quantified top-down and bottom-up ecosystem impacts of a hypothetical multi-use platform off the west coast of Scotland. Other themes that emerged included contamination or pollution risks of co-location. Banach et al. (2020) highlighted knowledge gaps surrounding potential human health risks of seaweed cultivation co-located with wind farms, while Elginoz and Bas (2017) conducted a life-cycle assessment of a hypothetical co-located wind and wave system, citing manufacturing as being a large source of pollution. While these studies provide crucial insight into some of the impacts and risks surrounding co-located systems, the scarcity of these analyses suggests that this is a research gap that needs further exploration.

Co-location publications tended to include offshore wind and studies were largely focused on activities in European waters. Wind energy was most often referenced as being co-located ($n = 146$), followed by wave energy ($n = 109$), aquaculture ($n = 99$), and tidal energy ($n = 57$). Other forms of ocean activities (e.g., marine conservation, tourism) were referenced being co-located 81 times (Figure 2). The spatial focus of co-location publications was widely

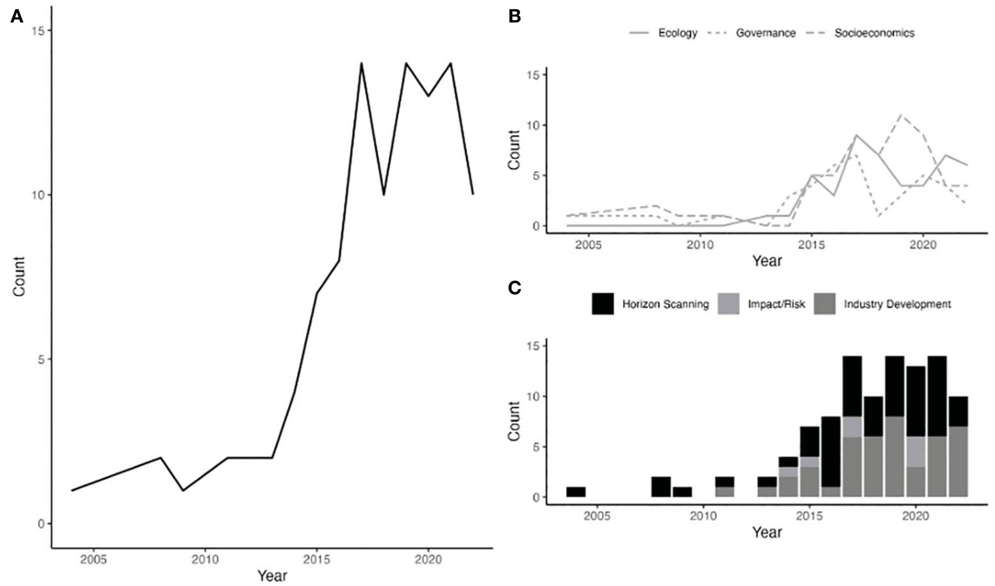

FIGURE 1
Frequency of publications over time (years 2000–2022). **(A)** reflects the total frequency of co-location publications published over time ($F(1,12)$ = 69.1, *p-value* = <0.001, R^2adj = 0.84). **(B)** reflects the frequency of co-location publications, separated by publication focus (i.e., ecology, governance, or socioeconomics), published over time. Publication focuses are cross-cutting, so many publications fall into multiple focus categories. **(C)** demonstrates the frequency publications, categorized by project motivation (i.e., horizon scanning, impact/risk, or industry development).

distributed, appearing near almost every continental coast but South America (Figure 3). However, the articles were largely focused on European waters, with the North Sea having the highest number of publication references (30%). In fact, the very first publication captured in our literature search was based in the North Sea, centered upon the legal constraints and opportunities of co-locating wind farms and aquaculture (Buck et al., 2004).

Recognizing peer-reviewed scientific literature may not reflect all actions occurring in a given region (North Sea expert communications, personal communication, 2024), we conducted a *post hoc* evaluation of available gray literature from co-location projects in the North Sea due to its dominance in the primary literature (N = 57). The Multi-uses in European Seas (MUSES) Project produced 29 reports, newsletters, and infographics that examined multi-use across seven case study locations (MUSES, 2024). MUSES was a two-year (2016 – 2018) project undertaken to explore the potential of multi-use in European waters. While we excluded the co-occurrence of fisheries with energy or aquaculture as a form of "co-location" in our synthesis of scientific WOS publications, the MUSES project included this scenario as a form of co-location. Therefore, we included those publications in our *post hoc* evaluation of the MUSES gray literature to accurately capture the MUSES findings. Notably, each MUSES case study incorporated a Drivers, Added value, Barriers, and Impacts (DABI) catalog and scoring assessment to categorize key opportunities and barriers across different scenarios (Bocci et al., 2017). More recently, the "multi-Use offshore platforms demoNstrators for boostIng cost-effecTive and Eco-friendly proDuction in sustainable marine activities" (UNITED) project operated from 2020 until 2023 and made a series of briefs available (n = 7), in addition to a series (n = 17) of pilot development deliverables (UNITED, 2024). Also, while some literature concerning the "Innovative multi-purpose offshore platforms: planning, design & operation" (MERMAID) project was captured in our synthesis (Simal et al., 2017; Xepapadeas et al., 2017; Bocci et al., 2019), the final report of the MERMAID project was reviewed in our *post hoc* evaluation (MERMAID, 2024). Lastly, as a follow-up to UNITED, a project integrating Low-Trophic Aquaculture within Offshore Wind Farms (ULTFARMS Project) launched in 2023 and will run until 2026. Thus far, there are some (n = 3) reports available that describe the monitoring efforts, communication of results, and stakeholder engagement deliverables (ULTFARMS, 2024). We conducted a search of materials for the OLAMUR and "North Sea Farm#1" projects, but given the early stages of these projects, no gray literature was publicly available (NSF, 2024; OLAMUR, 2024). All of the reports reviewed in our *post-hoc* evaluation made investigations into impact/risk (environmental, social, and/or technical). Given this additional evaluation, it is clear that many of the North Sea projects have produced gray literature that was not captured in scientific literature but is valuable in understanding the state of co-location research and highlights a disconnect in the field. Ultimately, these projects outline a site-specific methodological framework for evaluating trade-offs of co-location projects.

3.2 Metric trends

Of the publications that provided metrics (36%), there was no significant difference (Kruskal-Wallis, p = 0.387) in depth ranges across aquaculture (median ± interquartile range = 66.25 m ± 95.88), wave energy (104.00 m ± 95), and offshore wind studies (100.00 m ± 120) (Figure 4A). Notably, some of the depth metrics

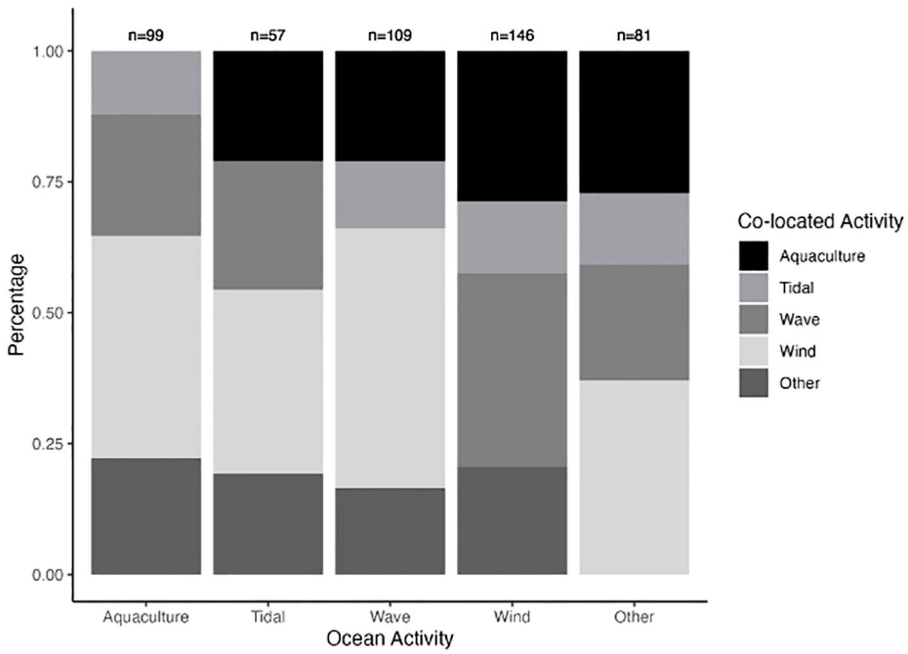

FIGURE 2
Each ocean activity and its frequency of co-location with another ocean activity. Many publications referenced multiple interacting co-locating activities.

provided in some publications far exceeded normal depth ranges (>100 meters) for both reported aquaculture (Froehlich et al., 2017) and wind energy projects (DOE, 2022). Though, later studies have used deeper limits for suitability mapping based on qualitative input from industry, such as 150 m (Morris et al., 2021) or 200 m (Gentry et al., 2017), which is more consistent with the co-location trends. Perhaps these outliers call into question some of the feasibility of co-location and/or suggest that it will push sectors at or past their current limits. While sample sizes were too small and uneven to conduct formal statistics, observationally the depth ranges of just the aquaculture projects seem similar across the different energy-ocean activities (Figure 4B).

Similar to co-location depth trends, there was no significant difference (Kruskal-Wallis, p = 0.59) in the distance from shore of aquaculture (16 km ± 21), wave energy (20 km ± 35), and offshore wind (17 km ± 33.5) publications in this corpus (Figure 5A). Observing the aquaculture distance metrics, the distances from shore are very similar (1.2–60 km), regardless of which ocean activity aquaculture is being co-located with (Figure 5B). While the distances from shore of co-located aquaculture studies fit within the ranges available in aquaculture literature (Froehlich et al., 2017), there is one outlier in the wind category that greatly exceeded the range of distances from shore currently represented in offshore wind projects (< 120 km; DOE, 2022) (Figure 5A). Also, many of the distances from shore for co-located wave energy studies fell outside the current range from wave energy projects (Tethys, 2023). As with the depth range outliers, the general disparity between distances from shore of current wave energy projects and those of studies on co-located wave energy studies could imply that these data lack feasibility. However, it may suggest that developing co-located systems could enable smaller ocean projects to operate farther from shore.

3.3 Aquaculture implications

Out of the original 102 scientific publications in the corpus, 50 (49%) were identified as being aquaculture specific and discussed a variety of different aquaculture types. Topics spanned technical evaluations, physical and biological siting studies, and social acceptance research. Co-located aquaculture publications were most often focused on mollusk culturing (n = 10), followed by fish (n = 8), macroalgae (n = 7), and crustacea (n = 1) (Table 2). The trend towards studies that incorporate unfed aquaculture is likely due to the lower cost and effort required to cultivate those species (Fujita et al., 2023). However, as fed marine species generally have higher market value, offsetting costs of those systems by co-locating with another ocean activity could be useful to the sector, particularly when it comes to aquaculture in waters that are exposed or farther from shore. Of the 61 gray documents, many had logistical or technical focuses that didn't necessarily evaluate co-location potential at the case study or pilot project level (n = 43). Of the remaining documents that did directly address co-location case studies or pilot projects (n = 18), roughly half included aquaculture (55%), including finfish in the beginning (2012–2018; MERMAID, 2024; MUSES, 2024) and later focusing primarily on low trophic aquaculture (i.e., bivalves and seaweeds) (2020–2024; UNITED, 2024; ULTFARMS, 2024).

Few of the co-located aquaculture science publications were focused on impacts or risk (8%) and only one was in the pilot study

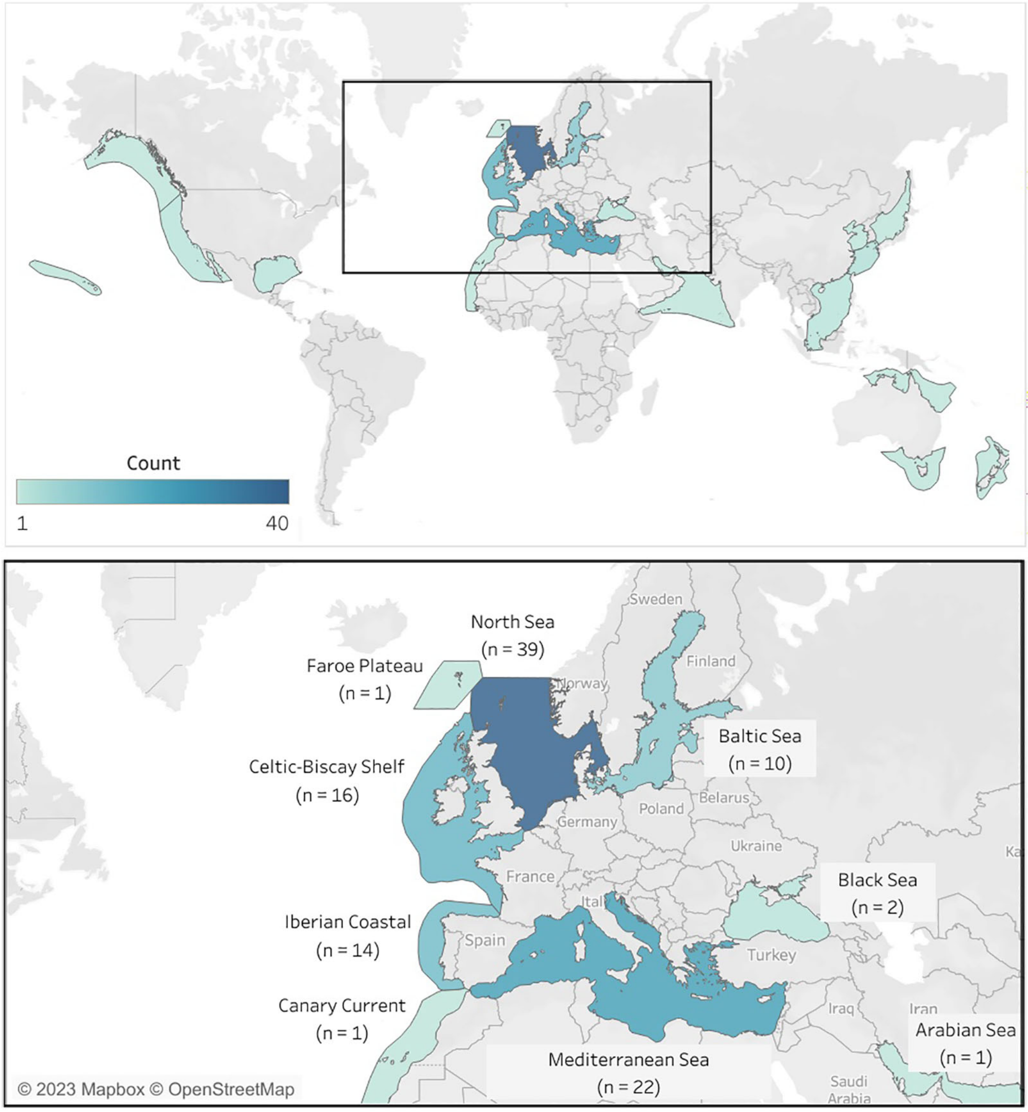

FIGURE 3
Regional distribution of co-location publications across Large Marine Ecosystems (LMEs) between the years 2000 and 2022. Multinational distribution (top panel) reflects publications that reference location, with a closer look at European waters (bottom panel). The North Sea (*n* = 39) was the most common LME referenced in co-location literature.

and testing stage (2%). Similarly to the broader corpus trends, the motivation for aquaculture co-location publication was more frequently horizon scanning (*n* = 29; e.g., Lacroix and Pioch, 2011; Green et al., 2019) or industry development (*n* = 17; e.g., Gimpel et al., 2015; Steins et al., 2021), rather than impact and risk (e.g., Banach et al., 2020; Benjamins et al., 2020). Also, the assessment type for co-located aquaculture publications was largely a model (*n* = 20) or review (*n* = 29). The only pilot/testing assessment was provided by Flikkema and Waals (2019) and consisted of technical testing of a floating multiple-use platform, both conceptually and in lab conditions. The relative scarcity of papers addressing the pilot stage and impact studies aligns well with the nascency of the aquaculture co-location field.

Similar to the broader WOS corpus trends, only 25 (50%) of aquaculture related scientific publications provided specific metrics. The metrics included depth (*n* = 18), distance to shore (*n* = 15), current velocity (*n* = 8), wave height (*n* = 8), sea surface temperature (SST; *n* = 6), and chlorophyll-a (chl-a; *n* = 3) (Table 3). An additional three publications referenced metrics but did not provide them and were thus not included in the final tally. On the whole, the aquaculture scientific publications that listed a yield estimate were scarce (*n* = 1). Aryai et al. (2021) reported an estimate of yield (80 tons/year/ha) for seaweed, but this was an estimate based on the industry standard from this system, rather than a site-specific dynamic model or *in situ* measurement. Other publications (*n* = 7) listed estimated production values, which could be calculated with farm size to determine yield (e.g., Söderqvist et al., 2017; Lagasco et al., 2019; Benjamins et al., 2020). For example, Benjamins et al. (2020) modeled a multi-purpose platform which includes wind turbines that would supply energy to a 2,500 metric

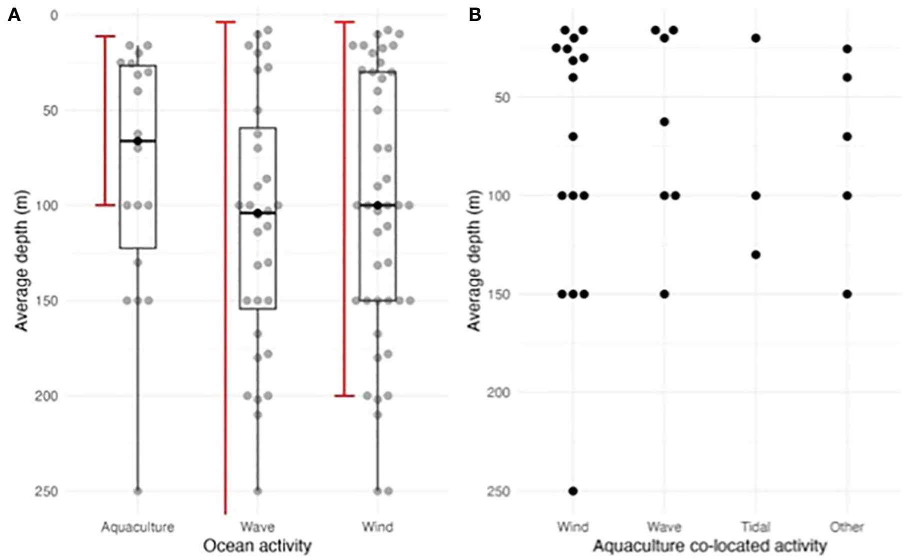

FIGURE 4
(A) Average depth (meters) across the three most common ocean activities in co-location literature: aquaculture (*n* = 18), wave energy (*n* = 32), and wind energy (*n* = 44) sectors. These ocean activities all reflect similar average reported depths (Kruskal-Wallis H = 1.9, df = 2, *p* = 0.39). Red lines represent current *in situ* depth ranges for respective technologies (Froehlich et al., 2017; DOE, 2022; Tethys, 2023). **(B)** In-depth examination of depth metrics when aquaculture is co-located with wind energy (*n* = 16, min = 0, median = 55, max = 500), wave energy (*n* = 7, min = 0, median = 62.5, max = 200), tidal energy (*n* = 3, min = 0, median = 100, max = 200), and other (*n* = 5, min = 0, median = 70, max = 300) sectors.

ton salmon farming system off of western Scotland. Again, this study reports the general anticipated production, but did not actually model the aquaculture yield itself. Yield in particular provides a critical and comparative measure; without reference, the ability to truly assess the potential of co-location of the overlapping industries is limited.

4 Discussion

Co-location research is increasing over time, with the most consideration being given to offshore wind and half of all publications including reference to aquaculture. The focus of publications in these studies were fairly evenly split between

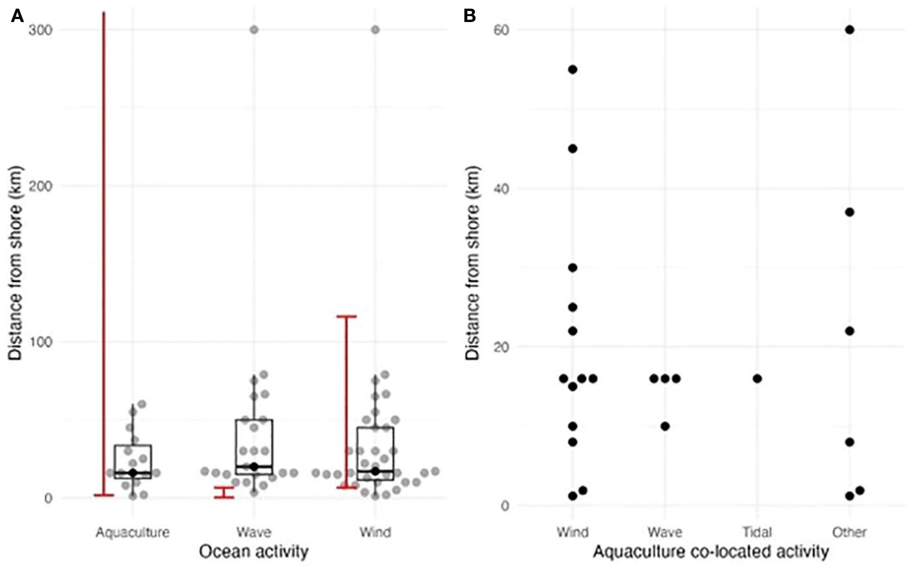

FIGURE 5
(A) Distance from shore (kilometers) across aquaculture (*n* = 15), wave energy (*n* = 23), and wind energy (*n* = 35). These sectors all reflect similar distances from shore (Kruskal-Wallis H = 1.1, df = 2, *p* = 0.59). Red lines represent current *in situ* depth ranges for respective technologies (Froehlich et al., 2017; DOE, 2022; Tethys, 2023). **(B)** Evaluation of these metrics when aquaculture is co-located with wind energy (*n* = 13, min = 1.2, median = 16, max = 55), wave energy (*n* = 4, min = 10, median = 16, max = 16), tidal energy (*n* = 1, min = 16, median = 16, max = 16), and other (*n* = 6, min = 1.2, median = 15, max = 60) sectors.

TABLE 2 Taxonomic groups of aquaculture species listed in any of the 50 aquaculture co-location scientific (WOS) publications.

Aquaculture Taxonomic Group	*N*	Example(s)
Mollusk	10	Jansen et al., 2016
Finfish	8	Zanuttigh et al., 2015; Lagasco et al., 2019
Macroalgae	7	Banach et al., 2020; Aryai et al., 2021
Crustacean	1	Gimpel et al., 2015

ecology, governance, and socioeconomics, which is in line with an EAA management framework that centers around interdisciplinary and holistic assessments (Soto et al., 2008; Lester et al., 2013; Ross et al., 2013). However, there was a general lack of studies assessing impact/risk, when compared to horizon scanning or industry development, though the *post-hoc* gray literature review of the most data rich and advanced North Sea region showed significant investment and coverage of impact/risk evaluations. That said, metrics in the scientific literature were rarely reported, particularly for aquaculture. Of the data that were provided, ranges fell beyond the currently reported individual, standalone industries (Froehlich et al., 2017; DOE, 2022; Tethys, 2023). These outliers could raise doubts about the feasibility of these proposed systems, or they may indicate that co-location is beginning to push industries beyond their current limits and into new extreme conditions. This "push" underscores the need for more risk and impact assessments given the challenges associated with moving ocean activities farther and deeper in the ocean, particularly when it comes to aquaculture.

While aquaculture accounted for half of co-location publications, focusing heavily on unfed species (mollusks and seaweeds), it lacked important comparative measures (e.g. yield) that allow researchers to truly understand co-location potential. The trend towards unfed species may be due to the typically lower cost but relatively high value for mollusks (Fujita et al., 2023), environmental sustainability of both mollusks and seaweeds (Gephart et al., 2021), and/or potential higher social license to operate in some regions (Fong et al., 2022). However, by this same reasoning, co-location in federal waters as a tool in culturing fed species of aquaculture, specifically finfish, could present an opportunity to reduce conflict around this somewhat more contentious taxonomic group (e.g., Carballeira Braña et al., 2021; Fujita et al., 2023). Notably, standalone offshore aquaculture research has largely focused on finfish production (Froehlich et al., 2017), an interesting divergence of trends. In fact, the gray reports in the North Sea focused on salmon aquaculture in the beginning – likely due to the proximity to Norway, the largest salmon producing nation in the world, and involvement of Scotland, a smaller but notable salmon producing country (FAO, 2022) – but later geared attention towards extractive species. Regardless, one problem with less offshore metric reporting of unfed species in the literature is it is not being compensated for in co-location publications. In addition, in the scientific literature the size and value associated with co-located marine aquaculture systems was unclear due to the general lack of data, including yield. While yield data is frequently underreported and highly variable in the aquaculture literature in general, it is a crucial metric in understanding the comparative scale and efficiency of production of aquaculture systems across taxa, geographies, and over time (Fong et al., 2024; Kebede et al., 2024). Similarly, the aquaculture co-located studies contained few impact/risk evaluations, which could affect the growth, survival, and safety of the farm, directly and indirectly.

TABLE 3 List of metrics available in co-located aquaculture scientific (WOS) publications and the number of publications (n) that provide those metrics.

Measure	*N*	Minimum	Maximum	Median
Depth (m)	18	16	250	66.25
Distance (km)	15	1.2	60	16
Current Velocity (m/s)	8	0	2.2	0.65
Wave Height (m)	8	1.25	5	2
SST (C)	6	12	20	16
Chl-a (mg/m^3)	3	2	20	10
Production (tons/year)	7	80	528,000	2,000
Yield (tons/year/ha)	1	80	80	80

All 25 papers provided at least once metric; some papers provided multiple measures of the same metric.
The maximum, minimum, and median values of the range of those metrics is also provided.

Studies that evaluate the impact and/or risk of co-located aquaculture projects will be especially necessary, though currently underrepresented in the peer-reviewed literature but more common in the North Sea gray literature. As co-location trends could be showing the potential to "push" industries beyond their normal physical range, co-located aquaculture projects may trend towards waters that are exposed or farther from shore. It is possible that co-locating aquaculture with other ocean activities could enable "exposed" and "open ocean" aquaculture by lowering costs and reducing risks within these operations (Buck et al., 2008; Stuiver et al., 2016; Fujita et al., 2023; Maar et al., 2023). However, it also could present new obstacles to aquaculture. For instance, co-located systems often have more structures in the water, which can affect the biophysical processes in that region (O'Donncha et al., 2017; Raghukumar et al., 2023). Also, there is some concern regarding the contamination risk of co-locating aquaculture with certain types of energy (Banach et al., 2020), as well as risk to physical operational safety to workers (Van Hoof et al., 2020). Most notably, there are a number of studies that highlight the need for a clear legal framework for co-located aquaculture (Michler-Cieluch and Krause, 2008; Stuiver et al., 2016; Calado et al., 2019). This is important because assigning liability across multiple user groups can be challenging and become an obstacle for co-located systems (Steins et al., 2021), particularly as sectors might be moving towards more exposed waters, where the environment is harsher and some risk factors increase (Fujita et al., 2023). Many of the publications that call for legal clarity of co-located systems originate from the North Sea (Stuiver et al., 2016; Depellegrin et al., 2019), in fact the gray literature categorized these systems as having the "unsolvable problem of liability" (Bocci et al., 2017). However, the MUSES case studies provide some legal clarity with the ultimate goal of implementation. The projects in this region offer a framework that includes liability and impact considerations, such as fishermen compensation, noise impacts, and social acceptance (MUSES, 2024).

Currently, co-location is being studied as a tool to strengthen the energy and food nexus around the world, but there is particular focus in European waters, largely in the North Sea. Due to this focus, we conducted a *post-hoc* evaluation of co-location in the North Sea region. The North Sea represents a unique set of attributes that make it favorable to co-location. It sits between many European countries (e.g., Denmark, Norway, Germany, the United Kingdom), which results in high multinational competition for space and resources though sectors like fishing, oil and gas, marine protection, and maritime transportation (Stuiver et al., 2016; Bocci et al., 2019). In the last decade, standalone industries entered the seascape, including offshore wind, providing additional demand for North Sea space (Buck et al., 2008; Michler-Cieluch et al., 2009; Benassai et al., 2014; Gimpel et al., 2015). Multiple sectors stemming from multiple countries requiring resources in the North Sea make it a fitting target for co-location. A series of co-location projects have laid a foundation of gray literature with regionally specific contexts and findings to the North Sea (MUSES, 2024; MERMAID, 2024; UNITED, 2024; ULTFARMS, 2024). Unlike the corpus of scientific publications, these gray reports have been largely supported with government funding and are implementation focused. Stemming from the gray literature, the first commercial scale, "in-the-water" co-location activities are taking place in the North Sea (NSF, 2024; OLAMUR, 2024). The North Sea Farmers are currently building the first commercial scale seaweed farm in between existing wind turbines in the Dutch North Sea (NSF, 2024). Similarly, OLAMUR is an EU project that supports commercially viable and sustainable low-trophic aquaculture, with one case study being placed within industrial-scale offshore wind farms at a North Sea pilot site (OLAMUR, 2024). As a result, the North Sea may be a "North Star" for the many other regions considering co-location of aquaculture and wind, moving beyond horizon scanning and modeling to actual application.

Our assessment revealed that only a fraction of co-location WOS papers (36%) included site-specific data. Ultimately, the shortage of quantifiable data within co-location studies hindered our ability to make statistical comparisons. A larger standardized dataset would be ideal and will hopefully be a goal for the future of co-location, especially for the purpose of knowledge sharing. However, in the absence of comprehensive empirical observations, scenario-based modeling could help provide insights into co-location opportunities and impacts at a particular location (Couture et al., 2021). Through modeling, decision makers can embrace uncertainty to help determine more explicit levels of risk and informed needs for co-location development and management, something more common in other maritime resource-use sectors (e.g., Privitera-Johnson and Punt, 2020). Several model-based studies included O'Donncha et al. (2017) on the East Coast of the United States, which assessed the effects of shellfish aquaculture on the water flow to a tidal stream-energy generator, and Clark et al. (2019) in the North Sea, which evaluated the lifecycle cost of wind and wave co-located systems. These studies and others like them could help inform future modeling efforts. For instance, though not captured in our synthesis of scientific publications due to its recent publication, Maar et al. (2023) presents a valuable spatial modeling study of co-located low-trophic aquaculture and offshore wind farm systems, including estimates of aquaculture biomass yield. In addition, gray literature clearly provides more potential details, although may not be peer-reviewed, archival, and/or as focused on reproducibility. While we included the extensive efforts of the North Sea given its significance in the multi-use arena, further aggregation and assessment of other regions could be done to bolster missingness in scientific publication – recognizing the potential difference in information collection and dissemination, and likely challenges to track down the many forms that may exist (Paez, 2017). As previously noted, this study was restricted to publications written in English on the WOS platform, likely excluding important published work, particularly in China where the respective sectors of aquaculture and wind development are expanding quickly (GWEC, 2023; Long et al., 2024). In fact, only 6% of papers in this study focused on Chinese waters. A logical next step of this paper would be to focus synthesis efforts on that particular region, which could provide a nice comparative to the efforts in the North Sea. Despite these caveats, this analysis does capture some important trends in co-location research and examines whether it might affect future ocean development, especially in terms of ocean-based aquaculture.

Our study sets the stage for future investigations into co-location of marine sectors, in particular aquaculture and clean energy in regions that have yet to adopt such spatial approaches. By developing a multinational understanding of co-location trends, researchers and decision makers can leverage the numerous existing models and approaches around co-location. However, there will be a lot of context dependencies to consider. To begin to understand more realized potential of co-location in a specific region, we encourage future research to include more detailed, standardized reporting and modeling of co-location measures – as exemplified in the North Sea gray literature. Incorporating uncertainty and other factors that may pose challenges (or opportunities) would provide useful context to model outputs and inform conclusions about the co-location potential of a site. Indeed, there is a deficit of measures in scientific publications to inform implementation, especially in relation to aquaculture production and associated impacts or risks therein. Seemingly, most of the modeling and data efforts have focused on the energy side of the co-location equation, while the arguably more challenging production of culturing living organisms via aquaculture remains under-assessed. While standalone reporting in the respective fields – like those featured within the reviews highlighted in this study (Froehlich et al., 2017; DOE, 2022; Tethys, 2023) – can provide some valuable insights for co-location, the interactions between the co-sited structures likely create unique challenges. Ultimately, greater attention to what type of aquaculture can grow and how it interacts with the energy it is sited with needs to be investigated more rigorously to understand the true potential of the integrative food-energy ocean future.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CG: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Visualization, Writing – original draft, Writing – review & editing. SC: Data curation, Investigation, Writing – review & editing. HF: Conceptualization, Funding acquisition, Supervision, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Utilisation of the site assessment energy indices for aquaculture in exposed waters: biology, technology, operations and maintenance

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When moving from a very sheltered aquaculture site to a very exposed oceanic aquaculture site, the energy increases proportionally in a continuum. Lojek et al. (in review) considered the primary influential parameters (water current, wave height, wave period, wavelength and water depth) which influence the species, structure, technology, methods, and operational aspects of any aquaculture endeavour and investigated six possible indices which cover these variables. Added to advanced computer modelling, assisted by detailed and constant environmental monitoring, it may be possible to refine site selection, structure selection and design, species selection, equipment and logistic requirements and health and safety requirements. This manuscript has selected two indicative indices: Specific Exposure Energy (SEE) index and Exposure Velocity (EV) index from the potential equations provided by Lojek et al. (in review) and compared them with known operational aquaculture sites highlighting present structural capability and limitations. The two indices are also utilized to reflect on their suitability for assessing sample sites with respect to biological, technological, operational or maintenance aspects of aquaculture activities. The indices have shown themselves to be useful tools in the general assessment of the energy that will influence the species and structure selection at potential aquaculture sites. This information can help prospective fish farmers characterize their sites concisely and accurately to consultants, regulators, equipment vendors, and insurance brokers.

KEYWORDS

mussels, seaweed, exposed aquaculture, energy index, site selection, marine finfish

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1 Introduction

Physical ocean energy is the main characteristic defining accessibility of any potential aquaculture site, as this dictates the feasibility of aquaculture in general as well as the species and the technology most appropriate for the site. Traditionally, aquaculture has been carried out in low energy, sheltered coastal and estuarine habitats (Olsen et al., 2008; Buck et al., 2024). Aquaculture has been increasing significantly worldwide over the last 40 years (FAO, 2022) in terms of the range of species, the quantity produced and the locations where aquaculture takes place. During this period, there has also been an increase in other stakeholder activities, which are in competition for the water space, especially in the coastal sea (Galparsoro et al., 2020). In addition, anthropogenic inputs have also had an influence on the quality of water at inshore and sheltered sites and more and more coastal waters are subject to special utilisation permits and are often declared worthy of protection, e.g. the establishment of marine protected areas (MPAs) (Rodriguez-Rodrıguez et al., 2015), which often excludes use for aquaculture.

Therefore, there has been an increasing trend to extend aquaculture into water bodies off the coast, referred to as offshore or open ocean aquaculture (FAO, 2022). However, we now know that it is not the distance from the coast, but rather the degree of exposure that determines the form of aquaculture that can be undertaken at a site (Buck et al., 2024; Lojek et al., in review[1]; Sclodnick et al., in review[2]). Nutrient concentrations in the water column vary locally and seasonally, but in many regions decrease with increasing distance from the coast (Painter et al., 2018). The advantages of these areas are that the water bodies have more stable conditions with regard to changes in temperature, oxygen content, pH and other abiotic factors, which are important particularly in view of future climate change (Ahmed et al., 2019). In addition, grazing/predation pressure is reduced, and biofouling decreases since predators and fouling organisms diminish with distance from the shore and with increasing exposure (Atalah et al., 2016; Visch et al., 2020; Morro et al., 2021).

A longstanding issue which has an influence on the understanding and progress into exposed sites is the terminology used to describe these exposed ocean locations. Other papers of this special edition (Buck et al., 2024; Dewhurst et al., in review[3]; Heasman et al., in review[4]; Lojek et al., in review[1]; Markus, in review[5]; Sclodnick et al., in review[2]) have investigated this aspect in some depth, but it is of value to outline the parameters here. The terminology used above and in other manuscripts (Froehlich et al., 2017; Morro et al., 2021) can vary in interpretation leading to misunderstanding of the locations, aquaculture technology, species, and logistic requirements. The main characteristics and their implications are found in Figure 1.

However, these descriptions are still relatively undefined in terms of the differences in requirements of these locations (Buck et al., 2024). Extending into high-energy zones found at exposed marine sites necessitates a combination of new thinking; new design; new technology; new materials; and new methods and not limited to making inshore structures bigger and stronger. (e.g. shellfish dropper lines; Gieschen et al., 2020; Landmann et al., 2021). Also, logistics, operation and maintenance as well as health and safety will have to be considered and advanced appropriately to enable a safe and viable enterprise. The question also arises as to whether the current technologies are the right ones to be used in high-energy environments. Perhaps a paradigm shift is needed in the expansion of aquaculture operations into exposed waters. This requires a clear understanding of the requirements for new technologies, and thus the categorisation of a water body in terms of the level of energy. Hence the investigation into the applicability of the indices established by Lojek et al. (in review)[1] to quantify the parameters and classification that inform the enquirer as to what technology and procedures are required for different forms of aquaculture and locations.

This alternative would contribute significantly to this classification issue by measuring the amount of exposure (at a worst-case scenario) found at any one point in the water column at a selected location. If the influence of various parameters which essentially indicate the amount of energy found at a site can be determined in a continuum from 0, in a very sheltered site, to a maximum in very exposed seas, then an aquaculture assessment of equipment, species, risk, amongst other variables, can be matched to those sites.

This manuscript investigates the parameters that influence exposure found at a site and also the potential of the exposure indices to support aquaculture farm location, aquaculture species selection and diversification, planning, equipment requirements, operational advancement and health and safety based on information from exiting farm operations.

It should be noted that this manuscript is one of a suite of papers comprising a special edition "Differentiating and defining 'exposed' and 'offshore' aquaculture and applications for aquaculture operation, management, costs, and policy". The special edition includes manuscripts focused on aquaculture policy and regulation in marine environments, the definitions of terms regarding aquaculture in marine systems, the derivation of the energy indices, trends required to advance aquaculture into high energy marine zones, costs and implications in aquaculture of using the indices and social science aspects relating to marine aquaculture (Buck et al., 2024).

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2 Sclodnick, T., Chambers, M., Costa-Pierce, B.A., Dewhurst, T., Goseberg, N., Heasman, K.G., et al. From "open ocean" to "exposed aquaculture": why and how we are changing the standard terminology describing "offshore aquaculture".

3 Dewhurst, T., Richerich, S., MacNicoll, M., Baker, N., and Moscicki, Z. The effect of site exposure index on the required structural capacities costs of aquaculture structures.

4 Heasman, K.G., Scott, N., Sclodnick, T., Chambers. M., Costa-Pierce, B., Dewhurst, T., et al. Variations of aquaculture structures, operations, and maintenance with increasing ocean energy.

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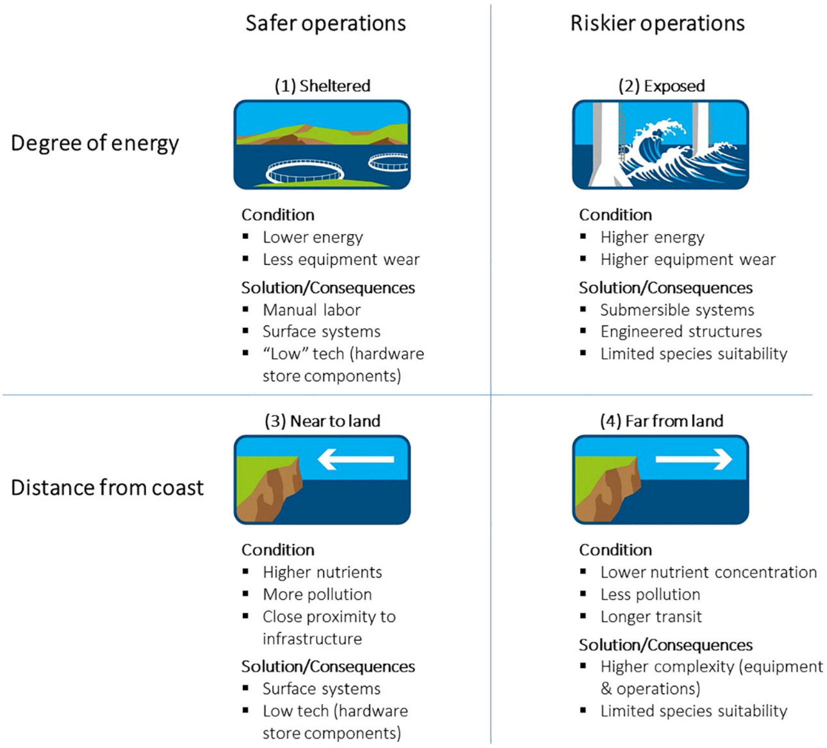

FIGURE 1
Comparison of "Sheltered" vs. "Exposed" (top) as well as "near to the land" (nearshore) vs. "far from land" (offshore) (bottom) environments along with a selected collection of general and specific descriptions of each (modified after Buck et al., 2024).

2 Methods

2.1 Utilisation of indices

The equations which provide a reference value (index) postulated by Lojek et al. (in review)[1] are assessed and considered in view of their sensitivities to various hydrodynamic energies and how they represent the sites where known aquaculture takes place. Indices that appear to be sensitive to wave height, water depth, and water currents, which are perceived to be the most influential parameters of water energy at a marine site, are used in case studies. Six indices (A–F) were proposed in Lojek et al. (in review)[1], and for the sake of completeness these are summarized in Table 1.

Since all of these indices were analysed in detail in Lojek et al. (in review)[1], we limit ourselves to those indices that include the parameters important for aquaculture, namely water depth (d), horizontal water current (U_c), and wave environment (i.e. height H_s, period T_p, direction, and wave-induced horizontal velocity magnitude u_w). The selection of these parameters is based on a list of the most important oceanographic parameters for open ocean as stipulated in Buck and Grote (2018), Buck et al. (2024) and Lojek et al. (in review)[1]. An assessment of these indices and their application has shown that two indices, namely the Specific Exposure Energy (SEE) index and Exposure Velocity (EV) index, were considered to be the most sensitive and responsive to the parameters describing an exposed location providing clearly

TABLE 1 List of indexes developed by Lojek et al. (in review)[1] for the application of aquaculture sites in high-energy environments.

No.	Index	Abbr.	Formula
A	Specific exposure energy index	SEE	$1/2\ (U_c(z) + u_w(z))^2$
B	Exposure velocity index	EV	$\sqrt{u_w(z)^2 + 2u_w(z)U_c(z) + U_c(z)^2} = U_c(z) + u_w(z)$
C	Exposure velocity at reference depth index	EVRD	$U_E = U_{c5} + u_{w5}$
E	Depth-integrated energy flux index	DEF	$\frac{\rho g^2 (H_s^2) T_E}{64\pi} + \frac{1}{2}\rho d(U_c)^3$
E	Structure-centered depth-integrated energy index	SDE	$\left(\frac{1}{8}\cdot g\cdot H_s^2 + \frac{1}{2}\cdot d\cdot U^2\right)\cdot\rho\cdot S\cdot A_{structure}$
F	Structure-centered drag-to-buoyancy ratio index	SDBR	$\frac{U^2}{2gD}$

distinguishable results as seen in Table 1. The derivation of the indices is covered in Lojek et al. (in review)[1] so this manuscript will only focus on the use of the selected indices.

Case studies will follow showing the positioning in the water column of already existing commercial operational sites and how the two indices SEE and EV will respond when using the sites parameter characteristics (see Section 3). All assessments were taken to be at the surface as this is the most conservative measurement and covers the culture of seaweed which must be done at, or very near to, the surface. Further, evaluation of the SEE and EV in these assessments make the simplifying and conservative assumption that the horizontal water current velocity and wave direction are aligned. As such, $U_c(z)$ and $u_w(z)$ can be considered magnitudes, referred to as the current speed and the wave-induced horizontal velocity magnitude. In alternative applications of the SEE and EV, the directionality of $U_c(z)$ and $u_w(z)$ can be considered.

The manuscript is focused on quantifying exposure as opposed to quantifying energy resources; therefore, it will assist both aquaculture and wave energy site assessments, but it will not define the energy resources per se that would be required for defining power outputs of specific wave or current energy systems.

An index calculator can be found online[6] which will allow the reader to use the calculator to generate an index for prospective aquaculture sites.

2.2 The influence of depth on wave motion

Water depth is of significant importance at an aquaculture site as it will have a substantial impact on the wave environment and therefore the energy at an aquaculture site. This energy potential in turn influences the farm technologies installed there, the aquaculture species candidates, as well as the daily routines such as operations and maintenance (O&M). Figure 2 shows the dependence of wave induced water movement on decreasing depth from the open ocean to the coast at different locations: (A) deep water (B) intermediate water, and (C) shallow water (Lojek et al., in review)[1].

Dynamically, as a wave approaches shallow water, wave heights increase and the speed at which the wave travels forward decreases (i.e. wave period remains constant and wavelength decreases). Beneath the water surface, waves induce the periodic movement of water particles; from deep to shallow water, these paths transition from circular to elliptical to nearly horizontal. The wave-induced horizontal velocity magnitude decays rapidly with water depth in deep water yet remains constant with water depth in shallow water—resulting in oscillating currents that extend over the entire water column (Figure 2). Finally, wave breaking initiates when the wave-induced velocity at the crest of the wave is greater than the wave speed. These processes show how wave induced velocities below the surface intensify with decreasing water depth (Dean and Dalrymple, 1991). For the aquaculture site, this often means that the total energy that an aquaculture structure is exposed to increases with decreasing depth, impacting the performance, operation and safety of the farm.

Since the interaction of the parameters water depth (d), wave height (H_s), wave period (T_P), current speed (U_c), and the position of the farm in the water column (d_s) is of great importance for the understanding of an index application, we will discuss the basics of this interaction in Figures 3, 4 and in Table 2. Figure 3 shows the dependence of an energy potential at a certain location (represented by a freely selectable index, e.g. EV or SEE) on the wave height (H_s) and the current speed at a given wave period (T_p). The parameters are indicated without numbers to give a basic understanding of the shape of the surface graph. The arrows parallel to the wave height axis, current speed axis, and index axis indicate the direction of the increasing values. The colour on the surface corresponds to the index value, which increases with progressive red-dark colouring. It can be clearly seen how the index value depends on the current speed and wave height for a given wave period. If current speed or wave height increases or the wave period decreases, there is also a corresponding increase in the index value. This phenomenon always applies and can be understood as a basic realisation for the further application of the various indices. The solid red 3D line "system survival limit" at a given index value means that the structure (longline, fish cage, etc.) was designed for a certain threshold value associated with the index. The system design is therefore robust and stable for exposed conditions that lie within this red defined area. The dashed black 3D line is intended to represent the limit value for "working conditions" at a specific index value. This line indicates that this threshold is application specific. The double black arrows within the graph are intended to show that the "working conditions" are dependent on several factors, such as the type of maintenance vessel, the particular work task (anchoring, inspection, harvesting, etc.) or other activities.

2.3 The comparison of SEE with EV at different depths and wave periods

By considering the above information and applying the SEE and EV indices, the comparability between the applied indices and the different aquaculture sites and operations can be achieved. To add clarity to the basic understanding of the indices before applying them to real existing aquaculture sites, two hypothetical reference sites (R1, R2) are defined. For this purpose the selection of the water depths and the duration of the wave periods are based on a parameter selection of exposed or offshore aquaculture sites known to us.

R1 and R2 are compared with different wave heights and current speeds using the two selected indices (SEE, EV). Figures 4A–D demonstrates that with increasing current speed (U_c) and wave height (H_s) and decreasing depth (d = 50 m to d = 25 m) and wave periods (T_P = 15 s to T_P = 10 s), the indices increase. It is important to understand that, in theory, any hypothetical wave height, period and depth can be chosen when applying the index formulae in order to understand the effect on the index value. However, not all theoretical data is physically realistic. For example, a wave height of H_s = 10 metres with a wave period T_P of 5 seconds

6 https://www.KelsonMarine.com/resources.

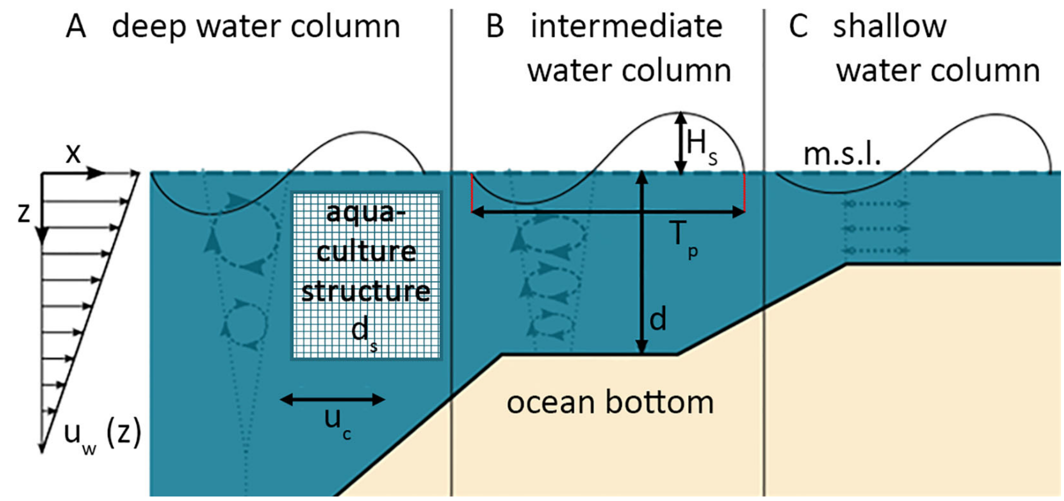

FIGURE 2
The relationship between wave height, form and water depth in **(A)** deep, **(B)** intermediate, and **(C)** shallow water wave environments, as characterized by the water depth (d) to wave length (L) ratio. Wave orbital velocity amplitudes and particle displacements underneath a progressive wave transform as d becomes small relative to L. Relevant variables include: z = vertical location in the water column, x = direction of wave propagation, uw(z) = wave-induced horizontal velocity magnitude, Hs = wave height, m.s.l. = mean sea level, Tp = wave period, d = depth, ds = depth of farm structure below surface, Uc = current speed. (Modified after Lojek et al., in review)[1].

cannot exist; it is unstable and would break, effectively limiting the wave height (see Appendix 1). Therefore, in Figures 4A–D, each surface calculated represents only physically realistic wave environments. A dashed black line along the SEE or EV surface in Figures 4A–D denotes H_s-T_P conditions where wave breaking is expected.

It is important to understand that the position of a farm within the water column also plays a significant role. For example, a mussel longline on the surface of the water experiences a much higher energy value (essentially due to the wave generated forces) than the farm that is submerged to 10m since there are decreasing wave generated forces with depth. Table 2 and Figures 5A, B shows the extent to which the two indices EV and SEE at R1 and R2 respond to the position within the water column (farm structure operation depth at the surface and in a submerged mode with d_s = 0 m, −5 m, −10 m, −15 m, and −20 m) at a given wave height of H_s = 5 m and a current speed of U_c = 0.75 m·s^{-1} for two different wave periods T_P = 10 s and T_P = 15 s. The percentage deviations between the positions of the farm structure in the water column are also documented. It can be seen that the index value decreases from d_s = 0 m to d_s = −20 m for submerged farms. Thus, any system design that is positioned in deeper water is most likely safer. The reduction in

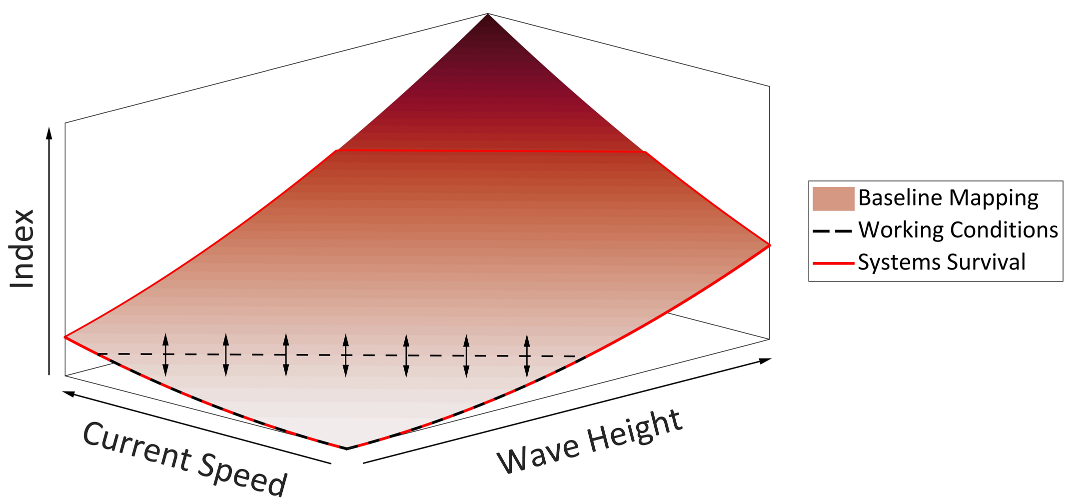

FIGURE 3
Surface graph to illustrate the magnitude of the index value as a function of the current speed and the wave height (for a given wave period). The red line is intended to illustrate the limit of the structures used ("system survival"), the black dashed line ("working conditions") shows the limit of the operation conditions, which can vary depending on the type of work (black arrows).

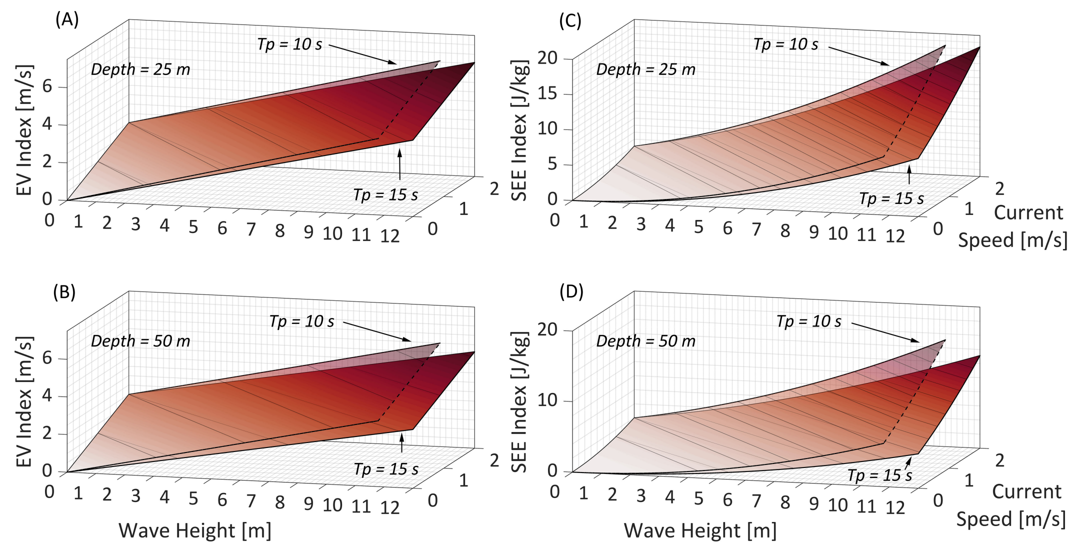

FIGURE 4
The influence of wave height [Hs in m] and current speed [U_c in m·s^{-1}] on the two indices SEE and EV at two water depths [d in m] 25 m and 50 m as well as two wave periods [T_p in s] 10 s and 15 s, respectively. **(A)** The influence of H**s** and U**c** on the EV-index at a site with d = 25 m in two different wave periods. **(B)** The interaction of H**s** and U**c** on the EV index at a site with d = 50 m in two different wave periods. **(C)** The influence of Hs and U**c** on the SEE-index at a site with d = 25 m in two different wave periods. **(D)** The interaction of H**s** and U**c** on the SEE-index at a site with d = 50 m in two different wave periods.

the index value can be clearly recognised by the % data in relation to the water surface d_s = 0 m. The gradual reduction from d_s = −5 m, −10 m, −15 m and −20 m can also be observed. The percent decrease in the index values of the respective d_s in relation to the water surface is shown in Figures 5A, B. This makes it possible to recognise in advance what energy potential can be expected with decreasing depth d_s.

3 Results

Selected existing aquaculture sites in exposed water bodies that were operational as of April 2024 will be assessed regarding indices developed in Lojek et al. (in review)[1] and the actions and changes that have been instituted to extend from sheltered waters to their more exposed locations.

3.1 The application and assessment of the indices in exposed aquaculture farms

All aquaculture requires some "energy" such as water flow to ensure the delivery of oxygen and/or nutrients and/or plankton. In addition, for both, extractive and non-extractive organisms, the dispersal of food remains, faeces and pseudo faeces rely on wave and current energy (Fujita and Goldman, 1985; Gaylord et al., 1994; Larned and Atkinson, 1997; Campbell et al., 2019). Flow also ensures enough oxygen-rich, fresh (clean) and colder water, which mixes and provides cooling during long warm periods, and is therefore an important aspect for many aquaculture candidates (Beveridge, 2008). When using IMTA-based concepts, a minimum movement of the water column is mandatory (Buck and Grote, 2018) for seaweed and organism cultivation to be successful.

As can be seen from the index variations of SEE and EV in Figures 4–7, water depth will also have a significant influence on the species and the aquaculture structural parameters to cultivate at a site. For seaweeds, which generally utilise the surface waters to maximize the sunlight exposure, (except species which are grown deeper such as *Macrocystis* sp., *Laminaria hyperborea*, etc.) (Lüning, 1990), the depth of a site is not as important from an operational point of view. However, surface and shallow waters generally have greater wave action and energy than deeper in the water column, therefore the structures need to be more robust. For bivalves such as mussels, there are systems that can tolerate the energy at shallow locations e.g., longtube and longline systems (Buck and Langan, 2017; Goseberg et al., 2017; Newell et al., 2021). The New Zealand longline system has a double backbone with dropper lines which would not be tolerant of shallow, high-energy areas because in order to be viable longer droppers or collectors are required to extend down from the backbone into the water column utilising the available water space efficiently (Newell et al., 2021). Surface finfish systems require depth to accommodate the pen nets as well as free clearance below the pen bottom to disperse effluent. In contrast to floating systems submersible pens require greater depth to accommodate free clearance above the pen for energy dissipation.

In this instance the index can play an illuminating role. A minimum water movement, through a combination of wave and current, is required for a particular species to prosper. Knowing the species minimum requirements and the site's parameters, it is possible to determine the suitability of the site location in terms

TABLE 2 Site parameters of two reference sites for comparison of extremes.

Reference sites	d [m]	H_s [m]	U_c [m·s^{-1}]	T_p [s]	EV Index	d_s [m]	% difference in index values at different farm structure depths d_s (m)				SEE Index	% difference in index values at different farm structure depths d_s (m)			
							−5	−10	−15	−20		−5	−10	−15	−20
R1*	25	5	0.75	10	2.6	0	–				3.5	–			
					2.3	−5	11.5	–	–	–	2.7	22.7	–	–	–
					2.1	−10	19.2	8.7	–	–	2.1	40.0	22.2	–	–
					1,9	−15	26.9	17.4	9.5	–	1.8	48.8	33.3	14.3	–
					1.8	−20	30.8	21.7	14.3	5.3	1.6	54.3	40.7	23.8	11.1
				15	2.4	0	–				3.0	–			
					2.3	−5	4.2	–	–	–	2.7	10.0	–	–	–
					2.2	−10	8.3	4.4	–	–	2.4	20.0	11.1	–	–
					2.1	−15	12.5	8.7	4.6	–	2.3	23.3	14.8	4.1	–
					2.1	−20	12.5	8.7	4.6	0.0	2.2	26.7	18.5	8.3	4.4
R2*	50	5	0.75	10	2.4	0	–				2.8	–			
					2.1	−5	12.5	–	–	–	2.2	21.4	–	–	–
					1.8	−10	25.0	14.3	–	–	1.7	39.3	22.7	–	–
					1.7	−15	29.2	19.1	5.6	–	1.4	50.0	36.7	17.6	–
					1.5	−20	37.5	28.6	16.7	11.8	1.1	60.7	50.0	35.3	21.4
				15	2.1	0	–				2.1	–			
					1.9	−5	9.5	–	–	–	1.9	9.5	–	–	–
					1.8	−10	14.3	5.2	–	–	1.7	19.1	10.5	–	–
					1.8	−15	14.3	5.2	0.0	–	1.6	23.8	15.8	5.9	–
					1.7	−20	19.1	10.5	5.6	5.6	1.4	33.3	26.3	17.7	12.5

% difference between index values at given farm structure depths (read horizontally) of d_s from 0 m to −20 m: d_s = −5 m and −10 m and −15 m and −20 m to surface (0 m); d_s = −10 and −15 m and −20 m to −5 m; d_s = −15 m and −20 m to −10 m; d_s = −20 m to −15 m. * = 50-year predicted maximum conditions, d = water depth, H_s = 50 year wave height, T_p = 50 year wave period at wave height, U_c = 50 year current speed, d_s = depth of farm structure below surface.

of the proposed activities. If the index (amount of energy) is below a minimum, the aquaculture species will not prosper and thus will have a clear detrimental effect on the local ecosystem (Loucks et al., 2012). The carrying capacity of intensive farming systems is directly related to water turnover. In turn, a high index at a given location may indicate the "maximum energy" that is beyond the structural capabilities designed for a particular species or indeed may indicate energy that exceeds the species tolerance. Seaweed and/or bivalves could be detached from the cultivation substrate and lost. Filter feeding of the bivalves can be reduced or even stopped to avoid damage of the filtration apparatus. Seaweed may not be able to uptake nutrients at a certain maximum energy. It could cause stress to the fish in a pen, which could be pushed against the nets, or the nets themselves could reduce their volume because of their enormously large projected area facing tidal currents (Lader and Fredheim, 2006; Fredriksson et al., 2014). This could result in loss of production, poor fish health, structural damage and increased maintenance. These sites are commonly defined as an unfavourable aquaculture site in the context of previously conducted site selection criteria surveys.

In addition to the health and survival of fish and all other extractive species, the technologies used for aquaculture must withstand the demands of sites with higher energy potential. Often the system design as well as the mooring of these high energy sites are different than those in more sheltered areas. In the following, we will analyse the main differences between farms in exposed areas and those in sheltered environments.

3.2 Mussels

Of all the bivalves being considered for cultivation in exposed environments, mussels (e.g. *Mytilus edulis*, *M. galloprovincialis*, *Perna canaliculus*) are becoming the forerunners of the options in terms of production. Mussels, being low value, must be produced in volume to enable a viable enterprise. To produce such volumes at exposed sites, requires large structures that are robust, relatively inexpensive, easy to maintain and operate, and most importantly support the survival, growth and conditioning of the cultivated species. Mussels are usually grown in suspended cultures where the crop hang from substrates on ropes, nets or in baskets, trays or other structures within the water column.

The SEE and EV indices have been applied to a selection of four commercial and semi commercial mussel farms (FS1, FS2, FS3, FS4; Table 3) located in exposed areas in the southern and norther hemispheres (northern hemisphere FS1, FS2, southern hemisphere FS3, FS4). The mean and maximum values (d, U_c, H_s and corresponding T_p) are known for these farms so that they can be assessed using the two indices. In this instance only the maxima 50-year indices will be shown. Since all existing farms are submerged below the water surface (between d_s = −3m and d_s = −12m), we have also calculated the indices for a hypothetical surface farm at the same locations to illustrate how the energy content at the surface compares to the actual farm position at depth. In Table 3 the four sites, FS1 to FS4 were tested with the primary variation being the water depth (d) of the sites and the position of the farm in the water column (d_s). While FS1, FS3 and FS4 are fully functional, FS2 is still in its early stages of development and experiencing several challenges.

FS1 has its backbone in a submerged configuration of −5 m in the water column, which leads to a reduction of the energy potential of almost 10% for the EV and even up to 20% for the SEE. For FS2 it is as much as approx. 17% (EV) and over 30% (SEE), for FS3 7.7% (EV) and as much as 20% (SEE), and finally 6.1% (EV) and 7.6% (SEE) for FS4, respectively (Table 3). It is evident that lowering a farm in the water column can lead to a reduction in energy. The reduction in energy is limited in the case of FS3 because the farm has a greater water depth (d). For FS4, the percent difference is also less than for FS1 and FS2 despite the similar water depth since there is only a slight reduction below the water surface (d_s). To illustrate this energy reduction, the % differences in the respective depths of the four farms FS1–FS4 are shown in the bar chart (Figures 6A, B). FS2 shows the greatest energy reduction, which is due to the worst-case data of this farm with a wave height of H_S = 9.3 m and a current speed of U_c = 0.90 m·s^{-1}.

3.3 Seaweed (macroalgae)

Except for a few species that have a high-value (bioactive) component (Holdt and Kraan, 2011), seaweed (e.g. *Macrocystis* spp., *Lessonia* app., *Ecklonia* spp., *Undaria* spp., *Laminaria* spp., *Saccharina* spp) have a low value and can only be grown in large mass cultures to be economically viable. Similar to the cultivation of mussels, large-scale culture facilities, usually in the form of horizontal backbones, grid, ring or raft structures (see Buck and Buchholz, 2004; Tullberg et al., 2022, Lian et al., 2024; Heasman et al. in review[4]), must be installed to provide substrate for the young plants to reach market size. Like all technologies in exposed areas, the materials used must be durable, robust and inherently stable in order to successfully grow the seaweed on site.

Most seaweed farms worldwide tend to be located in sheltered areas close to the coast, as is the case of China, Indonesia, South Korea, Philippines and other Asian countries (FAO, 2022). Production in the coastal waters of North and South America, Europe and Africa, and the South Pacific (including Australia, New Zealand) is marginal compared to Asia. Whilst many scientific research projects are working on the possibility of open ocean macroalgal farming (Moscicki et al., 2024, Buck et al., 2017), only a few producers have ventured into exposed waters. In Table 4 we have listed one commercial farm (FS5) and three semi-commercial or scientific farms (FS6–FS8). The mean and maximum values of these farm examples are known (d, U_c, H_s and corresponding T_p) and are evaluated using the two indices EV and SEE. As in Table 3, only the maximum indices are shown here, and these data are compared to structures floating at the surface with d_s = 0 m as well as in their current original position.

FS5 has its backbone in a submerged configuration at only −1 m in the water column, which results in a small reduction in energy potential of 3.9% for the EV and as much as 11.4% for the SEE. For FS6 the values are also lower, namely 5.1% (EV) and 7.9% (SEE), but for FS7 they are 9.5% (EV) and even 15.1% (SEE) and finally only 4.4%% (EV) and 7.1% (SEE) for FS8 (Table 4), respectively. The lowering of the farm structure results in a lower index (EV and SEE). However, the reduction of the energy potential is lower than in comparison to the mussel farms FS1–FS4, since only low submergible depths are permitted as solar radiation is required to realise good photosynthesis rates. Shading by the sediment load (if present) or the absorption of certain wave lengths at depth will reduce algae growth. The high wave regime and the shallow depth make a commercially successful farm difficult, especially at farm FS6. At FS7, the wave height makes aquaculture difficult so, similar to FS6, the site selection criteria for offshore and/or exposed farming with longline technologies are not met. FS5 has a good location and the wave climate at the given depth does not create any major problems. FS8 can also be declared as a good site as shown by the low indexes. Figures 7A, B illustrate this reduced energy, the percent differences in the respective depths of the four farms FS5–FS8. FS7 shows the greatest energy reduction, but the energy potential is still too high for successful farming of seaweed at this site.

3.4 Marine finfish

Open ocean finfish farms [e.g. Drum sp. (*Totoaba macdonaldi*), Pacific Red Snapper (*Lutjanus peru*), Salmon (*Salmo salar*), Cobia (*Rachycentron canadum*)] are also benefiting from utilizing submerged structures to reduce the ocean energy experienced by the crop and equipment. However, finfish farms require more engaged husbandry than bivalve or seaweed farms since daily feeding and mortality recovery are required. As such, submergence is just one of several strategies used to manage ocean energy and the surface conditions are still relevant at these farms to determine the feasibility of operations.

Table 5 shows the relevant oceanographic parameters and resulting EV and SEE values for three commercial fish farms and one perspective farm at the surface and the depth at which the grids are installed. The values reflect 50-year return conditions based on extrapolation of shorter-term data collection efforts at the sites (several years in most cases). The depth of the grid is used as the d_s term. The tops of the pens are usually near the grid depth when they are in the submerged position, but this can vary based

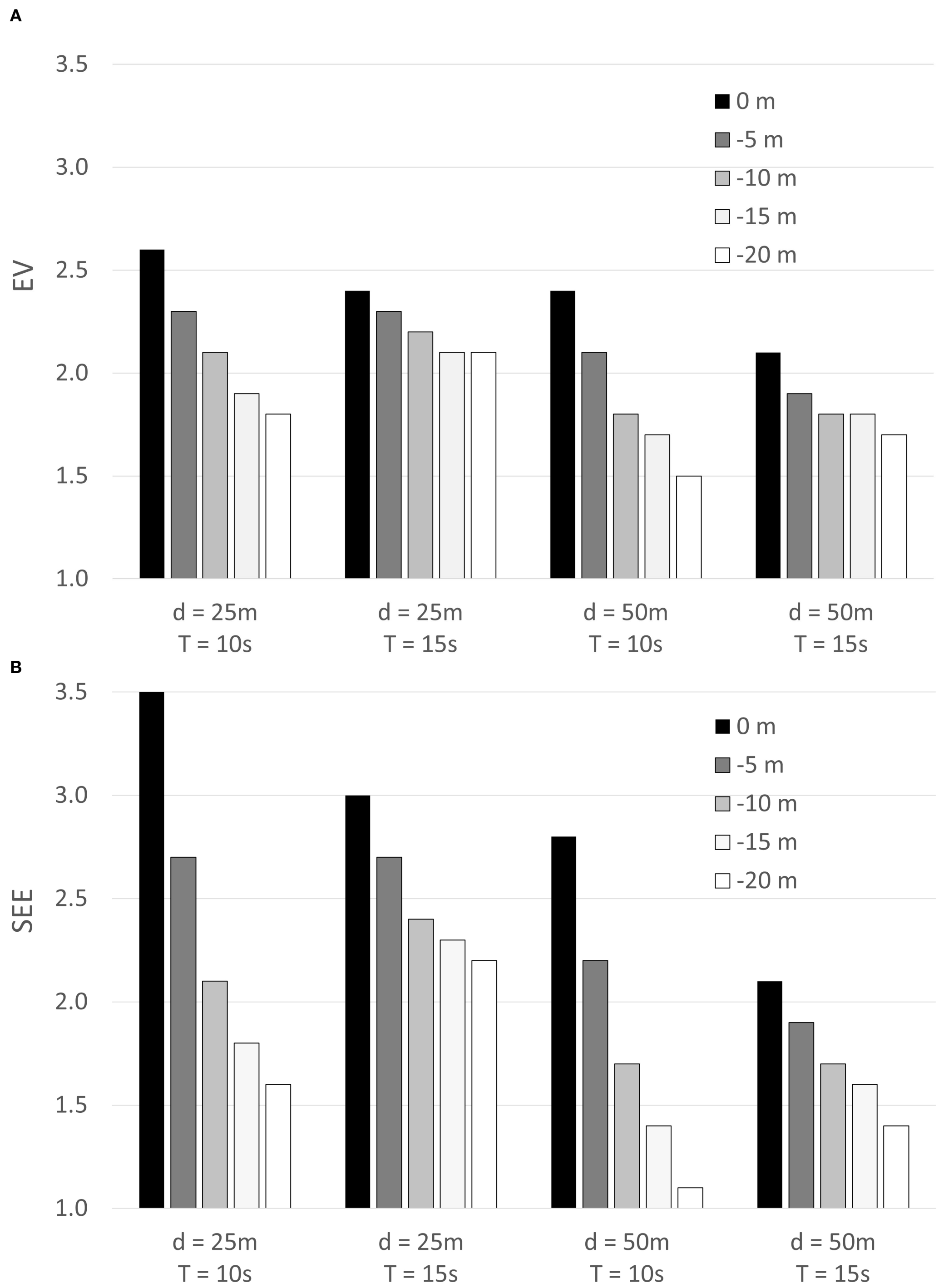

FIGURE 5
Indices **(A)** EV and **(B)** SEE at R1 and R2 related to the position of the farm structure in the water column with d_s = 0 m, −5 m, −10 m, −15 m and −20 m, a given wave height of H_s = 5 m and a current speed of U_c = 0.75 $m·s^{-1}$ for two different wave periods T_p = 10 s and T_p = 15 s and water depths of d = 25 m and 50 m, respectively. The bars show the reduction of the index value in % in relation to the water surface d_s = 0 m and the % deviation between the different depths d_s.

on the farm. Most of the pen volume and the bulk of the fish are below this level so the EV and SEE values reported in Table 5 are slightly higher than what the fish experience and the forces creating drag on the system. Still, using the grid depth for this analysis allows for consistent comparisons between farms and with FS1–8.

The finfish farm sites are submerged deeper in the water column than mussels or seaweed resulting in more significant reductions in EV and SEE. This is a result of deeper water at the sites and not needing solar irradiance for growth. FS11 enjoys the largest reduction in EV and SEE with index values falling 50 and 74.4% respectively. Managers at FS9, FS10, and FS11 have indicated that

TABLE 3 Extreme site and farm parameters of four commercial and semi-commercial mussel farms in exposed waters at two operation depths.

Mussel farm sites	d [m]	Max H_s [m]	T_p at max H_s [s]	d_s [m]	Max U_c [$m{\cdot}s^{-1}$]	EV Index	SEE Index
FS1 Lyme Bay, Devon, UK	28	8	12	0	0.5	3.2	5.2
				−5		2.9	4.2
				% deviation from surface index value →		9.4%	19.23%
FS2 Helgoland, North Sea, Germany	28	9.7	13.1	0	0.93	4.2	8.6
				−12		3.5	6.0
				% deviation from surface index value →		16.7%	30.23%
FS3 North Island, New Zealand	45	7.6	15.2	0	0.6	2.6	3.5
				−9		2.4	2.8
				% deviation from surface index value →		7.7%	20.00%
FS4 South Island, New Zealand	22	7.6	15.2	0	0.6	3.3	5.3
				−3		3.1	4.9
				% deviation from surface index value →		6.1%	7.6%

d = mean water depth, H_s = maximum wave height, T_p = wave period of maximum wave height, U_c = maximum current speed, d_s = depth of farm structure below surface.
Arrow (→) indicates where to find the % deviation from surface index value.

the ocean energy at their sites pose significant challenges for operations and equipment survival so submersible capability of the pens and reduction in EV and SEE are likely essential to make these sites viable.

Table 6 shows the same parameters for FS9 but using mean values instead of 50-year return values. This indicates the conditions, EV, and SEE values in which most operations occur. The values are substantially lower than those shown in Table 5 which is expected since these values are not used to evaluate equipment survival in extreme weather events, but rather the ability of a farmer to operate with reasonable ease and safety. Further, many equipment failures are due to high-frequency fatigue cycles, rather than extreme stress, making the EV and SEE values from averages conditions worthy of consideration in many contexts.

4 Discussion

The two indices have shown themselves to be able to provide useful insight to potential and existing aquaculture sites. They can also be used to assess the benefits of not only submerging the structures but how deep the submergence should be. Vessel capability and tolerance to conditions can also benefit from the indices.

These insights should not be considered independently however as there are concerns such as water quality (e.g. levels of oxygen) food availability (in the case of non-fed species), nutrients (in the case of seaweeds) that need to be assessed.

4.1 Extractive species: mussels and seaweed

4.1.1 Mussels

At sheltered, low exposure sites, such as those found in fjord bays or other sheltered regions, may have a maximum (storm conditions) index of approximately 1.5 (EV) and approximately 1.8 (SEE) (data taken from known sites within the Marlborough Sounds, New Zealand, as well as sites in Northern Europe, such as Norway, Denmark, and in Germany). At these index levels, access to the farm was possible more than 90% of the time with vessels capable of operating in 1 m swells. The double-header (also called a backbone) rope longline structure (e.g. New Zealand) or single header-rope longline structure (all countries worldwide) is used in these conditions (Newell et al., 2021). As bivalves grow, the amount of flotation is increased by additional buoys to compensate for the increasing mass. However, the way the double-header rope structure reacts to increased energy found on exposed sites means that this system-design has to be reduced to a single-header rope (Figure 8). The header rope is now also submerged to avoid the surface energy with only a few floats on the surface reducing the amount of energy transferred into the whole structure. Sites FS3 and FS4 (EV: 2.4 and 2.8, SEE: 3.1 and 4.9, respectively) use this general configuration (with some company variations).

Although the high energy has resulted in spat and seed rope wrapping around the header rope, floats becoming detached and occasional rope failure (Heasman, pers. obs., New Zealand), in general they are tolerant of conditions and can generate profitable quantities of quality products. Some of the issues and structural

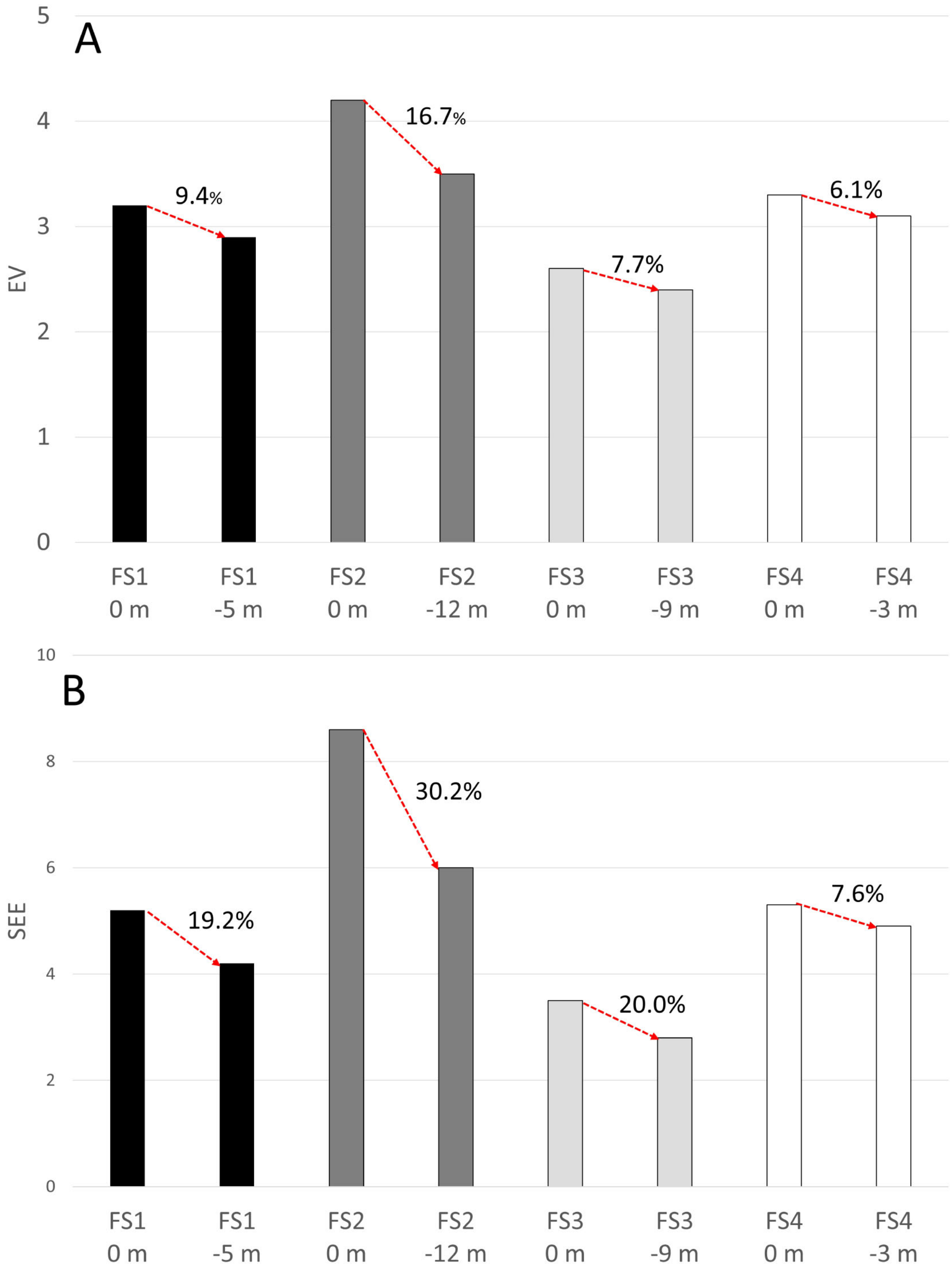

FIGURE 6
Effects of mussel farm positions within the water column at the water surface and up to −12 m below for farms FS1–FS4 using the **(A)** EV and **(B)** SEE indices.

stress can be mitigated by changing the orientation of the structure to waves and water currents (Heasman et al., in review)[4].

The location at FS4 is, however, shallower and modelling indicates that large waves may be steeper resulting in higher energy at the surface, and there is greater lateral water movement in high wave conditions near the seabed (see Figure 2). At this site the header ropes will be deeper to avoid the surface energy. However, if the header is dropped to 10m then the dropper ropes will be very close to the seabed and subject to the lateral energy being developed in that zone (Figure 2). Therefore, the droppers are shortened to have a safe zone between the seabed and the bottom of the production rope. This results in lighter production lines which results in greater movement. A shortened production line will also result in less production per m of header line, reducing viability.

FS1 is a submerged farm structure which, like FS3 and FS4, consists of a single backbone and is held in place by screw anchors

TABLE 4 Extreme site and farm parameters of four commercial and semi-commercial seaweed farms in exposed waters at two operation depths.

Seaweed farm sites	d [m]	Max H_s [m]	T_p at max H_s [s]	d_s [m]	Max U_c [m•s^{-1}]	EV Index	SEE Index
FS5 Funningsfjordur, Faroe Islands, Denmark	71	5.0	4.0	0	0.3	2.6	3.5
				−1		2.5	3.1
				% deviation from surface index value →		3.9%	11.4%
FS6 Roter Sand, North Sea, Germany	14	6.6	12.0	0	1.5	3.9	7.6
				−2		3.7	7.0
				% deviation from surface index value →		5.1%	7.9%
FS7 Helgoland, North Sea, Germany	28	9.7	13.1	0	0.93	4.2	8.6
				−5		3.8	7.3
				% deviation from surface index value →		9.5%	15.1%
FS8 Saco Bay, Maine, US	50	5.3	11.4	0	0.75	2.3	2.7
				−2		2.2	2.5
				% deviation from surface index value →		4.4%	7.1%

d = mean water depth, H_s = maximum wave height, T_p = wave period of maximum wave height, U_c = maximum current speed, d_s = depth of farm structure below surface.
Arrow (→) indicates where to find the % deviation from surface index value.

on the seabed and buoyancy floats on the surface. However, unlike FS3 and FS4, these are fitted with long cylindrical fenders. These dip deeper into the water column and do not ride the waves up and down. This means that far less energy from the surface waves is transmitted to the farm structure and mussels located below the surface.

FS2 is not a classic backbone, but a structure that resembles the Smart Farm AS (Norway)[7] in a modified form. A hollow HDPE-tube with watertight, welded ends floats on the surface of the water instead of the backbone with floats and serves as buoyancy for the entire structure. It is either connected to anchor blocks or suspended from piles driven into the seabed as is operated in Germany and the Netherlands. In the current, modified version, however, the tube is open and contains 5–7 sealed tubular bodies within that run the full length of the tube. These smaller independent tubes are filled with water or air depending on whether the intention is to submerge or float it. It can therefore be operated in a submerged mode experiencing only a little of the wave-generated surface energy. It is evident from the index value reduction of approx. 17% (EV) or approx. 30% (SEE) that the submerged mode is a necessary modification to the classic Smart Farm to enable it to be used for the safe cultivation of mussels at this site.

4.1.2 Seaweed (macroalgae)

The largest advantage of distant and/or exposed locations is the availability of space. Seaweed culture requires large arrays to be economically attractive, particularly with increased operating expenses associated with operating far from shore or in high energy environments. Further, those production systems must be at or near the surface to ensure algae receive sufficient light for growth. There are only a few cultivated species that can be grown in deeper areas of the water column. From a scientific point of view, most experience exists with the species *Macrocystis* spp., *Lessonia* app., *Ecklonia* spp., *Undaria* spp., *Laminaria* spp., *Saccharina* spp. or other kelp species from the Laminareales order. These algae can cope with lower irradiance and the accompanying light wavelength and do not necessarily have to be grown at the water surface (or slightly below). The near-surface system design excludes most other uses for this area. Thus, stakeholder conflicts are to be expected in the realisation of a seaweed farm at exposed but coastal sites. In addition, cultivation of seaweed near the surface in exposed sites subjects the crop to the strongest wave forces and possibly high-water currents which cause mechanical stress to the crop. Seaweeds with a relatively rigid and upright stipe may have disadvantages over those plants that have a flexible stipe. Rigid cauloids can become overloaded and consequently be damaged or even break, leading to the loss of biomass. More flexible cauloids are capable of quickly reorienting and thus becoming aligned with the direction of the current (Buck and Buchholz, 2005). In this regard, it is known that some kelp species can adapt to harsh conditions, as they develop an increased flexibility of the phyllodes compared to plants in sheltered areas and thus do not break off (Millar et al., 2021). It is also known that some seaweed can be pre-stressed during the nursery phase to reduce dislodgement. According to studies by Buck and Buchholz (2005), it is possible that laminarian species can adapt to strong currents by changing their morphology and taking on a streamlined shape. This

7 https://www.smartfarm.no/.

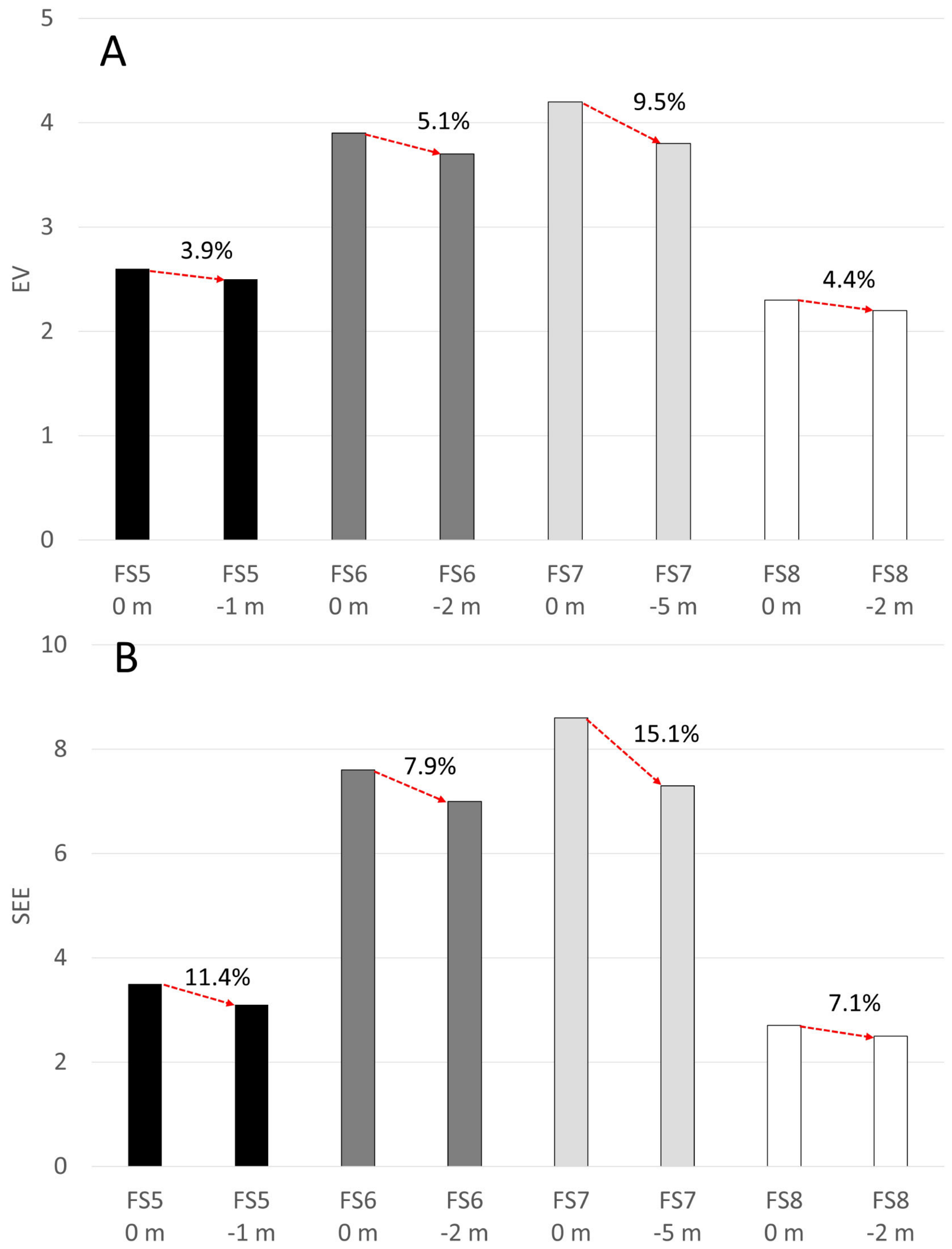

FIGURE 7
Effects of seaweed farm positions within the water column at the water surface and up to –12 m below for farms FS5–FS8 using the **(A)** EV and **(B)** SEE indices.

process can be accelerated by subjecting the kelp to an artificially induced current shortly after sowing on a substrate and before transferring the seeded ropes to the farm site (Buck et al., 2017). To achieve this, ropes were placed on a rotating drum device and gyrated in the water in the seeding tank. In this way, the plants strengthen their holdfasts and do not dislodge so quickly in harsh conditions. Over and above the stress effects on seaweed biology, care should also be taken to stay below a certain index value when looking for suitable farm sites as stress will affect the technology used. Neushul et al. (1992) indicates that a minimal current of 0.5–1.0 cm·s^{-1} is necessary for various macroalgal species to be able to absorb nutrients from the water column. In the scope of the SEE index, this would mean that a seaweed farm at the water surface would have to fulfil the index 0.5–1, both at a water depth of 25 m and 50 m. The EV index shows the same result at both depths (25 m and 50 m). A maximum limit for a flow is difficult to identify as each

TABLE 5 Extreme site and farm parameters of four commercial fish farms in exposed waters at two operation depths.

Fish farm sites	d [m]	Max H_s [m]	T_p at max H [s]	d_s [m]	Max U_c [$m \cdot s^{-1}$]	EV Index	SEE Index
FS9 Caribbean coast, Panama	64	5.9	11.0	0	1.6	3.3	5.5
				15		2.7	3.5
				% deviation from surface index value →		18.2%	36.4%
FS10 Hawaii, Kona Coast, US	60	5.7	9.0	0	2.1	4.1	8.4
				15		3.1	4.7
				% deviation from surface index value →		24.4%	44.0%
FS11 La Paz, Mexico	43	4.2	6.5	0	0.77	2.8	3.9
				12		1.4	1.0
				% deviation from surface index value →		50.0%	74.4%
FS12 New Hampshire, Gulf of Maine, US	58	10.0	12.0	0	0.8	4.6	10.7
				15		2.9	4.3
				% deviation from surface index value →		37.0%	59.8%

d = mean water depth, H_s = maximum wave height, T_p = wave period of maximum wave height, U_c = maximum current speed, d_s = depth of farm structure below surface. Arrow (→) indicates where to find the % deviation from surface index value.

species will vary. For *Saccharina latissima*, maximum values of up to 1.52 m/s have been identified (Buck and Buchholz, 2004, 2005), for Ulva spp. a maximum current speed of 0.45–1.2 m/s are destructive (Hawe and Smith, 1995). Knox and Kilner (1973) report data of up to 1.8 m/s which not only exceeds or severely limits available technology but would make operations and maintenance difficult or impossible. In the case of successful *Macrocystis* cultivation, data suggests it can be achieved in high water currents however in this instance a maximum value of 0.3–0.6 m/s is used from the known example farms listed in the Table 2. When choosing a site for growing seaweed with reference to maximum current velocities (and no wave height), no significant influence is found using either the SEE (less than 1 at both depths) or the EV index (1.2 at 25 m depth and 1.4 at 50 m depth), respectively. It may be useful to the reader to apply the additional lens provided by Frieder et al., 2022 who created the Macroalgal Cultivation Modelling System (MACMODS) to represent, among other things, changes in cultivated *Macrocystis pyrifera* within the farm in relation to different parameters such as light, flow and nutrients in regard to time and space.

However, the index becomes all the more important when wave height is included in the calculation. Some seaweed can withstand wave heights up to 4 m without having a negative effect on growth nor on stability. Wave heights of up to 6.4 m have been measured in some *Laminaria* reefs (Buck and Buchholz, 2005) without the algae breaking off or the cauloids breaking, but this seems to be an exception. Utter and Denny (1996) measured wave heights of up to 9 m, which severely affected the holdfast and lamina stability of *Macrocystis pyrifera*. Here, the loss decreased strongly with increasing depth. Based on the farms in Table 3, the wave height data ranges between 0.5 m and 1.0 m. This corresponds to an SEE of 0.5 and 1.2 for both depths, 25 m and 50 m, respectively. As soon as the seaweed farm is exposed to strong currents and additionally, severe wave heights, the energy (and therefore the indices) increase, and plants can be damaged (Denny and Gaylord, 2002), dislodged (Buck and Buchholz, 2005) or the "tip loss" can be increased (Kain, 1979). Therefore, when choosing a site for the cultivation of seaweed related to SEE, the index should not be higher than 4–5, or, in the case of EV, not higher than 5.5. If the exposed site is close to the shore, or the water depth is very shallow, the energy at the site is increased through wave interaction with the seabed increasing the risk of sediment resuspension in the water column. This could harm juvenile plants (Watanabe et al., 2016), create an abrasive effect on the entire plant (Araujo et al., 2012; Watanabe et al., 2016), and the sediment load causes light attenuation in the water column reducing the solar irradiance and algal growth (Kavanaugh et al., 2009). However, environmental conditions in nearshore waters can also vary extensively, affecting seaweed growth and the yield of farmed seaweeds (Kerrison et al., 2015; Bruhn et al., 2016).

Growth comparison of sugar kelp cultured on longlines nearshore at a mouth of a river and kelp grown 12 km offshore indicated significant growth differences based upon season, light variation, and nutrient availability (Chambers pers. Obs.). Nearshore, nutrients were available year-round allowing kelp to grow longer into the summer season before kelp health decreased due to warm temperatures and biofouling (Bartsch et al., 2013). Offshore, nutrient availability was reduced with calming seas and less vertical mixing of the water column. As a result, kelp health diminished by late spring.

In discussions on future seaweed cultivation in multi-use settings (combined with e.g., offshore wind farms) it is noted that

TABLE 6 Average site and farm parameters of the FS9 site.

Fish farm sites	d [m]	Max H_s [m]	T_p at max H_s [s]	d_s [m]	Max U_c [$m \cdot s^{-1}$]	EV Index	SEE Index
FS9 Caribbean coast, Panama	64	1.5	8.3	0	0.15	0.7	0.3

d = water depth, H_s = mean wave height, T_p = wave period of mean wave height, U_c = mean current speed, d_s = depth of farm structure below surface.

the nutrient availability at those sites far away from the coast is another key factor to allow seaweed farming. The tendency to position future offshore wind farms further from shore than they currently are (more than 50–100 km) would mean these areas become less attractive for seaweed farming due to lower nutrient concentration (BSH, 2019; van Duren et al., 2019; Paine et al., 2023).

4.2 Marine finfish

As mentioned in Section 3.4, not all net pens for finfish production in exposed environments utilize the submergence strategy. There are three broad categories employed; flexible gravity pens designed to conform to wave motion, rigid megastructures designed to resist wave energy, and submersible pens designed to evade the strongest surface energy (Heasman et al., in review)[4]. Production in flexible gravity pens does not create any novel problems or concerns although the existing concerns around equipment damage and fish stress from ocean energy are exacerbated. Pens need to be designed to managed the wave and currents and a fish species or strain needs to have the bioenergetic competency to grow at economically competitive rates in stronger currents and with higher turbulence.

There are very few rigid megastructure pens in operation which leaves a data gap in how this pen style interacts with the ocean environment and the biology of fish. Although several farm sites are in operation, data on specific operational or biological challenges are sparse. Salmar Aker Ocean operates the Ocean Farm 1 at a site with 5m significant wave heigh (currents speed not reported) and has completed three grow out cycles as of January 2024 (Romuld, 2024). Without further site data, the SEE and EV indices cannot be calculated.

Submersible systems create some significant differences from the technology used at sheltered sites. Perhaps the most important factor to note is the ability to utilize locations that have been deemed too rough for traditional net pens. The available space to farm fish using systems that can handle rougher environments is well beyond what is needed to meet global seafood demand (Kapetsky et al., 2013; Gentry et al., 2017; although it should be noted that macro-scale analysis like these may not capture economic constraints well). As shown in Table 5, submerging pens and grids 10–15 m below the surface reduces the effective energy level substantially, allowing higher energy locations to be utilized without a commensurate increase in the risk of equipment damage or fish escapes. Similarly, since the drag loads on the system do not increase as much at depth as is observed at the surface, anchors and rope sizes may not need to be increased as much, saving on capital costs relative to a surface-based system at that site. This is important from a global food security standpoint but is most impactful when considering certain regions that do not have sheltered coastlines. Many countries in Central America and Southeast Asia are in hurricane belts so even locations that do have some protection may still be subjected to extreme conditions with some regularity.

Turbulent water can affect fish in a few ways. Barbier et al. (2024) observed a 5% reduction in fish size over an 8-week grow out trial that created turbulent conditions in a tank environment. They observed significant differences in feed intake and behaviour during the first three weeks after which the fish acclimated and performed similarly thereafter. However, at a farm, turbulent conditions are

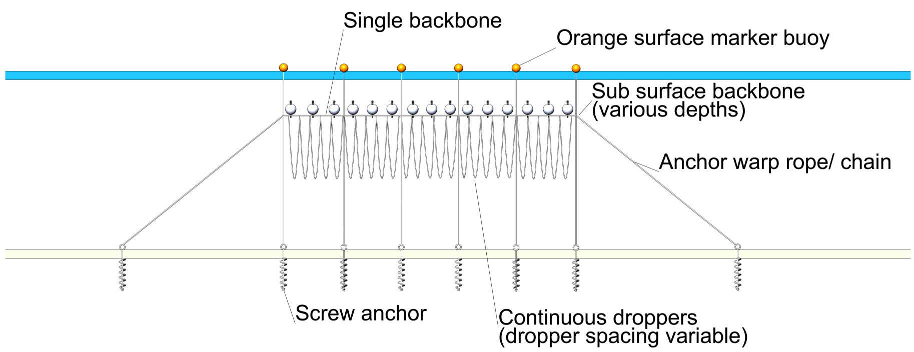

FIGURE 8
Diagrammatic set and forget system – next generation submersible backbone under testing. There is a clamp on the vertical moorings that holds the backbone under the surface.

episodic, so acclimation may be inconsistent between sites depending on how sever and frequent turbulent conditions are. Johannessen et al. (2020) has observed salmon avoiding surface waters during turbulent conditions indicating a stress response or less optimal conditions. The Barbier et al. (2024) article concluded that salmon should be able to adapt to turbulent conditions although exposed farms may observe different results depending on the specific site conditions. Submerging pens should alleviate this concern as wave energy is reduced. Studies on other species are not available although species with closed or no swim bladders may be better equipped to avoid surface waters. Likewise, farms with feeding systems that deliver feed below the surface would be expected to reduce exposure of the fish to rough surface waters.

High energy environments have a higher capacity to disperse nutrients and effluent from a fish pen, which can reduce impacts on the local benthic environment (Welch et al., 2019). In cases where fish farms have a high dispersion capacity and oligotrophic water, the stocking density at farms may be able to be increased above what is commonly observe elsewhere while maintaining benthic impacts at tolerable levels. Other limitations on stocking density such as density-related stress and disease risk would still be limiting.

The finfish species being cultured in open ocean environments are similar to what is produced in sheltered waters. Most species benefit from open ocean conditions as more stable temperature and dissolved oxygen are preferrable, as well as reduced connectivity with surface runoff. Stronger currents are also helpful to many species, stimulating growth (Jobling et al., 1993; Brown et al., 2011), reducing stress and aggression (Jobling et al., 1993), and improving flesh quality (Huang et al., 2021). However demersal or reef species often have lower aerobic scope so they may not see a benefit from stronger currents and can struggle in consistently high currents and suffer from the higher energy demand (Bjørnevik et al., 2003). If extreme currents are sustained for long periods, fish can become exhausted and pile up at the bottom and back of the pen creating stress, damage to scales and skin, and mortality.

Salmon is receiving the most interest due to market demand, familiarity with the species, and availability of seedstock. There are concerns around raising salmon in submerged pens since salmonids are physostomal and require access to air to inflate their swim bladders. Researchers are exploring techniques to mitigate this concern (Dempster et al., 2009; Korsøen et al., 2009; Yigit et al., 2024). Several tropical and sub-tropical species are gaining increased attention for open ocean farms since the technology needed to site farms in hurricane or typhoon-prone areas has only recently become available. Cobia, several *Seriola* species, red snapper, red drum, pompano, and tuna have all received commercial interest or are being actively produced in open ocean farms (Sclodnick, personal experience).

4.3 Vessels and operation and maintenance

Vessels that are being used for exposed mussel and seaweed farming at the farm sites FS1 to FS4 are generally large (>24 m length). The vessel size provides a platform that can tolerate the larger wave conditions ensuring access to the site for a minimum period during the year. This is about being able to maneuver freely within the farm and between the structures (longlines, longtubes etc.; Buck and Grote, 2018). Large vessel can add significant stress to the culture structures while attached to the structures during servicing, seeding or harvesting particularly if the current or wind speeds becomes stronger, or the wave height becomes higher increasing the indices.

The trends in vessel requirements for offshore production of finfish are similar to those for bivalves and seaweed. The distance between the farm and port is typically longer, making it essential that vessels can carry as much feed or harvested fish as possible. Also, the mooring system components (lines, anchors, etc) are subject to more wear and tear and are often larger, requiring more heavy-duty operations vessels. The rough conditions at open ocean sites makes it less feasible to use barges that are permanently station at the farm, requiring vessels to traverse the distance from shore each day, in most cases.

It has been demonstrated that with increasing submergence depth of any farm structure, be they mussels, seaweed or fish, the energy content that can act on the structure is reduced. However, with increasing depth and exposure, work on the farm becomes more complex and difficult. O&M on the structure, the mooring or the crop, such as monitoring, seeding, harvesting, other maintenance types of work or simply returning the structure back from its submerged position to the surface to allow further operation becomes more intricate and difficult. At this time there are three potential solutions to this issue. The first being a structure that is fully floated and is held down by releasable clamps e.g., set and forget (Figure 8) (Heasman et al., in review)[4]. A second solution could have the ability to be inflated either manually or automatically. The latter is appealing but is potentially complex and has further maintenance considerations. Access to electricity (possibly in wind farms) would greatly simplify some of these problems. This approach should be considered in any potential multi-use scenarios involving offshore wind energy farms (Buck and Langan, 2017; Schupp et al., 2019).

In terms of general structure operation and survival, the indices will provide an indication as to when the components of the structural system need to be improved, bolstered, or submerged. An important consideration for operation and structural survival is the interaction and transfer of energy between the floatation and moorings of a structure. Figures 9A, B shows examples of suggested improvements or changes required to accommodate the mooring/float relationship and variations to increase tolerance of the seas with rising energy. In general, an increase in robustness of mooring and header ropes (where applicable), floats and attachment points are required with increasing energy. In addition, the shape and attachment of floats may change (e.g. from a round to cylinder in shape) or floats may become more complex and include inflatable bladders or multiple inflatable tubes within a larger tube. As the energy increases further, the structure may be submerged to avoid the surface energy. In Figure 9A, examples of how buoyancy and design can be changed to improve durability and robustness with increased exposure. Object 1 is a standard spherical buoy, used in sheltered waters as it rides on the surface due to its shape. Object 2

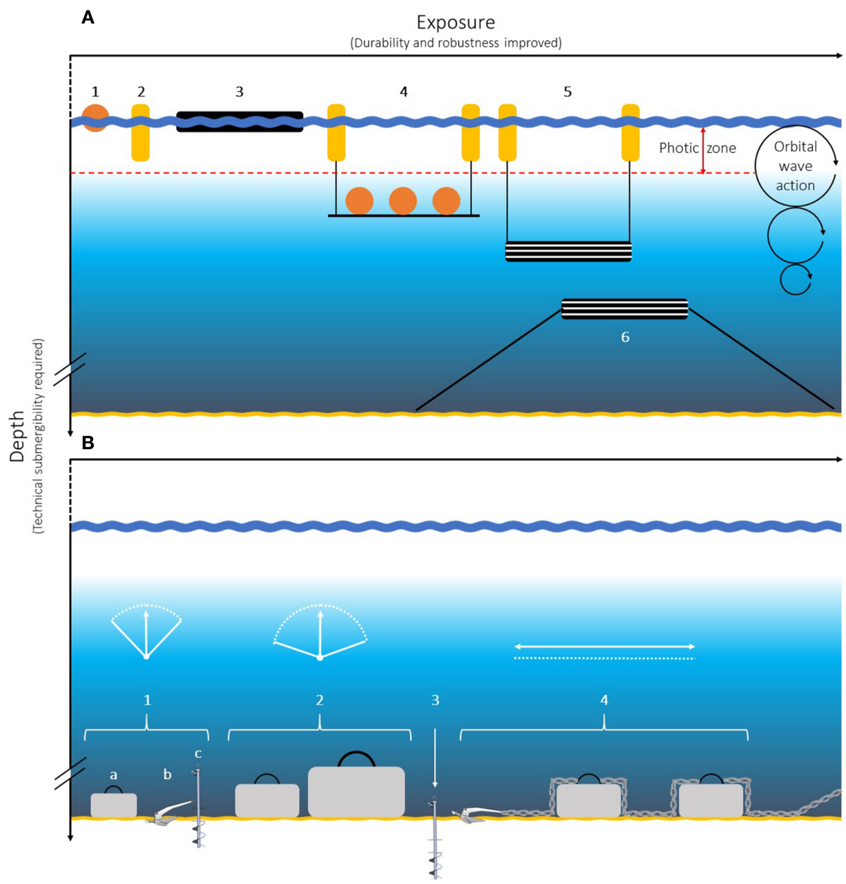

FIGURE 9
Illustration of primary components of farming systems for the cultivation of extractive organisms (mussels, seaweed). Shown are examples of buoyancy units **(A)** and moorings **(B)** of different system designs with increasing exposure.

represents a spar or fender float that can be used with increasing wave action, as it can be pulled down more easily and reducing tension shock events possibilities. Object 3 represents a long-tube design, where the backbone is hollow and thus forms the buoyancy body. Object 4 represent a header rope or long-tube design float that is submerged, fitted with additional small buoyancy buoys at depth and has spar/fenders at the top that only serve as markers. The culture ropes are hung from this unit. Object 5 is a submerged long tube with marker spar/fender floats and internal tubes or bladders where the air pressure can be changed. Object 6 is similar to Object 5, but with no marker to the water surface, and culture structures are suspended from this unit. The illustrations on the right in Figure 9 shows the decrease in the orbital wave (see also Figure 2). The red dashed line designates the photic zone where sufficient light still seeps through so that seaweed can photosynthesise. This can be taken a step further by having the structure completely bottom referenced (i.e. all structural flotation is submerged and maintained in position by direct attachment to the seabed) with only a surface marker, e.g. as seen in the Shellfish Tower (Heasman et al., 2021). Figure 9B show examples of anchoring and mooring for various degree of exposure. Mooring system 1 a, b and c (block, Danforth, screw/helix respectively) single moorings which can be used for lower energy areas. They generally have a narrow arc of attachment to the surface structures, while mooring system 2 involve larger blocks on which more vertical and lateral forces can be exerted without dislodgment. Mooring system 3 represents screw or helix moorings which, with the correct substrate, can be designed for vertical and lateral tensions. There are some limits to these anchors both in deployment depth and tensions applied; while mooring system 4 may be suitable for holding systems in high energy. They are generally a single direction, primarily lateral tensioned system where one anchor supports the next.

The increasing complexity associated with rising indices will indicate the need to include or upgrade smarter operational procedures, automation, submergence and a suite of sensors (e.g. wave height, duration and direction, water currents, turbidity). Operational procedures will include improved staff health and safety, increasing robustness of equipment, and tolerance of vessels to operating in larger waves. Semi or full automation will reduce the necessity of direct human involvement and could possibly respond to conditions without human intervention. This intervention may include submergence of the structures to avoid and escape from increasing surface energy. Sensors will be required to facilitate immediate data transfer for any human or automated responses.

4.4 Future needs

There are other potential structures that have either been tested and discarded or are in development for sites of increasing energy (e.g. the Smart Farm concept with a hollow, inflatable long tube or variations of it). Circular designs are possible and stronger in some respects as they distribute energy through the structure, but they are less space-efficient and more difficult to seed, harvest and operate (e.g., the Spanish Medusa shellfish structure or the offshore ring (Buck and Buchholz, 2004). Another disadvantage is the fact that such constructions have a one-point-mooring, which in principle is easy to handle, but in operation will have a certain radius as a watch circle and thus inevitably increases the necessary cultivation area. The linear designs are space-efficient and allow for continuous or "long lines" which are time-efficient for operations and management.

Structures to produce oysters in exposed regions are very limited but some are being tested. Structures suspended from mussel backbones (Heasman et al., in review)[4] have been used with success experimentally on FS3 (EV 2.4 or SEE 2.8) but are yet to be tested commercially. The shellfish tower (Heasman et al., 2021) has responded well to the conditions on the same site with ease and is suggested to be able to tolerate considerably higher conditions (EV >7.5 or SEE > 9) providing there is sufficient depth to submerge it below significant wave interaction. This structure is also being tested to produce scallops.

Our data sources utilised in the indices includes our most accurate estimate of the worst-case scenarios, reflecting extreme wave heights and current velocities which may only happen every 50 years. However future assessments may show that the estimations are insufficient since climate change is expected to both increase and decrease significant wave heights, depending on location (Lobeto et al., 2021) and wave form (Lemos et al., 2021; Lobeto et al., 2022). Therefore, vigilance will be required regarding the maintenance and updating of data when using the indices in the future. Catastrophic events such as tidal waves have not been considered however the indices may be used to estimate their potential influence.

5 Conclusions

The indices have shown themselves to be useful tools in the general assessment of the energy that will influence the species and structure selection at potential aquaculture sites. This information can help prospective fish farmers characterize their sites concisely and accurately to consultants, regulators, equipment vendors, and insurance brokers. Using case studies of successful farms in association with the energy indices there can be confidence in the determination of the tolerances of the structures and the ability of them to cultivate their relevant species.

It is important to note that the indices do not provide an indication as to the potential financial success of a site. This requires other inputs relating to structure costs, annual production, distance from port, CapEx, etc. Once the indices have indicated the practicability of the site relative to structural, species and vessel aspects to now add different lenses of assessment to determine the variables that are still open.

In the case of seaweed production in exposed seas the limiting factor is the tolerance of seaweed to energy and as such a maximum index can be described for seaweed production. For bivalves and finfish, the maximum index will be influenced by the structural design, position in the water column, orientation (for linear systems), species, depth, O&M and vessel access.

The indices will provide some indication of vessel size requirements, but its operational parameters will vary according to the species, structures it is supporting, its purpose within the husbandry/harvesting/maintenance process and the distances it has to travel.

Orientation of linear structures is important for the reduction of damage and maintenance and potential loss of crop.

Shallow waters in exposed conditions increase energy and the associated structure and husbandry requirements.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

KH: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. TS: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. NG: Methodology, Writing – original draft, Writing – review & editing. NS: Visualization, Writing – original draft, Writing – review & editing. MC: Writing – original draft, Writing – review & editing. TD: Methodology, Validation, Writing – original draft, Writing – review & editing. SR: Validation, Visualization, Writing – original draft, Writing – review & editing. HF: Writing – original draft, Writing – review & editing. BB: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

Authors TD and SR were employed by the company Kelson Marine Co. Author TS was employed by the company Innovasea.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Finding the right spot: laws governing the siting of aquaculture activities

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Marine aquaculture has grown enormously in recent decades, and with it the competition for space suitable for aquaculture. These developments have limited the areas available for aquaculture and, in some cases, have become a barrier to expansion. In response, aquaculture operations have moved further away from the coast. This development has created a need for clearer and more robust approaches to more comprehensively describe and secure sites for aquaculture. This article reviews the law governing the siting of aquaculture operations. In particular, it assesses the role of the widely used term “offshore” in the Law of the Sea to see if there are any legal aspects that need to be considered in moving towards the use of more specific concepts. It also aims to inform scientific discussions and political and administrative processes on the law governing the identification, description, and siting of aquaculture operations. This will hopefully contribute to more sustainable and less conflicted long-term aquaculture development.

KEYWORDS

aquaculture law, aquaculture governance, marine spatial planning, siting of aquaculture operations, sustainable aquaculture

1 Introduction

The farming of fish, crustaceans, molluscs and various marine plants has grown rapidly in recent decades. According to the FAO, in 2022 and for the first time in history, aquaculture has surpassed capture fisheries as the main producer of aquatic animals (FAO, 2024a). As a result, aquaculture is already making a significant contribution to meeting the global demand for fish in the face of a growing world population, changing consumption patterns among the expanding middle classes in developing countries, and mitigating the depletion of many wild fish stocks (see also FAO, 2022, pp. 211–216). Farmed seafood also performs well in terms of sustainability compared to other livestock production worldwide (Troell et al., 2023; Naylor et al., 2021).

Its dramatic expansion, however, has also raised a number of concerns and objections, particularly regarding negative environmental impacts and its overall level of sustainability (Jiang et al., 2022; Wilding et al., 2018; Weitzman et al., 2019; GESAMP, 1991, 2008), and lately also with neglecting animal welfare (Elder, 2014; Birch, 2017; Brown and Dorey, 2019; Mather, 2019; Ellwood, 2012; although different perspectives can be observed: Browman et al., 2019; Jacquet et al., 2019; Seibel et al., 2020).

Developing marine aquaculture – or mariculture – creates competition with the best places to fish. In some areas, useable marine space has become scarce and spatial conflicts intensify, particularly near populated coastal areas (Hipel et al., 2018; Tuda et al., 2014; Hamilton, 2013; Hovik and Stokke, 2007; Gowing et al., 2006). Traditional activities such as shipping (commercial and naval), fishing, extracting oil, gas, and minerals, and tourism have expanded, and new types of offshore activities have emerged (such as different types of renewable energy, etc.) (Kleingärtner, 2018). At the beginning of the 21st century, even the ocean's remotest spaces have become subject to exploitation (Koschinsky et al., 2018; Markus, 2018). Hance Smith has aptly coined this overall development as the "industrialization of the world ocean" (Smith, 2000) and others have referred to it as the "blue acceleration" (Jouffray et al., 2020).

The struggle for access to or use of marine waters has had a negative impact on the development of aquaculture. Conflicts between aquaculture projects, fisheries, and tourism have been reported and analysed (Bergh et al., 2023; Bienstman et al., 2020; Dempster and Sanchez-Jerez, 2008). Conflicts with nature conservation are also common (GESAMP, 2008). Aquaculture has also been adversely affected by agriculture and wastewater discharges (Díaz et al., 2012; Gowing et al., 2006). These developments limit the space available for aquaculture, especially as marine aquaculture requires areas with specific environmental and water quality characteristics. Often the lack of suitable space has been a barrier to expansion (Sanchez-Jerez et al., 2016).

Not least in response to increasing competition and conflict over marine space, aquaculture operations have moved further from the coast and often into more energetic environments, i.e. areas exposed to more wind, stronger tidal currents, and higher waves (Buck et al., 2024; Hipel et al., 2018). This development has created a need for terms and concepts that allow those involved in the siting of aquaculture operations to define sites in more than just vague terms of distance from shore (Buck et al., 2024). In particular, terms such as "offshore" or "open ocean" should be replaced by more robust concepts that refer to aspects of a site such as the geographical distance from shore or infrastructure, the degree of exposure to large waves and strong currents, the geographical fetch, the water depth, or a combination of these parameters (Buck et al., 2024). Increasing conceptual clarity can promote a common understanding and better identification of marine site characteristics and allow comparison and evaluation of sites for development (Heasman et al., 2024).

The purpose of this article is to review the existing Law of the Sea in general, and aquaculture law in particular, in order to assess what concepts and rules currently govern the siting of aquaculture operations. In particular, the role of the term "offshore" in the law of the sea will be assessed to see if there are any legal aspects that need to be considered in moving towards the use of more specific concepts. It also aims to inform scientific discussions and political and administrative processes on the law governing the identification, description and siting of aquaculture operations. This will hopefully contribute to sustainable and less conflictual aquaculture development in the long term.

This manuscript is part of a suite of papers comprising a special edition "Differentiating and defining "exposed" and "offshore" aquaculture and applications for aquaculture operation, management, costs, and policy". The special edition includes manuscripts focused on aquaculture policy and regulation in marine environments, the definitions of terms regarding aquaculture in marine systems, the derivation of the energy indices, trends required to advance aquaculture into high energy marine zones, costs and implications in aquaculture of using the indices and social science aspects relating to marine aquaculture (Buck et al., 2024; Sclodnick et al., in press).

The article is structured as follows: first, it describes some of the basic socio-economic impacts of aquaculture siting (Section 2). Second, it outlines the existing legal framework within which marine aquaculture activities take place in three sub-sections, international law relating to maritime zones, responsibilities and requirements for aquaculture projects, and the siting of aquaculture projects (Sections 3.1–3.3 respectively). Thirdly, it will assess how the basic geographical concept of "offshore" is used in the Law of the Sea and illustrate its limited use in locating areas suitable for aquaculture (Section 4). The paper concludes with a summary and discussion of the scientific and policy need for greater conceptual clarity and its use to better implement international and national legal requirements to promote responsible and sustainable siting (Section 5).

2 Social-economic effects of siting aquaculture operations

Aquaculture operations exclusively occupy ocean areas that were formerly freely accessible and where resources were shared (Bankes et al., 2016b, p. 7). Where governments support and strengthen operators' claims to these spaces, they turn into something economists would call economic institutions and lawyers would refer to as use or property rights (Munzer, 1990; Penner, 1997). Foreclosing other users from specific areas or resources, however, clearly has distributional implications (Markus and Markus, 2021; Posner and Sykes, 2010; Hallwood, 2014). At a fundamental level, aquaculture operations reduce the overall ocean space available to others. Other aquaculture operators are excluded and will have to move their activities to places where farming might be more expensive. Production costs may be higher because ocean spaces are further away from shores, not directly connected to harbors and markets, have lower water quality, or because they are more exposed to strong winds, waves, tides, and currents, etc (Buck et al., 2024). Potential users from other sectors are also excluded from using these areas. They may, for example, have to evade, reroute, or relocate their shipping, fishing, mining, or energy production activities. In addition to foreclosing access by others to aquaculture sites, operations may also generate costs for economic actors elsewhere. Facilities may, for example, lower the touristic value of coastal areas in close proximity to the farms, both due to spoiled views and (possible) negative impacts on the marine environment.

3 Legal frameworks for siting aquaculture operations

The following section outlines international and national policies and laws that order human activities in marine spaces in which aquacultures takes place. This includes policies and laws that direct and guide those who are actively involved in siting aquaculture projects. The first subsection outlines binding rules of international law that establish a zonal framework in which coastal states can develop their own spatial orders for aquaculture. The second subsection provides an overview of policies and laws that states should consider when ordering marine spaces and selecting specific sites, e.g. environmental responsibilities. The third subsection highlights policies specifically designed to guide the process of siting aquaculture projects.

3.1 Zones in international law and coastal states' spatial orders

The starting point of all law on sea-related investigations is the United Nations Convention on the Law of the Sea (UNCLOS) from 1982. It contains 320 articles and nine annexes and seeks to provide a global and comprehensive framework regime for the oceans. Its preamble explicitly acknowledges that the "problems of ocean space are closely interrelated and need to be considered as a whole". UNCLOS is often referred to as the "constitution for the oceans". Especially relevant for the purposes of this article, UNCLOS divides the seas into different zones and allocates the coastal states' sovereign powers, rights, and duties. With a view to aquaculture production, four zones are of importance. UNCLOS distinguishes between inland waters, territorial waters, exclusive economic zones (EEZ), and the high seas (the so called "archipelagic waters" are a special case, applying only to archipelagic states as defined in Art. 46 and Art. 47 UNCLOS). All zones extend from the baseline, i.e. the starting point for delimiting a coastal state's maritime zones. From this point onwards, the areas in question encompass inland waters, extending landwards, territorial waters up to 12 nautical miles seawards, and the Exclusive Economic Zone (EEZ) from the outer limit of the territorial waters to 200 nautical miles from the baseline. Whereas in principle, the sovereignty of the coastal states extends to inland and territorial waters, they only have functionally limited sovereign rights for the purpose of exploring and exploiting, conserving, and managing the natural resources in the EEZs (Art. 56 UNCLOS). The high seas stretch beyond the EEZ and the continental shelf (Art. 86 et seq. UNCLOS). Here the "freedoms of the high seas" apply (freedoms of shipping, overflight, laying submarine cables and pipes, installing systems, fishing, scientific research, etc.) which entitle all states to develop aquaculture projects.

Within the limits of rights granted under UNCLOS, coastal states are free to govern these zones. Most importantly, this means that coastal states can permit and regulate economic activities such as fishing, mining, energy generation, or – the case in point – aquaculture. They can thus also establish a marine spatial order in the sense that they may allow or ban such activities in certain areas. A spatial order is systematically developed by the responsible authorities and institutions of each coastal state. In federal states, such as Germany or the United States, authorities can be part of the federation or the federal states. Occasionally the division of powers between the different governmental levels and institutions can be quite complex and result in confusing governance structures regarding different maritime activities. In Germany, for example, the Constitution assign powers to regulate offshore mining in territorial waters and the EEZ to the central government, but it is the federal states who run the administrative procedures and grant or deny permissions. With regards to offshore-wind-farming, the central government regulates only activities in the EEZ, federal states have the right to do so up to 12 nm (but less if the central government would decide so). Commercial fishing activities, however, are exclusively regulated at the EU-level. It is the central government who implements these rules (particularly quotas and technical measures).

3.2 Laws and policies laying down substantive requirements for aquaculture projects

International and national law also sets out substantial requirements that states have to consider while shaping their respective marine spatial order. For example, legal requirements exist regarding environmental conservation, navigation, and health protection.

There is no binding international treaty specifically designed to govern aquaculture activities. David L. VanderZwaag has aptly summarized the overall status of international aquaculture law when he writes of a "complex mix of international agreements, documents and initiatives (that) has emerged to promote sustainable aquaculture (…)" (VanderZwaag, 2016). Binding treaties such as UNCLOS, the Convention on Biological Diversity (CBD), or the Convention on Wetlands of International Importance (RAMSAR-Convention) establish rather general environmental conservation requirements. States are obligated, for example, to take measures protecting specific areas (e.g. wetlands) or specific species (e.g. migratory birds and cetaceans), to reduce pollution, to establish and implement environmental impact assessment procedures for potentially harmful activities (EIA), or to prevent the introduction of alien species, etc (VanderZwaag, 2016).

Many of these general obligations are further spelled out in international non-binding instruments, some of which specifically address marine aquaculture (VanderZwaag, 2016). Most importantly in this regard is the FAO Code of Conduct for Responsible Fisheries. While the Code mainly addresses marine capture fisheries, its general principles and one provision apply to marine aquaculture. In general, the Code demands the application of the precautionary approach and calls on states to promote public participation of fish farmers in policy formulation and implementation (see Art. 6 of the FAO Code of Conduct). More specifically, Art. 9 calls on states, inter alia, to develop an appropriate legal and administrative framework for aquaculture, to produce and regularly update aquaculture development strategies and plans, to establish an EIA-system specifically for aquaculture, and to cooperate with neighboring countries in aquaculture development. These general responsibilities are further elaborated in eight non-binding technical guidelines, on Aquaculture Development (1997), on Good Aquaculture Feed Manufacturing Practice (2001), on Health Management for Responsible Movement of Live Aquatic Animals (2007), on Genetic Resource Management (2008), on Ecosystem Approach to Aquaculture (2010), on the Use of Wild Fish as Feed in Aquaculture (2011), on the Use of Wild Fishery Resources for Capture-based Aquaculture (2011), and on Aquaculture Certification (2011). Many other technical reports have also been published, including one addressing aquaculture governance, titled "Policy and Governance in Aquaculture: Lessons Learned and Ways Forward" (2014) (VanderZwaag, 2016).

Within and often encouraged by this international legal framework, coastal states adopt their own policies and laws that govern aquaculture activities carried out by their nations or within waters under their sovereignty or jurisdiction (inland and territorial waters, and their EEZ). Most countries who have an aquaculture sector of a certain size have developed sets of rules (overview provided at FAO, 2024b and for academic discussions see Bankes et al., 2016a; VanderZwaag and Chao, 2006; for Chile see Wack, 2013). These often include national aquaculture strategies, permit and licensing systems, specific environmental conservation obligations (e.g. the obligation to carry out an EIA), differing (spatial) planning, reporting, monitoring, control, and enforcement requirements, as well as regulations regarding taxation or public funding (Howarth, 2006). Only a few countries, however, have adopted a stand-alone aquaculture code, specifically and comprehensively addressing aquaculture (e.g. South Australia). Most states rely on different sets of rather uncoordinated, sometimes contradictory provisions included in fisheries, land use, spatial planning, and environmental conservation codes (Bankes et al., 2016a, c).

3.3 Laws and policies directing the siting of aquaculture projects

Generally, different countries have adopted strategic approaches to structuring the location of ocean activities through some form of marine spatial planning (MSP). MSP has been broadly defined as "a public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives that have been specified through a political process" (Ehler and Douvere, 2009; Maes, 2008). In many countries MSP has become a key tool for managing the conflicts resulting from the increasing utilization and industrialization of the world's seas and oceans (Schubert, 2018, pp. 465–466; Tuda et al., 2014; Carneiro, 2013; Jay et al., 2013).

Recognizing aquaculture's spatial needs in this strategic planning process is key to ensuring that aquaculture projects are directed to suitable places. This has been acknowledged in some of the abovementioned instruments. For example, the FAO Code of Conduct calls on states to adopt integrated coastal area management frameworks to assist in determining access right and avoiding conflicts (Art. 10). Where aquaculture activities could potentially affect transboundary aquatic ecosystems, it encourages states to cooperate to ensure "responsible choices of species, siting, and management" (Art. 9.2.2.). The FAO Technical Guidelines for Responsible Fisheries No. 5: Aquaculture Development more specifically require that "governments should ensure that aquafarms are sited and managed such that adverse effects on environments and resources of other States are avoided." (FAO, 1997, p. 17). In particular, the newly adopted FAO Guidelines for Sustainable Aquaculture of July 2024 highlight the importance of appropriate marine spatial planning tools for site selection. According to the Guidelines "spatial selection must be carried out in a responsible manner in line with international instruments and agreed good practice." To this end States should adopt a "clear, transparent, equitable and inclusive process to designate suitable areas for aquaculture and sites within each area." The process should be, inter alia, be based on the best available knowledge, involve identifying and including relevant stakeholders, evaluate the potential environmental, social and economic impacts, as well as potential synergies and conflicts with other activities or protected areas. Special attention should be paid to small-scale sector (FAO, 2024c, paras. 4.2.3, 4.2.4).

Aquaculture thus needs to be considered in the process of MSP, both when specifying the economic objectives that should be achieved by the spatial plans as well as in the process of developing the plan itself. Some countries have adopted national marine spatial plans, some of which acknowledge the importance of aquaculture, and some countries have adopted specific spatial plans solely for aquaculture (Bankes et al., 2016a; Schubert, 2018, pp. 465–466).

Ideally the process of integrating aquaculture into marine spatial planning entails four main steps (which could be broken down into further smaller steps): 1) national or subnational scoping, 2) zoning, 3) site selection, and 4) area management (see Table 1).

The zoning and siting steps include assessments concerning areas' general and sites' specific suitability for aquaculture. Assessments at both stages rely to varying degrees on a complex set of biophysical, environmental, social, and economic, as well as regulatory information and criteria.

4 Ambiguity of geographical terms in the law of the sea

Actors involved in aquaculture often operate with spatial concepts such as "inshore", "foreshore", "offshore", or "open ocean". Such concepts have been used to characterize different types of aquaculture, referring to farms' location in relation to the shoreline. But moving operations further seawards has revealed that such concepts are neither very precise, nor do they provide clear information about the site's environmental, economic, and social

TABLE 1 Scoping, zoning, site selection, and area management for aquaculture.

Steps	Process
National/subnational scoping	• Review of national/subnational priorities for aquaculture • Identification of relevant stakeholders • Review and possible adaptation of laws, policies, institutional framework affecting aquaculture • Identification of general issues and opportunities • Identification of potential for cultured species and farming systems
Zoning	• Identification of areas suitable for aquaculture • Identification of issues and risks in zoning • Estimation of broad carrying capacity • Legal designation of zones for aquaculture
Site selection	• Assessment of suitability for aquaculture • Detailed estimation of carrying capacity for sites • Biosecurity planning and disease control • Authorization arrangements
Forming management areas	• Grouping of farms into management areas (delineation with stakeholder consultation) • Establishing an area management entity

Source: FAO/World Bank (2017).

conditions for aquaculture operations (Buck et al., 2024). Accordingly, definitions of what such terms actually mean differ among scientists. This particularly holds true with regards to the term "offshore" (Froehlich et al., 2017; Morro et al., 2021). To illustrate these terms' ambiguity, the following paragraphs will investigate the meaning and relevance of the term "offshore" from a literal and a legal perspective. While the analysis is not necessarily comprehensive, it illustrates that there is neither a common understanding nor a uniform practice at the national or international level regarding the use of the term "offshore" within the law of the sea.

The term offshore consists of two elements. In a non-legal, spatial, or geographical context, the word "off" usually indicates a certain degree of separation between different entities ("away from", "removed from", "separated", "not at" etc.) (see, for example, Cambridge Dictionary, 2024). The term "shore", on the other hand, is most commonly used to describe an area of land that stretches along the edge of a body of water. Merely joining together such relatively straightforward terms, however, does not allow for an objective definition of a specific area at sea. Based on a literal interpretation alone, the exact location, i.e. the geographical line where the shore begins and ends, as well as the distance between that line and a chosen geographical point at sea, lying "off" the "shore", remains open to interpretation.

Despite its vagueness, the term offshore (sometimes "foreshore") has globally appeared in many different national laws governing a variety of maritime activities such as fisheries, shipping, or oil extraction. Its meaning under these rules, however, has not been consistent over the years. The term has been used to describe both areas within close proximity to states' coasts and areas lying further out in the sea.

Several national laws have used the term in connection with regulations which have been applicable outside their territorial waters or even further out in the sea. Notably, until the late 1970s, many coastal states claimed territorial waters only up to three nautical miles (Noyes, 2015). For example, the Philippines Fisheries Act from 1932 ruled that boats larger than 3 tonnes gross were eligible for an *off-shore fishing license* but banned them from fishing within three nautical miles from the shore line (Sec. 18 and Sec. 21 Philippines Fisheries Act No. 4003: UN, 1957, p. 559). According to the Malayan Petroleum Mining Act of 1966 "*off-shore land* means the area of the continental shelf" which, in turn, is defined as the "sea-bed and subsoil of those submarine areas (…) beyond the limits of the territorial water" (Malaysian Petroleum Mining Act, 1966: UN, 1970, pp. 375, 378). The famous American unilateral Truman Proclamation from 28 September, 1945, referred to the term *offshore* in order to point out that oil deposits of interest to the U.S. lie in areas beyond the traditional three nautical mile limit of national jurisdiction.[1] The Cuban General Fisheries Statute from 1936 demanded that the masters of fisheries vessels only discharged certain waste materials "into the sea *off-shore* at a distance of not less than five nautical miles from the coast" (Art. 46 General Law on Fisheries, 1936: UN, 1951, p. 65). Specifically with a view to aquaculture, the National Offshore Aquaculture Act of 2005 in the U.S. provides that the term "offshore aquaculture" means "all activities, including the operation of offshore aquaculture facilities, involved in the propagation and rearing, or attempted propagation and rearing, of marine species in the United States Exclusive Economic Zone" (i.e. in an area lying beyond territorial waters) (Sec. 3 No. 6 National Offshore Aquaculture Act 2005).

In contrast, other national laws governing maritime activities have used the term offshore to regulate activities closer to shore. For example, the US Federal Water Pollution Control Act of 1948 as amended in 1970 defined "offshore facility" to mean "any facility of any kind located in, on, or under, any of the navigable waters of the United States other than a vessel or a public vessel" (Sec. 10 of the US Federal Water Pollution Control Act, Public Law 91-224, 1970). The UK's Mineral Workings (Offshore Installation) Act from 1971 had as its territorial scope the "waters in or adjacent to the United Kingdom up to the seaward limits of territorial waters, and the waters in any designated area within the meaning of the Continental Shelf Act 1964" (Sec. 1, Sec. 8 Mineral Workings (Offshore Installation) Act from 1971: UN, 1974, p. 107). The Singapore Liability (Oil Pollution) Act of 1973 defined an offshore facility as "any facility of any kind located in, on or under many of the territorial waters of Singapore other than a ship" (Singapore Civil

1 "Petroleum geologists believe that portions of the continental shelf beyond the three-mile limit contain valuable oil deposits. The study of subsurface structures associated with oil deposits which have been discovered along the Gulf coast of Texas, for instance, indicates that corresponding deposits may underlie the offshore or submerged land. The trend of oil-productive salt domes extends directly into the Gulf of Mexico off the Texas coast. Oil is also being taken at present from wells within the three-mile limit off the coast of California. It is quite possible, geologists say, that the oil deposits extend beyond the traditional limit of national jurisdiction." Presidential Proclamation No. 2267: UN, 1951, p. 39.

Liability (Oil Pollution) Act, 1973). Finally, the Thailand Petroleum Act of 1971 provided that an "offshore exploration block" includes "the areas of those islands located therein (…)" (Sec. 28 Thailand Petroleum Act of 1971: UN, 1948, p. 102).

UNCLOS uses the term "offshore" seven times in total[2], referring one time to "offshore installations" and six times to "offshore terminals" (See Arts. 11, 211 (3), 216 (1) lit. c., 218 (1), (3), 219, and 220 (1) UNLCOS). Art. 11 UNCLOS mentions "offshore installations" and deals with the role of ports in delimiting costal states' territorial waters. It provides that for this purpose "(…) the outmost permanent harbor works which form an integral part of the harbor system are regarded as forming a part of the coast. Off-shore installations and artificial islands shall not be considered as permanent harbor works." In essence, Art. 11 UNLCOS regulates what is not an integral part of the harbor system. It aims to prevent coastal states from excessively pushing further into the sea – through building offshore structures – the points from which they can draw their baselines, i.e. the lines from which the outer limits of a state's maritime zones are measured (territorial sea, contiguous zone, exclusive economic zone (EEZ), and, to some extent, continental shelf). To not form such an integral part, structures need to be physically separated from the harbor system, that is, they must be located at a certain distance away from the harbor structures, which are themselves connected to the coastal landmass (on State practice see Symmons, 2017).

All other UNCLOS provisions using the term "offshore" are included in Part XII on the protection and preservation of the marine environment and specifically refer to "offshore terminals", i.e. Arts. 211 (3), 216 (1) lit. c., 218 (1), (3), 219, and 220 (1) UNLCOS. All of these provisions aim to ensure that the different UNCLOS provisions regarding the prevention of pollution by ships will be applied equally to coastal states' territories, ports, and offshore terminals. Offshore terminals have been defined as "artificial islands or installations outside the internal waters, which serve as port facilities for loading and offloading mainly oil and gas (…)" (König, 2017). There are, again, no exact criteria or methods to define the exact distance between territories, ports, and offshore terminals.

The most elaborate and systematic approach to defining the term "offshore" in an international treaty has been adopted within the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) of 1992. The definitions, however, mainly focus on describing certain activities, rather than defining the exact location where they will be carried out. The Convention defines "offshore activities" as "activities carried out in the maritime area for the purposes of the exploration, appraisal or exploitation of liquid and gaseous hydrocarbons" (Art. 1 j), OSPAR-Convention). In addition, an "offshore installation" means "any man-made structure, plant or vessel or parts thereof, whether floating or fixed to the seabed, placed within the maritime area for the purpose of offshore activities" (Art. 1 l), OSPAR-Convention). It also defines "offshore pipelines" as "any pipeline which has been placed in the maritime area for the purpose of offshore activities" (Art. 1 m), OSPAR-Convention). An "offshore source" includes "offshore installations and offshore pipelines from which substances or energy reach the maritime area" (Art. 1 k), OSPAR-Convention). All of these definitions refer to the "maritime area", which according to the geographical scope laid out by the OSPAR Convention, entails parties' territorial waters, their exclusive economic zones, as well as the high sea areas governed by the OSPAR-Convention.[3]

In essence, the term offshore only has two general implications: first, it points to a geographical spot not located on land, and second, this spot is to some extent physically detached from or not integrated into the shoreline (however that may be defined). It does not designate specific geographical points, lines, areas, or spaces, nor a certain distance. The term's vagueness is reflected in its inconsistent use within both national and international law of the sea. States have used it variably to describe locations either distant or close to their shores, sometimes lying inside and sometimes outside their territorial waters. Accordingly, where lawmakers need to define specific areas at sea more clearly, they are required to apply additional, more objective and more specific criteria or methods.

5 Discussion

The struggle for access to or use of marine waters can slow the development of aquaculture. Not least in response to increasing competition and conflict over marine space, aquaculture operations have moved further from the coast. This development has led to calls for clearer terms and concepts to enable those involved in aquaculture to describe and define sites with increasing precision. Greater conceptual clarity can support a better understanding and identification of marine site characteristics and allow comparison and evaluation of sites for development. At best, this will reduce conflicts and improve the economic and environmental outcomes of aquaculture operations.

The Law of the Sea does not prevent the development and application of such clearer concepts. In essence, it establishes a spatial order by defining maritime zones and assigning rights and obligations to States in these areas. Within these rights and obligations, coastal states are free to permit and regulate aquaculture. They can also establish their own marine spatial order in the sense that they can allow or prohibit activities in certain areas, including aquaculture. International and national laws also impose specific requirements on aquaculture operations,

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2 It only uses the term "shore" one more time in Art. 10 (3) on Bays. It uses the term "coasts" which has been defined in the UN Glossary as "the sea shore. The narrow strip of land in immediate contact with any body of water, including the area between high- and low-water lines" (UN Office for Ocean Affairs and the Law of the Sea, 1989, p. 52).

3 "Maritime area" means the internal waters and the territorial seas of the Contracting Parties, the sea beyond and adjacent to the territorial sea under the jurisdiction of the coastal state to the extent recognized by international law, and the high seas, including the bed of all those waters and its sub-soil, situated within the following limits (…), see Art. 1, OSPAR Convention.

including obligations to protect the environment, navigation and public health.

In general, various countries have adopted strategic approaches to structuring the location of marine activities through some form of marine spatial planning (MSP). Recognizing the spatial needs of aquaculture in this strategic planning process is key to ensuring suitable space for aquaculture. Ideally, the integration of aquaculture into marine spatial planning will involve a process of scoping, zoning, site selection, and area management. This is where approaches to defining aquaculture sites become relevant. As projects move further out to sea, the diversity of possible conditions increases and clearer concepts for scoping, zoning, site selection, and management are required.

For a long time, the term "offshore" was used interchangeably to refer to aquaculture sites further away from the coast. The literal and legal analysis of the term "offshore" has shown that rather vague geographical concepts alone cannot help to identify, assess and locate suitable aquaculture areas or projects. The growing diversity of possible aquacultures sites requires more clear and robust concepts to include aspects of a site such as the exact geographical distance from shore or infrastructure, the degree of exposure to large waves and strong currents, the geographical fetch, the water depth, or a combination of these parameters.

While various international treaties and national laws use the generic term "offshore" and other vague geographical terms to describe sites at sea, this does not prevent the development of clearer concepts to define aquaculture sites. In fact, the opposite is true.

It can be argued that the international obligations outlined above to take measures to protect specific areas and species, to reduce pollution, to prepare and implement EIAs, or to prevent the introduction of alien species, etc., require and call for the development of clearer approaches. In particular, the non-binding FAO Code of Conduct calls on states to adopt integrated coastal zone management systems and to cooperate with each other to ensure, among other things, "responsible siting" (where aquaculture projects may have transboundary impacts). In addition, the "Guidelines for Aquaculture Development" more specifically encourage "sustainable siting" meaning that "aquaculture production should be economically and socially appropriate, raise minimal conflicts with other users, and respect nature reserves, protected areas and sensitive habitats". There is also widespread agreement in the scientific community that a systematic process of scoping, zoning, site selection, and site management is required to implement all these requirements. All this argues for the development of approaches to define aquaculture sites. Only if aquaculture sites can be adequately described can marine spatial planning, including zoning and site selection, be adequately informed and help to secure suitable aquaculture sites and allow aquaculture development.

The above analysis also shows that the overall suitability of marine areas for aquaculture production depends on a number of other factors. Accordingly, assessing the characteristics of projects and sites requires a multi-dimensional descriptor-based assessment, reflecting the scientific, technical, economic, legal, and social characteristics of larger marine areas and of specific sites (see also Taylor and Kluger, 2018). A multi-dimensional set of assessment criteria for areas' and specific sites' suitability for aquaculture will have to be developed in the future. This paper has highlighted three general trends that may need to be considered as aquaculture moves further away from the coast. First, the number of conditions to be considered increases as the diversity of conditions for aquaculture operations increases. Second, facilities' exposure to higher energy levels in addition to longer distances from harbors and possibly markets is likely to make marine aquaculture more costly and risky. Third, while use interests from other individual users may decrease the farther operations move seawards, other countries' interests and legal rights will increase and have to be considered in the process of planning and site selection (e.g. other countries' rights in the EEZ with a view to navigation).

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Recommendations for facilitating offshore aquaculture: lessons from international experience

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In 2017, the Chilean government through the Chilean Economic Development Agency (CORFO) (an agency under the Ministry of Economy) launched a public call for the execution of a Technological Program to adopt, adapt, and/or developing enabling technologies for the development of Ocean Aquaculture in places with high-energy (strong waves, winds and/or currents). The consortium of companies, technology centers, and universities led by Ecosea Farming (Ecosea), focused its efforts on aspects related to structural engineering, mooring systems, sensors, Internet of Things (IoT), and other integral components, as well as essential aspects of regulation and standards. On this last topic, intensive collaborative work was carried out between the technical teams of the Andrés Bello University, the Undersecretariat of Fisheries and Aquaculture (Subpesca), the National Fisheries and Aquaculture Service (Sernapesca), and CORFO, with the aim of gathering relevant information from international experience, and establishing the main differences between aquaculture traditionally developed in the fjords, coast, estuaries, and inland sea of southern Chile and aquaculture in the high seas – a practice not yet clearly defined and still indistinctly known as offshore or open ocean aquaculture. This document summarizes the main findings obtained and can be a useful guide for future experiences in other countries with important aquaculture developments.

KEYWORDS

offshore aquaculture, ocean aquaculture, environment, spatial planning, mariculture

1 Introduction

In the last decade, aquaculture has been the fastest-growing food industry (Aanesen et al., 2023; Cantillo et al., 2023). One of the factors contributing to this growth is the efficiency of fish farming in terms of feed conversion rate (FCR) and carbon footprint. Unlike other protein-producing industries fish farming maintains a low FCR

(Cantillo et al., 2023), indicating that aquaculture can generate a higher amount of animal proteins with less feed (Yi and Kim, 2020a). Another relevant factor is the increase in demand for seafood products driven by population growth (Luna et al., 2023), which has pushed the salmon industry toward rapid growth and significant economic success (Garlock et al., 2020; Olsen et al., 2023). In Norway for example, remarkable changes have taken place over 50 years. The industry has gone from being a small sector guided by small entrepreneurs to becoming an industrialized, science-driven sector with high social and economic impact, currently being Norway's third-largest exporting industry (Hersoug, 2022). Another example is Chile, which has significantly increased its production to become one of the leading global producers of salmonids (Poblete et al., 2019), with a production of over one million tons in 2023 (www.subpesca.cl/portal/618/articles-120507_documento.pdf), focused mainly on Atlantic salmon (*Salmo salar*), which represents about 55% of the total national aquaculture harvest and approximately 75% of the country's salmonid production (Chávez et al., 2019; Lorena et al., 2022).

Although the contribution of aquaculture to human development is evident, negative perceptions of the industry have proven to be a major obstacle to its growth (Mazur and Curtis, 2008; Froehlich et al., 2021; Nathan Young; Whitmarsh and Palmieri, 2009). For example, in 2013 public scrutiny was partly responsible for the provincial moratorium on new salmon farm leases in Canada (CBC, 2015), societal interest in environmental sustainability is in more demand than ever before, and marine ecosystems and their interrelationships are better understood (Garza-Gil et al., 2016). In many cases, mariculture is an important ecosystem modifier in coastal areas, and one that can bring enormous social and economic benefits while potentially generating serious impacts on the health of marine ecosystems and humans (Uglem et al., 2014). Therefore, understanding public perception of the industry is crucial for policymakers and industry actors seeking to improve societal support (Olsen et al., 2023).

One of the most important impacts of intensive aquaculture is the release of large amounts of waste from fish cages in aquaculture areas, which are transported by the water currents and eventually settle on the sea bottom, consequently leading to deoxygenation of the aquatic environment (Yokoyama, 2002; Troell et al., 2009). Opposition groups have successfully slowed or even stopped the development of the industry in protected areas, demonstrating the importance of considering social dimensions when designing development strategies (Noakes et al., 2003; Barton and Fløysand, 2010; Knapp and Rubino, 2016). This criticism of social and environmental issues has hindered the growth of the salmon industry in several countries (Olsen et al., 2023). One example is the present situation in Chile, where the Chilean government is planning a new department for "Biodiversity and protected areas". The new department is expected to reduce the number of existing aquaculture concessions and impose constraints on the growth of this sector[1]. Consequently, there is a tense atmosphere between the current government and the aquaculture companies.

As an alternative to reduce competition for space in coastal areas and increase salmon farm production, offshore aquaculture has gained increasing attention in recent years (Watson et al., 2022), with this new way of production the farms will be moved farther off the coast, into the less protected ocean environment (Froehlich et al., 2017). Welch et al. (2019) conducted an environmental assessment of a fish farm operating in an exposed area under stronger currents and greater depths off the coast of Panama and demonstrated that wholesome marine fish for human consumption can be produced with minimal environmental impact. However, moving the farms to the open ocean can still present several challenges, such as fish escapes and the spread of disease (Jacquet et al., 2024), moreover, offshore aquaculture will not be free from ecological risks, which may be very similar to those associated with coastal aquaculture (Fujita et al., 2023).

Despite the increasing interest in offshore aquaculture, there is no clear consensus on the definition of "offshore aquaculture" (Holmer, 2010; Fujita et al., 2023), but it clearly involves activities located in open waters several kilometers from the coast (Morro et al., 2022). Recently, leading aquaculture countries (e.g., China and Norway) have moved toward large-scale salmon farming using offshore platform technologies, which would overcome environmental constraints (Zhao et al., 2019). Thus, China launched the Deep Blue 1 facility, which operates in shallow marine layers (Yi and Kim, 2020b). Another example is Chile, with the development of the offshore aquaculture consortium which is working with a submersible copper net pen (The Fish Site, 2021). Therefore, much of the current interest in aquaculture expansion has been stimulated by the development of infrastructure capable of containing marine organisms in waters with strong currents, bigger waves, and technology capable of supplying feed and monitoring operations at facilities located offshore (Fujita et al., 2023). Thus, the offshore aquaculture operation will require a review of the current regulations and their update, which will include logistics, environmental protection, and other relevant aspects (Watson et al., 2022).

In this research, we address three questions that the Chilean aquaculture and fishery authority has regarding offshore aquaculture. As a major world producer of salmon in ocean cage systems, Chile can simultaneously contribute and benefit from interacting with other major producing countries. The questions are:

1. What limitations does the current legislation have in granting aquaculture farms in offshore zones?
2. What do we understand by offshore aquaculture? Which term to consider in its definition?
3. What parameters should be considered in evaluating the suitability of future offshore aquaculture areas?

1 https://cooperativa.cl/noticias/pais/medioambiente/industria-salmonera-afirma-que-proyecto-de-areas-protegidas-seria-un/2023-05-26/091039.html

2 Materials and methods

For the first question, we analyzed the current regulation of aquaculture activity in Chile, especially those carried out in maritime areas under aquaculture concessions granted by the administrative authority. Although there are extensive regulations, for the purposes of this study, we focused on the norms found in the following regulatory bodies: a) General Law of Fishing and Aquaculture and its main regulations; b) Law of Maritime Concessions and its regulation; c) General Law of Environmental Bases and its Regulations; d) United Nations Convention on the Law of the Sea (analysis of the powers of coastal states in the Exclusive Economic Zone).

For the other two questions, the main methodology employed in this research involved conducting literature searches across two databases: Scopus and Google Scholar. The review process is outlined in Figure 1. The keywords used for the literature search were "Offshore aquaculture" and "Ocean aquaculture". To refine the search results further, the search was restricted to 'Title' for the Google Scholar database and "keywords" for the Scopus database. The search yielded 172 articles for Scopus and 20 for Google Scholar for the keyword "offshore aquaculture", and 4 articles for Scopus and 10 for Google Scholar for the keyword "ocean aquaculture". Out of these initial papers, 72 were discarded due to duplication, with only incidental mentions of "offshore aquaculture or ocean aquaculture" without being the main topic of research or being inaccessible. Ultimately, 134 articles were analyzed. We thoroughly examined each article to determine if they provided a definition of "offshore aquaculture" or "ocean aquaculture." In our research, we did not search the keyword "Open Ocean" as it could excessively broaden the scope of studies to analyze, given its wide use in various research topics such as fisheries (Gordon and Shipley, 2019; Joseph et al., 2019), microplastics (Pham et al., 2023; Sambolino et al., 2023), nutrient cycles (Bonelli et al., 2022; Baumas and Bizic, 2024), and migratory route studies (Hays et al., 2020), among many others. In addition, by searching the term "open ocean aquaculture," we found the studies we had already considered evaluating with the other keywords.

In parallel with the literature search, we conducted a search for documents from governmental agencies, bill proposals, or laws that defined "offshore aquaculture" or "ocean aquaculture" around the world. Each definition was coded using the software NVivo 14 to explore the main concepts and relevant words. We categorized the definitions into two groups: "literature" for definitions from scientific papers and "government documents" for definitions from government agency files, bills, or other documents required from a legal authority. In conjunction with the above analysis, we identify the main features that are mentioned in each definition.

Our research on Chile's legal framework is restricted to laws, decrees, norms, and other legal documents in force until April 2024. The literature search encompasses works in Spanish or English. The exploration for definitions of ocean aquaculture or offshore aquaculture in legal documents of countries other than Chile is limited to four countries: Norway, the United States, Australia, and

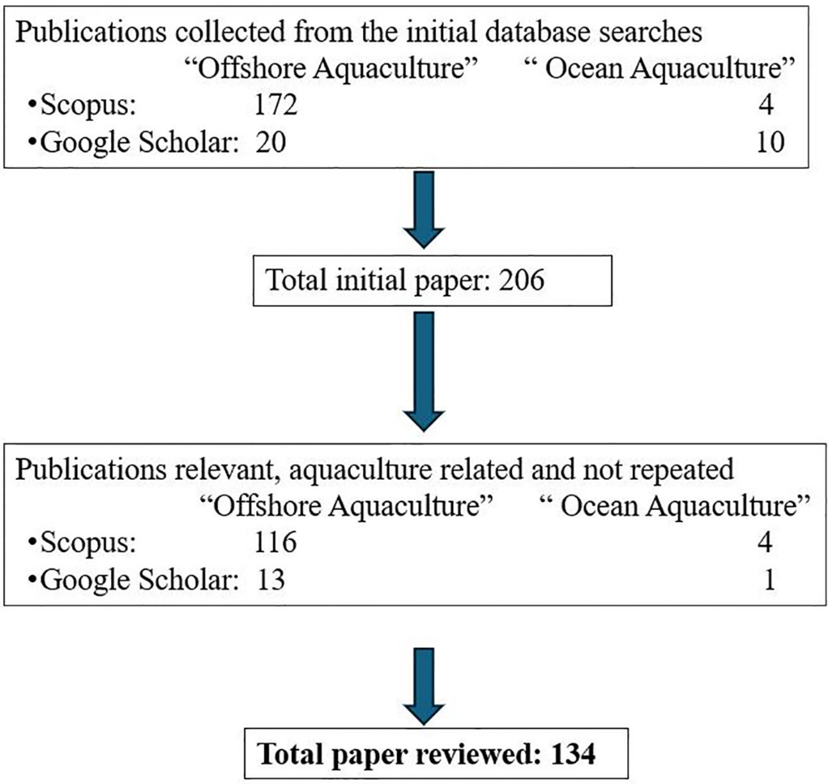

FIGURE 1
Overview of the literature search.

New Zealand. In a previous (unpublished) study conducted by our team for the Chilean authority, additional countries were analyzed. However, the aforementioned countries have research programs in offshore aquaculture that are relevant to Chile's interests, and a form of offshore aquaculture is expected to be more aligned with Chile's development. Therefore, we decided to confine the search to these four countries.

The current methodology confines itself to literary research conducted between January 1, 2010, and April 1, 2024. Our scope is restricted to English language materials accessible for download in any format that permits complete readability.

3 Results

3.1 Main laws and regulations in the aquaculture sector in Chile

The aquaculture sector in Chile is a highly regulated industry. Through the analysis carried out, various regulatory bodies dedicated to each aspect of the sector's activity were identified. A summary of the most important ones can be seen in Figure 2. As evident, all regulations stem from the political constitution of the country, which establishes rights leading to the creation of other rules and laws. For instance, Article 19, paragraph 8, establishes "the right to live in an environment free of pollution. It is the duty of the State to ensure that this right is not affected and to protect the preservation of nature." Additionally, numeral 21 establishes "The right to develop any economic activity…, respecting the legal norms that regulate it." Law 18,892 regulates this economic activity in its Title VI, "On Aquaculture," outlining the legal norms to be observed for its development. This includes aspects such as the concession title granted for carrying out this activity on national public property and the operation and exercise of the farming activity.

At the same time, another relevant norm is the Law on General Bases of the Environment, the law 19.300 established a system whereby various economic activities outlined within it are required to undergo an evaluation of their environmental impacts prior to their execution or modification. The National Policy for the Use of the Coastal Border created by the Supreme Decree 475 of the year 1994, applies to fiscal beach lands situated within an eighty-meter-wide strip, measured from the highest tide line of the coastline. This policy encompasses the beach, bays, gulfs, straits, inland channels, and the territorial sea under the control of the Ministry of National Defense and, Undersecretary of the Navy. This area is referred to as the Coastal Border of the Littoral.

Other, more specific laws and decrees stem from the aforementioned regulations, addressing matters such as the procedure for allocating concessions. For instance, Supreme Decree No. 290 of 1993 establishes the regulations for aquaculture concessions. In 2001, the Ministry of Economy, Development, and Reconstruction issued Supreme Decree No. 320, approving the Environmental Regulations for Aquaculture (RAMA). These regulations stipulate that aquaculture concessions must operate within the capacity limits of the water bodies in which they are situated. Simultaneously, the Regulation of Protection, Control, and Eradication Measures of High-Risk Diseases for Hydrobiological Species (RESA) was established through Supreme Decree 319 of 2001. This decree sets forth measures to protect and control against the introduction of high-risk diseases affecting hydrobiological species, whether originating from aquaculture

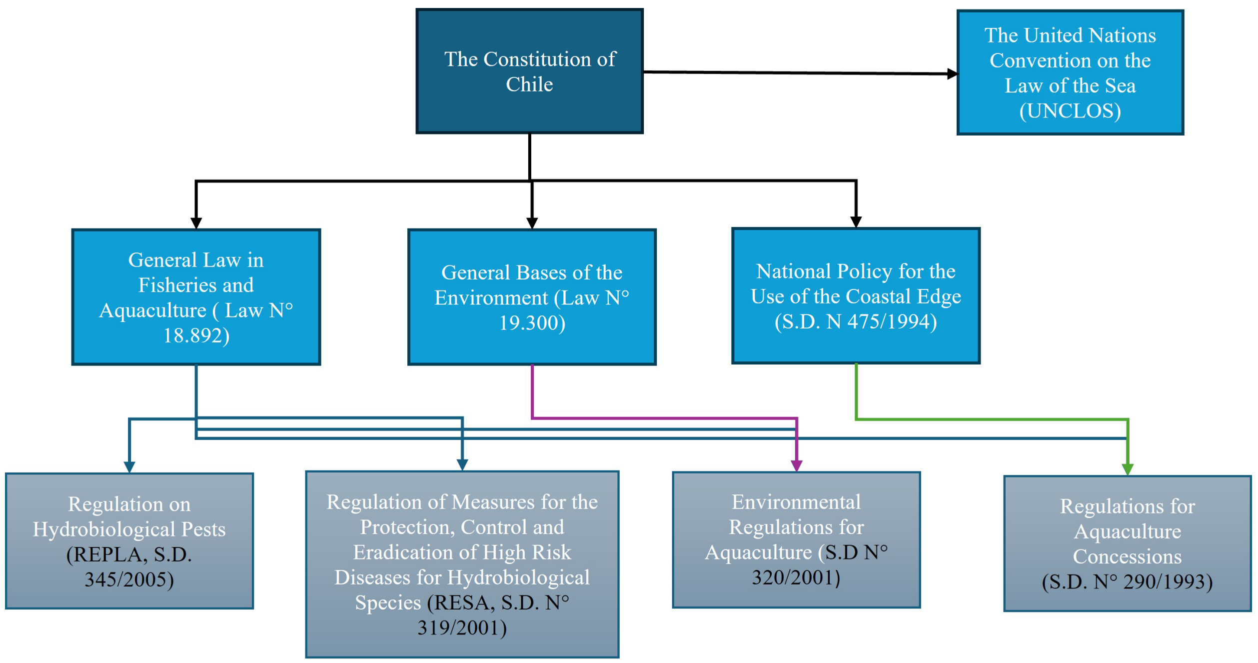

FIGURE 2
Main laws and norms in the Chilean framework.

activities for any purpose or in the wild. It mandates the isolation of any such diseases, prevention of their spread, and efforts toward their eradication.

3.2 Literature review

Only twenty-three out of the total articles reviewed included definitions of offshore aquaculture or ocean aquaculture, accounting for 17% of the total. Conversely, we found only seven government documents that define offshore aquaculture or ocean aquaculture. Consistent with Figure 1, we found more definitions in the literature search that used the term “offshore aquaculture” over “ocean aquaculture.” Legal definitions tend to use “marine aquaculture” over “offshore aquaculture”, the main term used in each group of definitions could be observed in the word cloud in Figure 3.

Similarly, scientific publications’ definitions of offshore aquaculture often mention environmental and/or oceanographic attributes, including “energy” (1.17%), “depth” (1.17%), and “water” (1.87%), with the latter term typically referring to depth. In contrast, legal definitions tend to focus on distances or specific locations, such as “miles” (2.11%), “nautical” (2.11%), and “areas” (1.41%). Regarding the main term in Figure 4, we observe that the distance from the coast is the primary term in both literature and legal definitions. Simultaneously, the term “open ocean” or “open sea” is the second most relevant. Furthermore, definitions derived from literature often encompass a broader array of environmental characteristics, including depth, currents, and waves, while also considering technological attributes. In our examination of government documents, we identified 24 relevant sources, comprising five from the Australian government, seven from Norway, seven from New Zealand, and five from the United States.

Of all the research and scientific papers reviewed from the countries surveyed, 37 describe the need to develop a maritime spatial planning process for offshore areas that consider other interests such as fishing, energy production, tourism, national defense, or conservation. However, only 9 of these documents conduct an empirical study to identify suitable areas for ocean aquaculture, providing criteria, parameters, and methodologies that can be replicated or adapted to other locations. The parameters used in these studies, along with the sub-models, specific weightings assigned to each criterion, and the target species for each study, are detailed in Table 1.

4 Discussion

4.1 Internal limitations to grant offshore aquaculture farms

It is necessary to determine if there are any limitations in the current legal framework for moving forward with offshore aquaculture in Chile. The General Fisheries and Aquaculture Law (LGPA) stands as a pivotal legal framework for regulating aquaculture activity in Chile. Under this law, aquaculture is defined as “the production of hydrobiological resources organized by humans” (LGPA, Article 2, paragraph 3) and is subject to specific legal standards for its development. Recognizing various forms of aquaculture, including concessions on national public assets, private waters, and private lands, the LGPA establishes a comprehensive regulatory mechanism.

According to the LGPA, aquaculture concessions, granted by the Ministry of National Defense, have a duration of 25 years and are renewable subject to environmental and location requirements (LGPA, Article 2, paragraph 12). The process for obtaining a concession entails the submission of a technical project and compliance verification by the Undersecretariat of Fisheries and Aquaculture (Subpesca) and the maritime authority.

Moreover, the LGPA integrates with the Law on General Principles of the Environment (Law No. 19.300), which mandates environmental impact assessment for various economic activities, including aquaculture. Specifically, Article 10 of the LGPA, in conjunction with Article 3 of the Environmental Impact Assessment System Regulation, outlines the types and magnitudes of aquaculture projects subject to environmental evaluation.

The United Nations Convention on the Law of the Sea (UNCLOS), provides a comprehensive framework delineating the rights and jurisdictions of states across diverse maritime zones. Within territorial waters, internal waters, the territorial sea, and

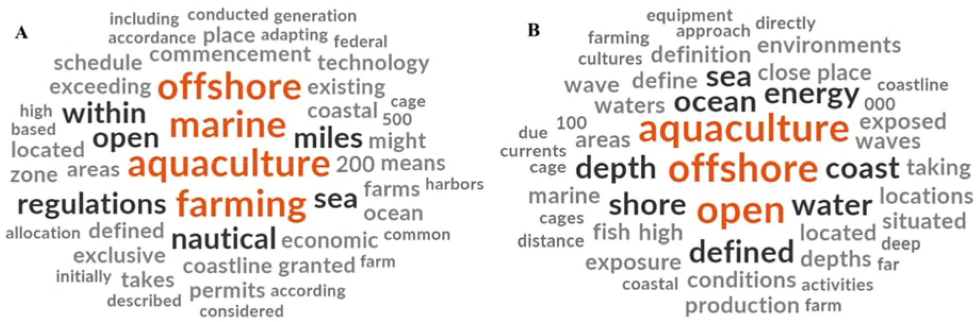

FIGURE 3
Word cloud for the two groups of definitions: **(A)** Government document definitions, and **(B)** Scientific literature definitions.

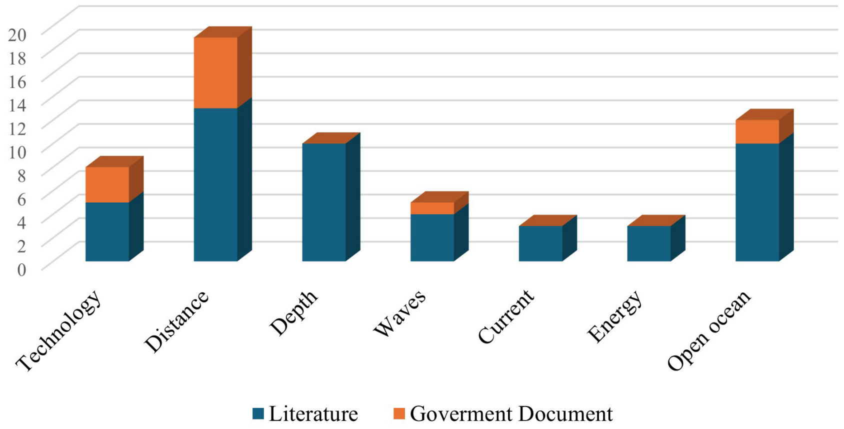

FIGURE 4
Main concepts in the definition of offshore aquaculture for literature review and government document.

contiguous zone states exercise full sovereignty, in these areas the coastal state extends its sovereignty to the air space over the territorial sea as well as to its bed and subsoil. This authority is explicitly stated in UNCLOS, which underscores states' rights in these areas (UNCLOS, Articles 2 and 3).

Moving beyond these areas, the Exclusive Economic Zone (EEZ) emerges as a distinct domain where coastal states possess sovereign rights for various economic activities, including exploration and exploitation of natural resources. However, it is essential for coastal states to acknowledge the rights of other states and ensure their actions align with the provisions of UNCLOS. Specifically, Articles 56 and 58 of UNCLOS outline the scope of these sovereign rights within the EEZ and emphasize the need for compatibility with international norms and agreements.

Moreover, UNCLOS acknowledges the exclusive right of coastal states to regulate activities such as exploration, exploitation, conservation, and management of hydrobiological resources, allowing to coastal state to construct and install structures for diverse economic purposes within the EEZ. This provision, as articulated in Article 60 of UNCLOS, extends to potential activities like aquaculture, providing a legal basis for coastal states to engage in such endeavors within their EEZ. However, it is crucial for any regulations governing aquaculture within the EEZ to adhere to the principles laid out in UNCLOS, particularly regarding the rights freedom of navigation, as stipulated in Article 87, thus preventing any undue interference or infringements on this fundamental right.

Based on the preceding analysis, the primary constraint hindering the progression toward offshore aquaculture in Chile pertains to the jurisdiction of the Ministry of National Defense, specifically delegated to the Undersecretary of the Armed Forces, which is limited to granting aquaculture concessions within the territorial sea. Consequently, Chile's ability to extend its aquaculture operations into offshore regions is restricted, limited to a distance of only up to 12 nautical miles. Article 47 of the LGPA law designates the first five nautical miles, measured from the coast's baseline, for artisanal fishing. This allocation does not restrict the granting of offshore aquaculture farms. However, to prevent potential conflicts with this economic activity in the future, it is advisable to explore areas beyond the fifth nautical mile to the west. Based on the current legal framework, offshore aquaculture farms can be granted in Chilean maritime areas within the territorial sea, located west of the 5 nautical miles measured from the normal baselines, spanning from the country's northern to southern limits. Figure 5 provides an example of the recommended area for advancing offshore aquaculture, we showed potential areas for zones in the south, center, and north of Chile. Aquaculture could be promoted according to the environmental characteristics of each zone. Finally, the Chilean authorities should incorporate additional criteria, to determine the definitive suitable areas.

4.2 Legal definition of offshore aquaculture

Terminology is important for streamlining marine policy, communication, and research. A better understanding of how words or terms are used can help identify key areas of overlap and/or differences and help make terms more tractable to stakeholders. Indeed, communication between the public, managers, and scientists requires better elucidations of terms, particularly at a global scale (Froehlich et al., 2017). Within this context, the definition of offshore aquaculture holds considerable significance for the prospective industry and its regulatory framework. The delineated terms within this definition possess the potential to delineate permissible operational zones for industry and requisite technological infrastructures. In our search, we discovered that literature predominantly discusses terms associated with the physical conditions in the environment, technological characteristics of the equipment and infrastructure used for farming, and political terms related to the spatial planning, in which offshore aquaculture farms operate. For a better understanding of the results, we classified the different terms used in the definitions into three categories: physical-environmental terms (such as current speed, wind, waves, depth, and distance to

TABLE 1 Parameters, their specific weights, and sub-models utilized in determining suitable areas for offshore aquaculture as per the literature.

Parameters	Weight	Sub model	Sub model Weight	Target species	Author
Military areas	0.33	National Security	0.25	Without target species	Riley et al., 2021
Special Use Airspace	0.33				
Military Training routes	0.33				
Cargo Vessel Traffic	0.5	Industry & Navigation	0.25		
Touristic Traffic	0.5				
Sensitive Habitat	0.5	Natural & Cultural Resources	0.25		
Protected Species	0.5				
Commercial Fishing	0.5	Fishing & Aquaculture	0.25		
Recreational Fishing	0.5				
Shipping lanes	0	Constraints	0		
Environmental sensor & Buoys	0				
Coral & Hardbottom habitat	0				
Active Oil & Gas wells	0				
Current Velocity (m/s)	0.3	Not sub model		In total, 21 species of seaweed, bivalves, fish, and crustaceans were identified as adequate aquaculture candidates accounting for their native occurrence in the German North Sea	Gimpel et al., 2015
Salinity (PSU)	0.1				
Sea surface temperatures (°C)	0.3				
Wave Height (m)	0.3				
Military areas	0.1				
Underwater pipes	0.1	Socio-Economic	0.33/0.125/0.75/0.125	Pacific Oyster (*Crassostrea gigas*)	Barillé et al., 2020
Bottom trawling	0.3				
Pelagic trawling	0.1				
Net fishing	0.1				
Touristic traffic	0.3				
Total oyster weight	0.75	Optimal Growth	0.33/0.125/0.125/0.75		
Coefficient of variation	0.25				
Bottom current	0.1	Environment	0.33/0.75/0.125/0.125		
Surface current	0.1				
Natura 2000 zone	0.4				
Bottom type	0.3				
Sole nurseries	0.1				
Bathymetry	Constrains			Finfish Aquaculture	Dapueto et al., 2015
Slope					
Marine Protected Area					
Marine SICs					
Diving sites					
Offshore sewage pipes					
Main harbors					

(Continued)

TABLE 1 Continued

Parameters	Weight	Sub model	Sub model Weight	Target species	Author
Area inside ports					
Forbidden areas					
Sea Ecological status		1st Environmental quality	0.176		
River and Streams		2nd Optimal conditions for fish	0.164		
Commercial & industrial facilities		Socio Economic evaluation	0.66		
Distance from highway					
Port size					
Distance to port (m)					
Sea surface temperatures (°C)				Atlantic salmon (*Salmo salar*) and Rainbow trout (*Oncorhynchus mykiss*)	Yu et al., 2022
Sea bottom temperature, SBT					
Sea surface salinity, SSS					
Sea bottom salinity, SBS					
Current Velocity (m/s)	Uninformed	Environmental Conditions	Uninformed	Atlantic salmon (*Salmo salar*)	Hasankhani et al., 2023
Dissolved Oxygen (mg/L)					
Salinity (PSU)					
Sea surface temperatures (°C)					
Wave Height (m)					
Wave Period (s)					
Bathymetry (m)					
Distance to port (m)					
Marine Protected Area	Uninformed	Conflicts			
Military areas					
Offshore wind					
Shipping lanes					
State and federal water					
Bathymetry (m)	0.4			Finfish Aquaculture	Cosgrove et al., 2023
Current Velocity (m/s)	0.3				
Wave Period (s)	0.3				
Bathymetry (m)	Was not weighted due to the uncertainty in the relative importance of each parameter			Finfish Aquaculture with wave energy	Garavelli et al., 2022
Wave Height (m)					
Current Velocity (m/s)					
Wave power density					
Shipping lanes					
Distance to port (m)					

(Continued)

TABLE 1 Continued

Parameters	Weight	Sub model	Sub model Weight	Target species	Author
Salinity (PSU)	Uninformed	Biological suitability	Uninformed	European *seabass Dicentrarchus labrax*; Gilthead seabream *Sparus aurata;* Atlantic salmon *Salmo salar*; Atlantic Bluefin tuna; Meagre *Argyrosomus regius*; Greater amberjack *Seriola dumerili*; Cobia *Rachycentron canadum*	Weiss et al., 2018
Sea surface temperatures (°C)					
Current Velocity (m/s)	Uninformed	Structural suitability			
Wave Period (s)					
Wave Height (m)	Uninformed	Operational suitability			
Bathymetry (m)					
Bathymetry (m)	The weight of each parameter in the final model is not reported.			Atlantic salmon (*Salmo salar*)	Fiskeridirektoratet, 2019
Sea surface temperatures (°C)					
Current Velocity (m/s)					
Wave Height (m)					
Salmon migrations					
Spawning areas					
Fish migration					
Vulnerable marine ecosystems					
Marine mammal observation					
Spread of Diseases					
Shipping lanes					
Military areas					

the coast), technological terms (such as the type of naval structures and vessels used), and legal terms (such as borders and definitions into UNCLO).

This group contains the largest number of terms, including distance to the coast, depth, current speed, wave height, and wind, on the one hand, the last three being particularly influenced by factors such as lunar cycles, seasonal patterns, and temporal variations. Froehlich et al. (2017) observed that the literature indicates offshore conditions typically commence with current speeds ranging from 0.1 m/s to 0.5 m/s. In our investigation, we encountered only three studies incorporating "current" as a component in their definition of offshore aquaculture. These studies describe the currents as "strong currents" (Holmer, 2013), "high-energy currents" (Morro et al., 2022), and "strong ocean current circulation" (Fukae et al., 2021). However, none of these definitions specify a particular threshold to define what constitutes a "strong current". In the case of waves, Froehlich et al. (2017) identified twelve distinct studies that referenced "waves" as a component within their definitions of offshore aquaculture, with reported wave heights ranging from 0.4 to 12 meters. In our investigation, we encountered five studies incorporating "waves" as a term in their definitions. Similar to the term current, four of these studies referred to "high waves" without specifying a particular threshold. (Silva et al., 2018; Morro et al., 2022; Visch et al., 2023) and "expose to waves" (FAO, 2013), Only one research provided a specific value for high waves in offshore conditions, indicating a threshold of 5 meters (Holmer, 2010). Moreover, there is no mention of the wave period, which is an important factor to consider. Because the increase in wave height and period leads to a non-linear increase in drag forces on the net pent (Martin et al., 2021), this can cause deformations and damage to the structures under extreme oceanographic conditions (López et al., 2024).

Some definitions of offshore aquaculture also mention the term "winds" as a differentiating factor, but to a lesser extent than the previously mentioned terms, in the study by Froehlich et al. (2017), only four research studies were identified that provided values for winds in the context of offshore aquaculture, with reported ranges spanning from 4 m/s to 35 m/s. In our investigation, only two definitions included the term winds. However, both instances merely indicated that winds in offshore areas are described as "strong" (Holmer, 2013) and without specifying numerical values, or farms are "exposed" (FAO, 2013). Including these terms in the definition of offshore aquaculture may introduce more uncertainty than clarity when delineating an offshore aquaculture site, a concern amplified by the potential impact of climate change on these physical phenomena. Furthermore, projections indicate that by the end of the century (2100), sea surface temperature (SST) will have increased by an average of 2.58°C and pH will have decreased

FIGURE 5
Potential offshore aquaculture zones within the current limitations of the legal framework in Chile.

by 0.32 units (IPCC, 2022; de Almeida et al., 2023). Consequently, potential future climate change scenarios could alter physical-environmental terms such as ocean currents (Bhanu Deepika et al., 2024) and waves (Liu et al., 2024). As a result, ranges previously defined as "high" or "strong," which were characterized as sporadic, could become the new "normal." This shift may necessitate redefining offshore aquaculture according to these new ranges.

On the other hand, physical environmental terms such as depth and distance from the coast do not exhibit significant seasonal or temporal variation. Consequently, these two terms systematically emerge as constants in the literature. Froehlich et al. (2017) and Watson et al. (2022) highlight the prevalence of these terms across various definitions of offshore aquaculture. Additionally, in our research, these terms exhibited consistent mentions, with 19 references to distance from the coast and 10 references to depth (Figure 4). For depth, the ranges presented in the literature mentioned offshore starting from 20 meters deep (Lester et al., 2018; Wu et al., 2024). Furthermore, other studies mention that the offshore condition begins at 30 meters (Froehlich et al., 2017), or even at 50 meters deep (Holmer, 2010; Sanz-Lazaro et al., 2021; Zheng et al., 2024).

In the Chilean context, the depths indicated as starting points for offshore conditions are often found within coastal aquaculture. According to current legislation, aquaculture farms are classified into seven categories according to the depth, production level, and characteristics of the seabed. Salmon farms with a depth greater than 60 meters are classified as category 5 (resolution No. 3612 of 2009 of the Ministry of Economy), these categories apply exclusively to farms located in channels and fjords. In the years 2021 and 2022, at least 168 and 153 category 5 salmon farms operated, respectively. This means that more than 150 farms each year were operating in sites deeper than 60 meters (SUBPESCA, 2023). In our analysis, we found that various definitions suggest distances ranging from two (Holmer, 2010; Nam et al., 2014; Zheng et al., 2024) to three kilometers (Sanz-Lazaro et al., 2021). Froehlich et al. (2017) also noted discrepancies, in his results he reports that different studies determine the distance from the coast that characterizes an offshore farm and that they can start from 0.38 nm to 25 nm, with an average of 3 nm. Although there is no clear consensus on the distance from the coast or depth at which the offshore zone begins, it is possible to state that this term refers to areas without large seasonal fluctuations. The small temporal fluctuation allows for terms such as depth and distance to the coast to be used in the definition of offshore aquaculture without major limitations, while simultaneously differentiating offshore aquaculture from coastal aquaculture.

Another term included in the definition of offshore aquaculture pertains to the technology utilized for operations in offshore aquaculture areas. Morro et al. (2022) state that specialized equipment and practices are necessary for accordance with the environmental conditions of offshore areas, additionally, Fukae et al. (2021) mention that offshore aquaculture has the ability to install larger-scale cages compared to coastal aquaculture, because, farms will have more physical space (will be larger in size) allowing for bigger farms (Fukae et al., 2021). Due to the more dynamic conditions in offshore areas, efforts have been made to design new structures that ensure reliable and safe farming, thereby preventing fish escapes and safeguarding human lives (Morro et al., 2022), The new offshore aquaculture infrastructure and equipment must withstand or be resilient to strong offshore waves, winds, and currents as well as resist corrosion and fouling (Fujita et al., 2023). In order to achieve that, there are 15 initiatives worldwide evaluating technologies to enable offshore aquaculture at the experimental level, and 18 at the commercial or pilot commercial level (Fujita et al., 2023). Consequently, today offshore aquaculture farms vary significantly in scale (Fujita et al., 2023). Among these designs, the famous Ocean Farming 1 by SalMar stands out, comprising a structure of 110 meters in diameter and 69 meters in height (Yi and Kim, 2020b), or the more traditional design used by Open Blue in Panama with submerged net pens measuring 35 meters in diameter and 24 meters in height (Welch et al., 2019). As a result, considering that offshore aquaculture technology is still in development, it would be unwise to include any technological term in the legal definition of offshore aquaculture.

The last group of terms used in the definition of offshore aquaculture is the political terms, as those outlined in the UNCLOS agreement could offer a viable alternative. This is exemplified by the proposed legislation exclusively aimed at regulating offshore aquaculture, as seen in the AQUAA bill 2023, which defines offshore aquaculture as "aquaculture conducted in the exclusive economic zone." These political divisions would facilitate the differentiation between traditional aquaculture, typically conducted in territorial or inland sea waters and offshore aquaculture. Today the National Oceanic and Atmospheric Administration (NOAA) classifies "Oceanic Aquaculture" as the aquaculture "which takes place in Aquaculture Opportunity Areas, in federal waters (from mile 3 to 200)" (Riley et al., 2021). In the case of New Zealand, offshore aquaculture is defined under the Resource Management (National Environmental Standards for Marine Aquaculture) Regulations 2020 as follows: "Offshore marine farm means any of the 5 existing marine farms initially granted coastal permits before the commencement of these regulations and located according to Schedule 2, and marine farms granted coastal permits after the commencement of these regulations but not located within 500 meters of mean high-water springs or within harbors and other areas described in Schedule 3." In Schedule 2, the government of New Zealand provides the geographic coordinates of the five offshore aquaculture farms, while Schedule 3 outlines the geographic boundaries in various areas of New Zealand where offshore aquaculture farms can be located.

Similarly, Norwegian authorities utilize a distinct definition when examining potential new offshore aquaculture sites. Although this definition has not yet acquired legal status, it draws a clear distinction between aquaculture operations in traditional farming sites and prospective offshore farms. It defines offshore aquaculture as "aquaculture that takes place further out at sea than is common today. In accordance with the salmon allocation regulations" (Fiskeridirektoratet, 2023). It is important to note that this definition is directly translated from Norwegian and may vary from an official translation provided by the Norwegian state. Following the previous direction and the recommendations outlined earlier, the definition of offshore aquaculture in Chile could be "all aquaculture activities conducted west of the artisanal fishing reserve area, between the Exclusive Economic Zone and the territorial sea".

4.3 Parameter to determining the feasibility areas for offshore aquaculture

The identification of appropriate areas for marine aquaculture development is a critical concern for spatial planning. A site selection study prior to determining the feasibility of offshore aquaculture by Benetti et al., 2010, addresses this issue. This research outlines essential criteria for selecting offshore aquaculture sites, including logistical, environmental, and regulatory factors. Furthermore, the study recommends assessing the economic and social conditions of potential locations, examining the hydrography of the area, and utilizing numerical models to estimate the environment's carrying capacity based on the food supplied to the fish (Benetti et al., 2010). Another pertinent study in this field is the research conducted by Gentry et al. (2017). They devised a comprehensive methodology that integrates scientific analysis to aid spatial planning for offshore aquaculture development. Their suggestions entail selecting sites characterized by strong currents and deeper water to mitigate impacts on the benthic ecosystem and minimizing connectivity between farms to manage disease outbreaks (Gentry et al., 2017).

The criteria and priorities chosen by decision-makers strongly determine the results of identifying suitable areas. For example, the NOAA study in the Gulf of Mexico and Baja California evaluated general criteria without targeting a specific species, aiming to open marine spaces for all species that can utilize these areas (Riley et al., 2021). In contrast, the study conducted by the Norwegian government focused solely on Atlantic salmon as the target species and could incorporate animal welfare criteria over operational or structural criteria (Fiskeridirektoratet, 2019). All the studies were multi-criteria, considering more than one parameter or constraint to decide which site is the most optimal for offshore aquaculture.

In studies that construct models for offshore aquaculture, current velocity (m/s) is the parameter most commonly chosen to explore the suitability (Gimpel et al., 2015; Weiss et al., 2018; Fiskeridirektoratet, 2019; Garavelli et al., 2022; Cosgrove et al., 2023; Hasankhani et al., 2023). In most of the studies, current velocity is used as a limiting factor for the structures. For example, in the work of Weiss et al. (2018) utilized a 50-year dataset to determine suitable areas for cages, and the current was assessed to evaluate whether the structure could withstand the conditions, they employed a generic cage across three distinct environmental scenarios: high exposure (more than 1.5 m/s), substantial exposure (1.0–1.5 m/s), and moderate exposure (0.5–1.0 m/s). The authors found that current velocities were not a limiting factor, with percentages of suitable areas exceeding 95% across all three conditions for each ocean (Weiss et al., 2018). The previous findings are corroborated by Garavelli et al. (2022), who found that current velocities were not a limiting factor. In their work, they identified suitable areas for offshore aquaculture and wave energy plants. Their research delineated suitable areas within the range of 0 to 1 m/s, employing the HYCOM hydrodynamic model to estimate currents in the study area.

Another point of view with respect to current velocity is in the research of Fiskeridirektoratet (2019) on a study commissioned by the Norwegian Ministry of Trade, Industry, and Fisheries, also involving the Directorate of Fisheries in partnership with the Institute of Marine Research. Their objective was to map and identify areas potentially suitable for offshore aquaculture. However, this mapping was confined to opportunity areas located beyond one nautical mile outside the baseline and within the exclusive economic zone, the baseline for the Norwegian authority is the line that defines the political maritime territory, according to UNCLOS technical requirements (Geirr Harsson and Preiss, 2012). In this study, the authors utilized ocean currents as a constraint on the swimming capacity of salmon. The aim of the Norwegian authority is to maintain optimal conditions for salmon welfare. They studied the Critical Swimming Velocity (CSV) for Atlantic salmon, the CSV is the maximum prolonged swimming speed and is obtained in laboratory trials by using swim tunnel systems (Hvas et al., 2021). Fiskeridirektoratet (2019) referenced the findings of the report by Hvas et al. (2021). In their research, the authors observed that the critical velocity varies with water temperature, oxygen concentration, fish size, and feeding status because after eating the fish reduces swimming capacity. The Norwegian authority's model aims to identify locations where ocean currents do not exceed 80% of the salmon's critical swimming velocity. With these criteria and the other parameters of the model, the State of Norway was able to identify 11 probable offshore aquaculture zones.

The second most selected parameters to study the suitability for offshore aquaculture are bathymetry (m), wave height (m), and sea surface temperature (°c) (Dapueto et al., 2015; Gimpel et al., 2015; Weiss et al., 2018; Fiskeridirektoratet, 2019; Garavelli et al., 2022; Yu et al., 2022; Cosgrove et al., 2023; Hasankhani et al., 2023). Bathymetry appears to be one of the primary limiting parameters for offshore farming structures, in the study conducted by NOAA to determine the aquaculture opportunity areas in the Gulf of Mexico, it was determined that the minimum depth to allow proper anchoring of the cages was 36.5 meters (120 feet). Dapueto et al. (2015) considered depths greater than 50 meters and less than 10 meters as limitations for their model, since depths greater than 50 meters increase costs and make anchoring more difficult. Garavelli et al. (2022) defined suitable areas within the range of 25 to 100 meters, depths greater than 100 meters are unfeasible for combining offshore farms and wave energy plants. Hasankhani et al. (2023), utilized a broader range of 0–250 meters, with a constraint over 250 meters. In general, depths over 200 meters are increasingly expensive as the depth increases (Gentry et al., 2017), longer mooring lines will be required in deeper waters, and optimal configurations may vary (Morro et al., 2022), with the development of new offshore technologies, the range in which an offshore farm can be installed will expand to deeper waters.

In addition to bathymetry, areas previously designated for other purposes have also been considered as restrictions. For instance, Dapueto et al. (2015) incorporated areas such as marine protected areas or diving sites as constraints into their model, this could be particularly relevant for countries where there is a conflict between coastal aquaculture and Marine Protected Areas (MPA). This is particularly relevant for Chile, where salmon farms often operate in MPA areas and generate social conflict. However, certain uses like military zones were not deemed as limiting constraints; instead, they were assigned lower percentages in the models. For example, Gimpel et al. (2015) and Riley et al. (2021) assigned weights of 10% and 25%, respectively, to military areas compared to other parameters considered in their models, as shown in Table 1.

Concerning the structure of the models used to estimate suitable areas for offshore aquaculture, a balanced model is built with the same weight for each parameter, an example of this is the model of Riley et al. (2021) which assigns equal weight to each of its sub-models (25%), which means that each of the four sub-models (National Security, Industry & Navigation, Natural & Cultural Resources, and Fishing & Aquaculture) is of equal importance. Conversely, Barillé et al. (2020) assess different scenarios by adjusting the values of their sub-models to determine the best approach for allocating offshore oyster farms, in their study, Barillé et al. (2020) evaluate which submodel most limits offshore areas by considering three submodels: socio-economic submodels, optimal growth, and environmental conditions. Dapueto et al. (2015), meanwhile, employ varied weights in their sub-models, with socioeconomic factors carrying the most weight in the outcome of their model.

Regarding the constraints of the models, we found that there is a wide variety of criteria. For example, Natura 2000, a network of protected areas, emerged as the most limiting factor for offshore aquaculture in Europe (Barillé et al., 2020), as strong environmental studies are required in these areas. In the study by Weiss et al. (2018), the primary limiting factors for offshore aquaculture areas were biological criteria, specifically salinity and sea surface temperature. Similarly, Yu et al. (2022) found sea surface temperature to be the limiting factor in their model of the Yellow Sea. On the other hand, Garavelli et al. (2022), explored suitable areas for aquaculture and energy generation, for their research, the most limiting factor was wave-generated power, which was not an inherent parameter of farm structure or the biology of the target species (Vázquez Pinillos et al., 2023). Similarly, Riley et al. (2021) considered the presence of active oil and gas wells, shipping lanes, coral and hardbottom habitats, environmental sensors, and buoys as constraints for their model.

To structure the model for estimating suitable areas for offshore aquaculture, it is interesting to analyze the two different approaches used by Riley et al., 2021, and Fiskeridirektoratet, 2019. The first study emerged from Executive Order 13921, which aims to promote competition and growth in the seafood production industry (Riley et al., 2021). Therefore, the model developed by the NOAA does not have a specific target species and does not employ specific biological parameters. On the other hand, the model developed by Fiskeridirektoratet, 2019, aims to expand aquaculture in Norway, specifically focusing on Atlantic salmon. Thus, significant factors considered in this model include fish welfare, disease proliferation among these fish, and their interaction with coastal aquaculture farms. It is the responsibility of the legal authorities, who possess the legitimacy to make decisions, to select the appropriate criteria, parameters, and methodology to determine suitable sites.

If a new aquaculture industry is to be created, we should learn from the past and consider the opinions of different stakeholders and local communities. Decision-makers should incorporate these opinions to determine suitable areas in collaboration with these stakeholders from the beginning. As outlined by Riley et al. (2021), this participatory approach involves conducting workshops with stakeholders to document the permitting framework and evaluate opportunities for offshore aquaculture development. These workshops also facilitated the establishment of initial parameters essential for commencing the study of aquaculture opportunity zones. Riley et al. (2021) indicate that over 175 one-on-one sessions were conducted with stakeholders and experts to inform their methodology and analysis. In the case of Norway, a new process was developed with extensive participation from stakeholders to determine the most suitable methodology for identifying offshore areas (Fiskeridirektoratet, 2023), The process establishes at least three instances where public consultations are deemed necessary to define sampling methodologies and analyze the results. These examples aim to foster greater social consensus during the industry's expansion.

5 Conclusions

In conclusion, the establishment of offshore aquaculture encounters various domestic constraints and necessitates a comprehensive understanding of legal frameworks, technological factors, and environmental parameters, as well as social issues. Chile's legal framework, governed by the LGPA and supplemented by international agreements like the UNCLOS, does not pose a constraint for granting offshore farms within Chilean waters. However, limitations arise from jurisdictional constraints within the Undersecretariat of the Armed Forces, which can solely issue maritime concessions in the territorial sea. If Chile intends to expand its aquaculture activities beyond this zone, modifications to the legal framework are imperative to broaden the jurisdiction of the Undersecretariat of the Armed Forces.

The precise definition of offshore aquaculture holds paramount importance for both effective governance and industry advancement. While physical parameters like depth and distance from the shore commonly serve as reference points, consensus regarding the specific criteria marking the transition to open ocean conditions varies considerably depending on the intended location of the offshore farm. Nonetheless, employing criteria that remain constant over time, unaffected by seasonal fluctuations, such as depth and distance from shore, could facilitate the establishment of a legal definition applicable uniformly across territories. However, incorporating technological aspects into the definition might prove counterproductive due to the dynamic nature of aquaculture technology, with diverse projects worldwide proposing various technological solutions. Instead, aligning with established policy frameworks such as the territorial sea divisions delineated in the UNCLOS agreement could offer a more standardized approach to defining offshore aquaculture.

Parameters for determining the feasibility of offshore aquaculture include bathymetry, wave height, sea surface temperature, and current velocity. These parameters vary in importance depending on the specific objectives of the model and the environmental conditions of the target area. Additionally, factors such as stakeholder and local community support, as well as previous uses of the space, play significant roles in determining suitable areas for offshore aquaculture. The structure of models used to estimate suitable areas for offshore aquaculture varies, with some employing a balanced approach while others prioritize specific factors such as socioeconomic considerations. Understanding these different approaches is essential for policymakers and stakeholders involved in offshore aquaculture development.

Author contributions

CC-M: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. DF: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. CH: Investigation, Supervision, Writing – original draft, Writing – review & editing. FP: Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. DB: Resources, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Status of off-bottom mariculture in wave-exposed environments. Part 2. Comparative loading and motion of longline designs currently used in exposed commercial farms

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A global inventory of extractive species mariculture in wave-exposed temperate waters shows that the longline is the technology used in more than 99% of the sites (Part 1 of this review). In this second part, I compare the static (longline at rest), quasi-static (tidal sea surface elevation, steady currents and mainline lifting operation) and dynamic (wind seas and swells) loading and motion of surface, semi-submerged and fully submerged longlines used to grow bivalves and kelp. This review is based on a hundred papers published on the subject mostly after 2010 and on simple analytical models used to illustrate the many compromises that must be made to ensure the survivability of the structure and the survival (retention), growth and quality of the cultured biomass. Surface longlines are unsuitable for fully exposed environments. To mitigate storm energy it is necessary to minimize the volume of surface buoys and submerge the mainline to the maximum depth possible. There is however a limit to minimizing the volume of surface buoys due to the uplifting of the mainline by currents. In the case of kelp, its optimal growing depth is within a few meters from the sea surface. This limitation can be partly circumvented by having the kelp float above the mainline. In the case of bivalves, mainline depth can be tens of meters below the sea surface. This comes with some disadvantages including difficulties in maintaining the delicate buoyancy balance, particularly for fully submerged longlines without legs, and reduced access to the mainline, particularly for fully submerged longlines with legs. Devices that allow autonomous or remote-controlled changes of mainline depth on a daily, occasional (husbandry and harvest operations) or seasonal basis have been tested but are not yet used commercially on longlines.

KEYWORDS
aquaculture, extractive, exposed, longline, loading, motion, currents, waves

1 Introduction

Aquaculture is currently expanding offshore in more exposed sites in response to the increasing demand for seafood and seaweed. As defined by Buck et al. (2024), exposed sites are unprotected from strong currents, large waves and strong winds and they may be near to land or far offshore. Compared to sheltered sites, exposed sites have several potential advantages, including more space (larger leases), fewer user conflicts, more stable and better water quality, better growth of the cultured biomass and fewer environmental impacts. However, they also have several disadvantages, including the need for larger and more powerful vessels, shortened operating window, increased risks of structural failure and cultured biomass loss caused by storms, and increased risks of marine mammal entanglement and for human health & safety (ICES, 2012; Lovatelli et al., 2013; Mizuta and Wikfors, 2019; Yang et al., 2020; Mascorda Cabre et al., 2021; Bath et al., 2023).

The companion article (Part 1) to this paper (Gagnon, 2024) presents a systematic inventory of extractive species (non-fed) off-bottom commercial farms in exposed temperate waters. This inventory shows that shellfish, tunicate and kelp grow-out in wave exposed sites (as defined in Part 1) are currently absent in many regions with a large extent of sheltered sites such as Norway, Scotland (UK), British-Columbia (Canada), Alaska (USA) and southern Chile. They are a new venture since 2010 in many countries such as Portugal, Spain, Turkey and New Zealand and have been practiced for more than 30 years in Japan and France. The longline (LL) is the culture method used in more than 99% of the exposed farms. In the sites for which the information is available, the submerged LL on which the cultured biomass is maintained more than 2 m below the sea surface is the adopted design.

Currently, the main constraint to extractive species aquaculture in exposed sites is its low profitability (van den Burg et al., 2017a, 2017b). Capital and operational costs are higher compared to those in sheltered sites while the market value of the cultured biomass remains relatively low compared to fin-fishes. Up-scaling, mechanization, and automation of farm installation, seeding, monitoring, and harvesting operations still need to be developed and tested. However, the survivability of the structures and the survival (retention), growth, and quality of the cultured biomass in exposed sites remain crucial. These depend largely on how much the lines and anchors are loaded and the cultured biomass is agitated by currents, waves and husbandry operations.

Few reviews focus on the loading and motion of longlines in currents and waves and most of them are technical reports that have limited diffusion and are more than 10 years old. Bompais (1991) provides an in-depth review of the design of various types of LLs and Priour (1995) reviews mooring and anchoring alternatives applicable to LLs. Gagnon and Bergeron (2011, 2014) review the various designs of submerged longlines, the physical and hydrodynamic characteristics of their components and buoyancy management alternatives applicable to this type of LL. Since these early reviews, more than 70 original research papers on various case studies have been published (Supplementary Table S1A and B). These include *in-situ* measurements of the tension in the lines and the motion of buoys and suspensions (e. g. mussel droppers, lantern nets, kelp-lines), tests on full-scale and physical models of suspensions and complete longlines in current and wave flumes as well as static and dynamic LL simulations using numerical modelling. It is out of the scope of the present paper to make a systematic review of this extensive literature. The purpose of this article is rather to compare the loading and motion of three types of longlines (surface, semi-submerged and fully submerged) used to grow bivalves and kelp on four types of well-documented suspensions (mussel droppers, scallop lantern nets, horizontal kelp-lines and floating vertical kelp-lines) and to review how farm layout affects currents and waves inside the farms. Section 2 provides a description of the LL components, LL types and suspension case studies. The static equilibrium attained by LLs in the absence of external forces is addressed in Section 3. Section 4 covers the quasi-static equilibrium attained by LLs when lifted to the sea surface and forced by tidal sea surface elevation and steady currents. Finally, Section 5 addresses how LL design affects their loading and motion by wind seas and swells.

2 Longline components, longline types and suspension case studies

A longline (LL) consists of a long horizontal rope (mainline or backbone) supported by buoys (floats) and anchored individually to the sea bed at both ends or in arrays of several parallel ropes anchored by a grid of mooring lines. The following descriptions of the LL components and LL types are based on reviews by Bompais (1991) and Goseberg et al. (2017) and the LL designs used on wave exposed commercial farms (Gagnon, 2024). Figure 1 provides a schematic illustration of the types of LLs and their main components.

2.1 Longline components

2.1.1 Anchors

The various types of anchors used to ensure station-keeping are deadweight anchors, screw anchors, drag embedment anchors and piles. Unless their holding capacity is exceeded, their characteristics have no effect on LL loading and motion and for this reason they are not further discussed in this review.

2.1.2 Lines

The main types of lines on a individually anchored LL are the mainline (ML), the mooring lines, the legs, the dropper lines, the kelp-lines and the lines used to attach the buoys and suspensions to the mainline. The mainline is the long horizontal rope to which the suspensions, the compensation buoys and, for some types of LLs, the legs are attached. The mooring lines are attached between both ends of the mainline and the anchors; their main function is to transmit the forces exerted on the ML to the anchors. The legs are vertical lines attached between the mainline and sinkers resting on the sea bottom; their main function is to keep the ML at a constant

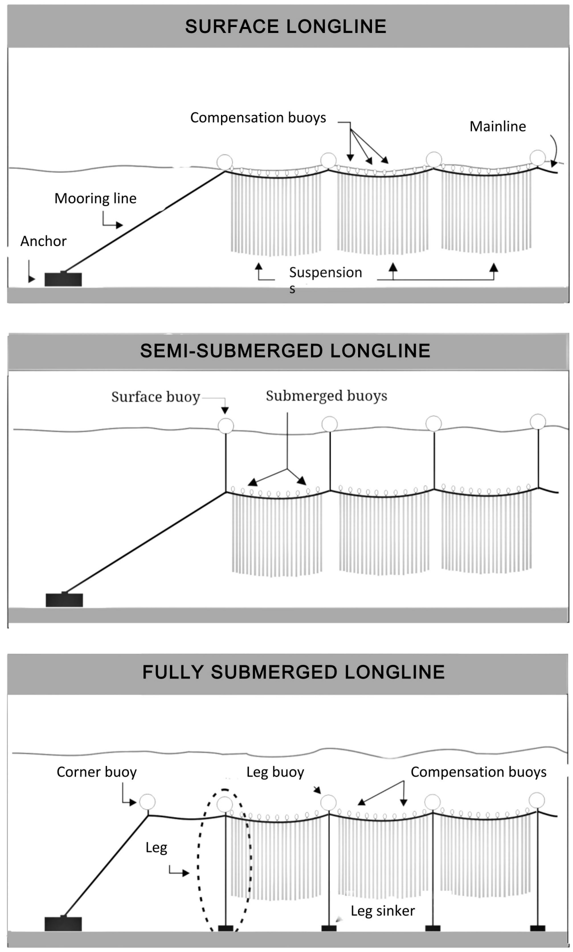

FIGURE 1
Schematic representation of the three types of longlines compared in this article. Not to scale.

depth above the sea bottom. The dropper line and kelp-lines are described in Section 2.3. All these lines are usually synthetic fiber ropes which are nearly neutrally buoyant (Table 1). Their buoyant weight (weight in water) has a negligible effect on the buoyancy balance unless they are covered by a thick layer of biofouling (see Section 2.1.4). Their elasticity is important in determining the geometry of the longline. For given rope type and tension, rope elongation (% of initial length) is roughly inversely proportional to the squared rope diameter (Fredheim and Lien, 2001).

2.1.3 Buoys (floats)

On individually anchored LLs, four types of buoys can be distinguished: corner buoys, compensation buoys, leg buoys and tensioner buoys. Corner buoys are large buoys (or a combination of many small ones) placed at the junction of the mainline and mooring lines; their main function is to exert a pretension in the lines. Compensation buoys are attached along the mainline to compensate the buoyant weight of the suspensions and fouling on the lines and buoys. Leg buoys are attached at the junction of the legs and ML; their function is to keep the legs taut thus maintaining constant the height above the bottom of fully submerged LLs.

TABLE 1 Typical values of the mass density of longline components (WHOI, 1952; Yamamoto et al., 1988; Gagnon and Bergeron, 2011; Macleod et al., 2016).

Component	Mass density (kg/m^3)
Floats/buoys (depending on type and size)	50–200
Ropes (synthetic fiber)	920
Soft fouling	1,100
Hard fouling	1,370
Kelp (*Saccharina latissima*)	1,100
Mussel droppers (fully grown)	1,260
Bivalves	1,450–1,500
Lantern nets (including shellfish and fouling)	1,300–1,600
Concrete anchors and sinkers	2,300
Chain	7,540

Tensioner buoys used on some LLs are submerged floats attached to the mooring lines at some distance from the anchors; their main function is to dampen the forces exerted on the mooring lines by sea surface elevation. Most submerged buoys are pressurized thick-walled hollow or foam-filled plastic buoys. Their mass density (kg/m^3) depends on their shape, size and make (Table 1). The effective buoyancy of surface buoys depends on their degree of submergence while submerged floats that resist the local hydrostatic pressure have a constant effective buoyancy. Buoys must resist the hydrostatic pressure to which they are submitted during the grow-out cycle. Even buoys designed to remain at the sea surface must be able to withstand pressures > 1 bar because they will likely be pulled at greater depths in various situations including drag forces on the LL and the loss or implosion of adjacent buoys (Bompais, 1991; Fredheim and Lien, 2001).

2.1.4 Fouling

When left uncleaned for several months, lines, buoys and nets can be colonized by large volumes of biofouling. Soft fouling (seaweeds, anemones, tunicates, hydroids) is nearly neutrally buoyant while hard fouling (mussels, barnacles, tube worms) have a mass density similar to that of mussel droppers (Table 1). In temperate waters on the continental shelf mussels are by far the main contributor to the fouling buoyant weight on buoys and lines (WHOI, 1952; Macleod et al., 2016; Bannister et al., 2019). The lines and buoys on the part of the ML accessible from the sea surface are usually cleaned during husbandry operations but the inaccessible part of the ML, the mooring lines, tensioner and corner buoys and the legs are usually covered by a thick layer of mature mussels within several months (Paul and Grosenbaugh, 2000; Buck, 2007; Gagnon and Bergeron, 2014).

2.1.5 Sinkers

Sinkers are usually concrete blocks of various sizes that are attached to the bottom end of the legs, kelp-lines on surface and semi-submerged LLs to maintain their depth constant and to mooring lines with or without tensioner buoys to dampen the effects of sea surface elevation. The buoyant weight of concrete is roughly 55% of its weight in air (Table 1).

2.2 Longline types

In this article, the following three types of LLs are compared (Figure 1): surface, semi-submerged and fully submerged. The latter two may be fitted with legs or not (Table 2). To illustrate the effect of some parameters, a standard longline (StdLL) will be used in the following sections. The characteristics of this standard longline are given in Table 3.

2.3 Suspension case studies

The suspensions are the ropes, cages, nets and other structures with the cultured biomass and fouling they contain or hold that are attached along the ML. This article focuses on the following four types of suspensions: 1) blue mussel droppers, 2) scallop lantern nets, 3) horizontal kelp-lines, and 4) floating vertical kelp-lines. Table 4 presents the characteristics of these four case studies.

2.3.1 Mussel dropper

The first case study is a typical fully grown blue mussel (*Mytilus edulis*) dropper that is seeded with juvenile mussels (15 to 25 cm length) and is grown until harvest (average length of 5.5 to 6 cm) in 10 to 24 months, depending on latitude. The physical and hydrodynamic characteristics of mussel droppers are reviewed by Gagnon and Bergeron (2011) and Gagnon (2019) and are summarized in Table 4. They consist of a central rope to which mussels attach by their byssal threads to form a dense cylindrical and porous matrix. Mussels can be grown at a relatively large depth where good conditions for growth may be found (Mizuta and Wikfors, 2019; Gagnon, 2024). The droppers can be vertical droppers of various lengths individually attached along the mainline. Their buoyant weight at seeding is high enough that there is no need to attach a sinker at their bottom end. Another technique consists of attaching very long droppers (continuous droppers) in consecutive loops along the mainline. When the biomass is evenly distributed along the dropper and no sinker is attached at the dropper free end, this type of suspension may be modeled as a free hanging rigid circular cylinder (bluff body).

TABLE 2 Longline type definitions based on the designs currently used in wave exposed sites (Gagnon, 2024).

Longline type	Mainline depth	Corner buoy depth	Compensation buoy depth	Legs
Surface (S)	surface	surface	surface	no
Semi-submerged without legs (SS)	submerged	surface	all or partly at surface	no
Semi-submerged with legs (SS-L)	submerged	surface	all or partly at surface	yes
Fully submerged without legs (FS)	submerged	surface or submerged	submerged	no
Fully submerged with legs (FS-L)	submerged	surface or submerged	submerged	yes

TABLE 3 Characteristics of the standard longline (StdLL).

Characteristic	Value
Site depth (Z)	25 m
Mainline (ML) length (L_m)	120 m
Mooring line length (L_a)	21.21 m
Mooring angle (from horizontal) (θ)	45°
Distance between anchors (D_a)	150 m
ML height above sea bed (H)	15 m
Rope nominal diameter	25 mm
Rope modulus of elasticity	1.1 GPa
Buoyancy of corner buoy (F_b)	1030 N
Pretension in ML (T_h)	1,030 N
ML linear net buoyant weight (W)	0 N/m
Percentage of ML accessible at surface	78 %

2.3.2 Scallop lantern net

The second case study (Figure 2) is the lantern net used for the final grow-out phase of the Japanese scallop (*Mizuhopecten yessoensis*). The cylindrical enclosure consist of circular metal frames covered by a net of various mesh sizes (depending on scallop size) and is subdivided into 10 superposed chambers by porous floors. Juveniles are grown to market size in these enclosures during 18 to 30 months (Kosaka, 2016). Scallops are very sensitive to wave induced motion and are usually grown at depths of more than 10 m. Lantern nets are individually attached to the mainline at intervals of roughly 1 m. Their buoyant weight at seeding is high enough that there is no need to attach a sinker at their bottom end. Their physical and hydrodynamic characteristics depend on the level of fouling and the weight of the scallop biomass. Table 4 provides the characteristics of a typical fouled lantern net containing fully grown scallops (Yamamoto et al., 1988; Wang et al., 2023). When the biomass is evenly distributed in the enclosure, this type of suspension may also be modeled as a free hanging rigid circular cylinder (bluff body).

2.3.3 Kelp-lines

Cases 3 and 4 are sugar kelp (*Saccharina latissima*) fully grown kelp-lines attached to the longline with two different methods that have a significant effect on their hydrodynamic characteristics: the

TABLE 4 Characteristics of the four suspension case studies.

Characteristic	Mussel dropper	Scallop lantern net	Horizontal kelp-line	Floating vertical kelp-line
Distance between suspensions (m)	0.75	1.0	–	2.0
Length (m)	5.0	2.0	1.0[1]	10
Envelope diameter (m)	0.15	0.5	–	–
Mass density (kg/m^3)	1,260	1,400[2]	1,100	1,100
Buoyant weight per m of ML (N/m)	128	93	8	20
Top buoy net buoyancy (N)	–	–	–	50

1. Plant length. 2. Including scallops and fouling.

horizontal kelp-line and the floating vertical kelp-line. *S. latissima* is composed of a single long blade, a short stipe and a holdfast. In commercial farms, these suspensions are currently seeded by winding around the kelp-line a string that holds a high density of small plants (length< 1 cm). Hundreds of plants per m attach by their holdfast around the circumference of the kelp-line while the blades are free to move with the currents and waves. The kelp-line may be the ML itself or a rope placed parallel and under the ML (horizontal kelp-lines) or several vertical ropes attached along the ML with a buoy attached at their free end (floating vertical kelp-line; Bak et al., 2018). Table 4 provides the characteristics of typical kelp-lines at harvest. They differ from mussel droppers and scallop lantern nets in many ways. Firstly, kelp needs sufficient light to grow so it must be kept near the surface in the case of the horizontal kelp-line and at a maximum of 10 m in relatively clear water in the case of the floating vertical kelp-line. Secondly, grow-out time is much shorter (6–9 months including the winter season) than for the mussel dropper and scallop lantern net and does not include the summer fouling season; consequently, the buoyant weight of fouling on kelp-lines at harvest is negligible. Thirdly, the mass density of kelp is nearly neutral. The buoyant weight of the kelp-lines per m of mainline is nearly zero at the start and is one order of magnitude lower than that of the mussel and scallop longlines at harvest (Table 4). In the case of the horizontal kelp-line, sinkers are usually attached to the mainline to maintain it at the design depth (Flavin et al., 2013). Fourthly, kelp-lines can be partially harvested by cutting the blades above their junction with the stipes and the blades regrow from the stump left on the line (Bak et al., 2018). Finally, kelp-lines cannot be modeled as bluff bodies because their shape changes significantly with changing current velocity and angle of attack (see Section 4.3.1).

3 Static analysis

In the absence of currents, waves and other external forces (LL at rest), the LL reaches a static equilibrium that depends on its geometry and the balance between the buoyancy and the buoyant weight of its components. Of particular interest in static conditions are the pretension and the sag in the ML and buoyancy management alternatives.

3.1 Pretension in mainline

When the LL is at rest, the tension in the ML is called the "pretension". This force depends mostly on the mooring geometry and the effective buoyancy of the corner buoys which may be at the sea surface or submerged. In the case of LLs with submerged corner buoys of effective buoyancy (F_b), if we assume to simplify that the mainline is neutrally buoyant and the mooring line is a simple rope of length L_a which makes an angle θ with the horizontal (Figure 3), from basic geometric force analysis (Gagnon and Bergeron, 2014), the horizontal tension in the ML is given by Equation 1:

$$T_h = F_b / \tan\theta \tag{1}$$

The horizontal component of the pretension in the ML (T_h) increases with increasing buoyancy of the submerged corner buoys and with the increasing length of the mooring line (decreasing θ); it is zero when θ = 90° (L_a = H), equal to F_b when θ = 45° and infinite when θ = 0°. If we assume that the lines are stiff (no elongation), the distance between the anchors (D_a) and the height of the ML above the sea bottom (H) are given by Equation 2:

$$\begin{aligned} D_a &= L_m + 2(L_a \cos\theta) \\ H &= L_a \sin\theta \end{aligned} \tag{2}$$

where L_m is the length of the ML. From the above it can be seen that if the distance between the anchors is increased without changing L_m and L_a, θ decreases, the pretension (T_h) increases and the ML height above the bottom (H) decreases. Conversely, if D_a decreases the pretension decreases and the ML height increases.

In the case of surface corner buoys, the pretension in the ML is maximal when these buoys are fully submerged. If D_a is decreased from that situation, the corner buoys progressively emerge, their effective buoyancy decreases and the pretension in the ML decreases. At a certain value of D_a the corner buoys are fully emerged and the ML becomes slack. The D_a range where the corner buoys go from fully emerged to fully submerged is smaller for spherical buoys than for pencil (spar) buoys as illustrated in Figure 4. Thus, LLs with surface corner buoys require higher precision in anchor placement and are more sensitive to anchor movement (slippage) than LLs with submerged corner buoys. Spar

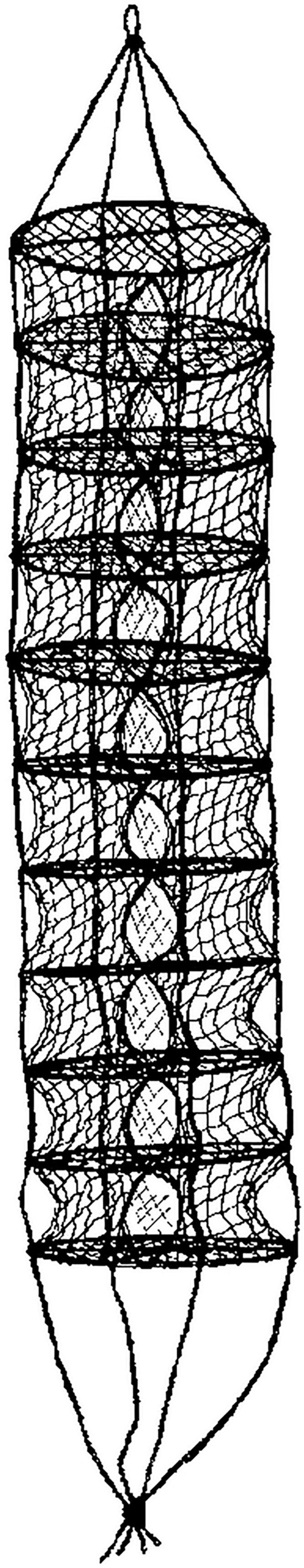

FIGURE 2
Example of an empty lantern net.

corner buoys are preferable to spherical ones when they are positioned at the sea surface (Bompais, 1991).

3.2 Sag in mainline

When the LL is at rest the ML is supported by the buoys with a buoyancy reserve and the ML segments between these supports sags towards the bottom if their net mass density (suspensions, fouling and submerged floats included) is higher than that of sea water or rises towards the surface in the opposite situation. The position of the support floats depends on the type of LL. On surface and semi-submerged LLs, all surface floats act as supports. On fully submerged LLs without legs only the corner buoys act as supports. Finally, on fully submerged LLs with legs, the corner buoys and the leg floats with a buoyancy reserve act as supports. The sag between two supports can be estimated by using the parabolic approximation (Equation 3) (Gagnon and Bergeron, 2014):

$$Sag = WS^2/8T_h;\quad L_s = S + (W^2S^3/24T_h^2) \tag{3}$$

where the Sag is vertical distance (m) from the supports attained by the middle point of the ML segment (positive when the mainline sags downward), the span (S) is the horizontal distance (m) between the supports; W is the linear net buoyant weight or the net buoyancy (N/m) of the ML segment between the supports; and L_s is the length (m) of the ML segment. Since the sag is proportional to the squared span (S^2), fully submerged LLs without legs are prone to large sags if the buoyancy is not adjusted frequently to minimize W. This type of LL is fitted with large corner buoys (large T_h) for that reason (Langan and Horton, 2003). With all other variables constant, adding one leg in the center of a fully submerged LL (i.e. reducing the span roughly by half) reduces the sag in each of the two spans by 75% and adding three equally spaced legs (reducing the span by 75%), reduces the sag in each of the four spans along the ML by 94%.

3.3 Buoyancy management

During a normal grow-out cycle, the weight of the cultured biomass and biofouling increases continually. In temperate waters, kelp and bivalve growth is relatively slow during the winter and fast during spring and summer while the fouling on a newly installed LLs usually starts to affect the buoyancy balance only during the first summer. This increasing weight must be compensated by adjusting the buoyancy installed on the ML and, between buoyancy adjustments, by the buoyancy reserve on the ML. A buoyancy reserve can only be installed on surface buoys or leg buoys. Moreover, lifting a submerged ML to the sea surface to adjust its buoyancy is time consuming, often requires a trial and error process and may have harmful effects on the cultured biomass (fall-off, shell breaking, reduced growth; Matsubara, 2000; Myamoto et al., 2020). In the case of surface and semi-submerged LLs, the frequency of buoyancy adjustments must be relatively frequent because the

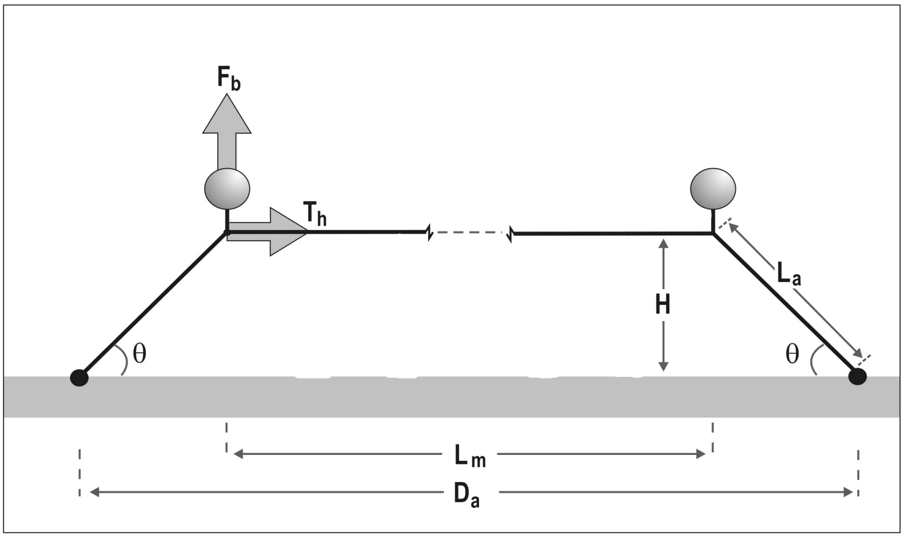

FIGURE 3
Diagram explaining how the pretention in the mainline (T_h) is determined by the LL geometry and the effective buoyancy of the corner buoys (F_b). D_a: distance between the anchors; L_m: ML length; L_a: mooring line length; H: ML height above the sea bottom; θ: mooring angle.

presence of a large buoyancy reserve in the surface buoys increases the risks of unwanted wave effects (Bompais, 1991; Langan et al., 2010). In the case of fully-submerged LLs without legs, buoyancy management is a critical element of their operation. The only way to keep the mainline close to the design depth is to add buoyancy frequently during the grow-out cycle. When unsuitable weather conditions or other problems prevent buoyancy adjustments a large sag may appear in the ML, buoys may implode due to their increased depth and a chain reaction may occur resulting in the complete collapse of the ML to the sea bottom (Fredheim and Lien, 2001; Langan et al., 2010; Lindell, 2015). Finally in the case of fully-submerged LLs with legs, three alternatives are possible (Figure 5): 1: frequent buoyancy adjustments, 2: a few buoyancy adjustments; or 3: no buoyancy adjustments by installing on the legs at the start a buoyancy reserve that will be sufficient to compensate the projected weight at harvest (the "set and forget" approach; Goseberg et al., 2017). One problem with the third alternative is that the net weight that must be lifted to the sea surface for servicing and harvesting (including the weight of the leg sinkers) increases constantly until harvest time as illustrated in Figure 5I. However, if a single buoyancy adjustment is made during the grow-out cycle (Alternative 2), the weight of the leg sinkers can be reduced considerably as is the force required to lift the ML to the sea surface at harvest (Figure 5F).

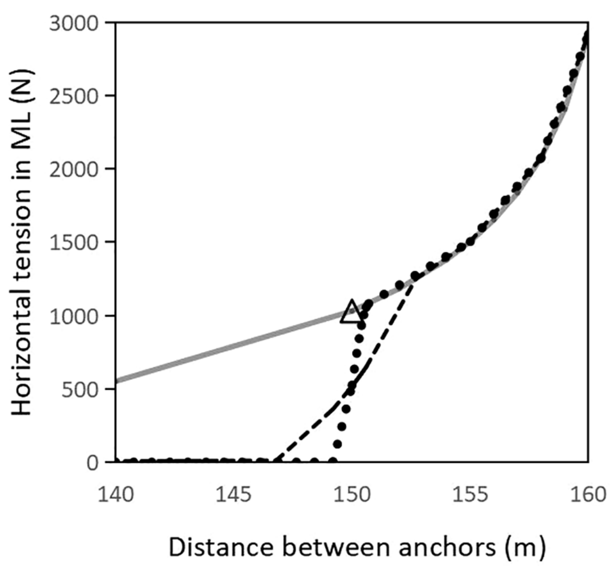

FIGURE 4
Variation of the horizontal component of pretension in the mainline as a function of the distance between anchors with submerged corner buoys (full gray line), spar surface corner buoys (dashed line) and spherical surface corner buoys (dotted line). The triangle is the standard LL (Table 3).

4 Quasi-static analysis

When external forces acting on a LL are slow-varying the LL attains a quasi-static equilibrium. Such forces are exerted by steady currents, tidal sea surface elevation and when the ML is lifted to the sea surface in the absence of waves.

4.1 Mainline lifted to the sea surface

The force that can be used to lift the ML to the sea surface is limited by the lifting capacity of the vessel, the breaking strength of the lines and holding capacity of the anchors. One disadvantage of semi-submerged and fully submerged LLs is that a part of the ML at both ends is usually not accessible from the surface (Bonardelli, 1996). Bergeron and Gagnon (2003) developed a simplified model to approximate the percentage of the mainline accessible from the

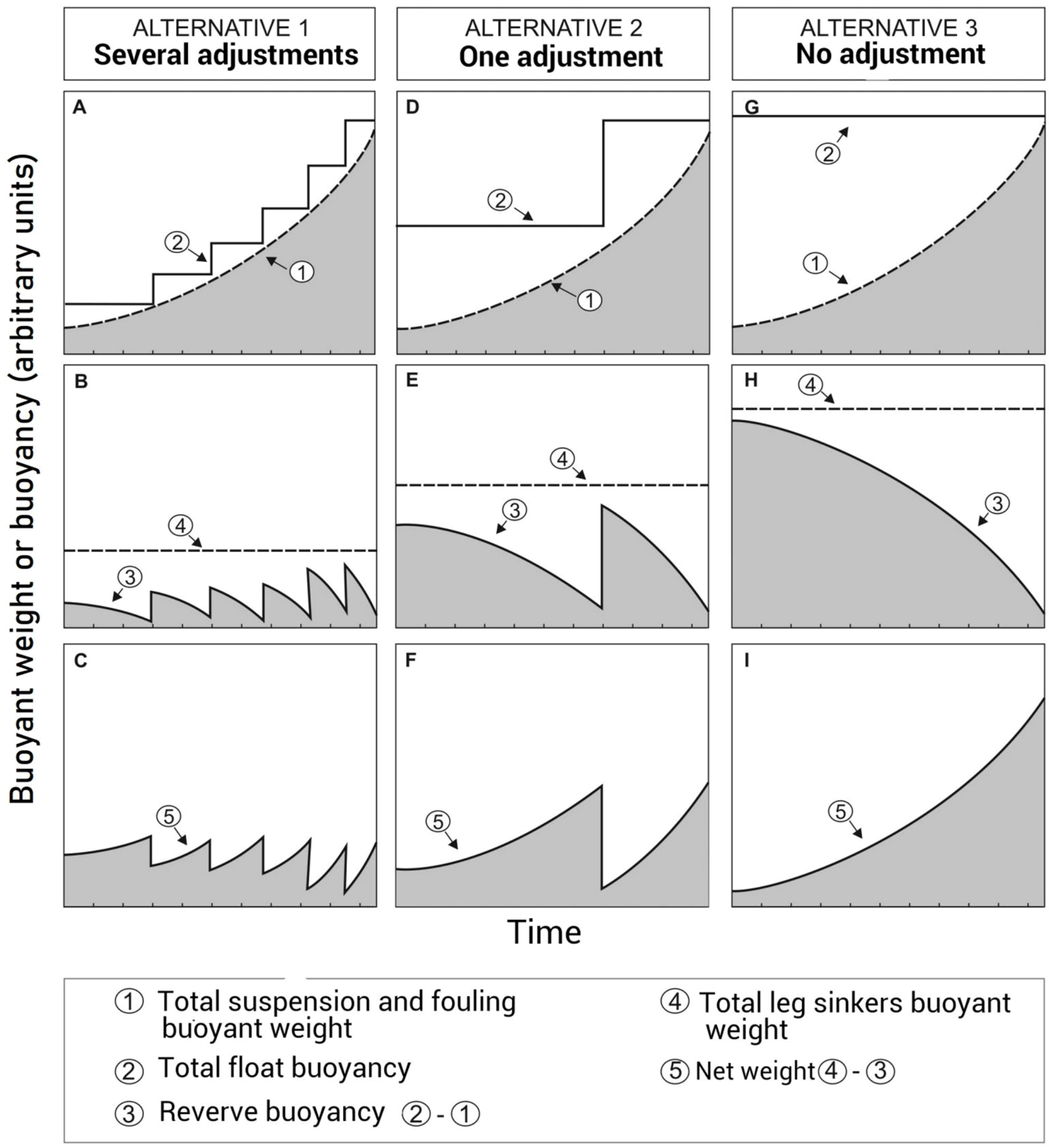

FIGURE 5
Buoyancy management alternatives for a fully submerged longline with legs. **(A–C)** Several buoyancy adjustments during the grow-out cycle; **(D–F)** one adjustment; **(G–I)** no adjustment required. **(A, D, G)** evolution of the total buoyant weight of the suspensions and fouling and total buoyancy of the compensation buoys; **(B, E, H)** evolution of the buoyancy reserve and total buoyant weight of the leg sinkers; **(C, F, I)** evolution of the longline net buoyant weight (buoyant weight of leg sinkers minus buoyancy reserve).

surface based on the basic geometry of an ellipse where the focal points are the anchors and the sum of the distances of a point on that ellipse to the two focal points is equal to the total length of the ropes (Figure 6). This model provides a rough estimate of the percentage accessible as a function of L_m, L_a (or θ), ML height above the bottom (H), water depth (Z) and rope elongation (as a surrogate for the maximum allowable tension in the lines when one end of the ML is lifted 3 m above the sea surface). Figure 7 presents how these variables affect the percentage accessible for the StdLL (Table 3). With all other variables constant, this percentage increases with increasing ML length (Figure 7A), decreasing ML depth (Figure 7B), decreasing site depth, increasing rope elongation (Figure 7C), and decreasing rope diameter. The effect of mainline length is significant only for lengths smaller than 200 m. The effect of the mooring angle (which decreases with increasing mooring line length) is complex (Figure 7D): with stiff ropes (1% elongation) the percentage accessible is zero for mooring angles between 12 and 22°, and increases with increasing and decreasing mooring angle on both sides of this minimum. However, with typical ropes (at least 3% elongation) the entire length of the mainline is accessible at low mooring angles and the percentage accessible tends towards 79% as this angle increases to 90°. In fully exposed sites, it is likely that water depth is more than 25 m, rope diameter is larger than 25 mm (stiffer lines) and the mainline depth is as large as the cultured biomass growth allows. Thus, the results indicate that the MLs in these sites should have a length of at least 200 m to maximize the percentage of the mainline accessible to the surface.

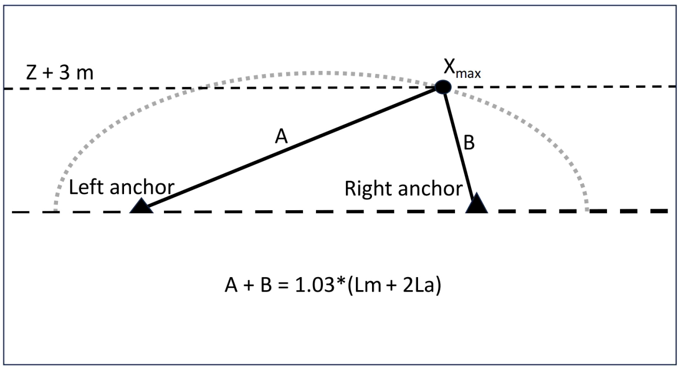

FIGURE 6
Basic assumptions of the simplified model used to determine the percentage of the ML that can be raised 3 m above the sea surface with a 3% elongation of the lines. Z is the water depth. The dotted gray curve is the half ellipse whose foci are the two anchors and the set of points are such that the sum of the distances to the foci (A + B) is equal to the total length of the stretched ML (Lm) and the two mooring lines (2La). The leftmost point of the LL that can be brought 3 m above the sea surface is denoted X_{max}.

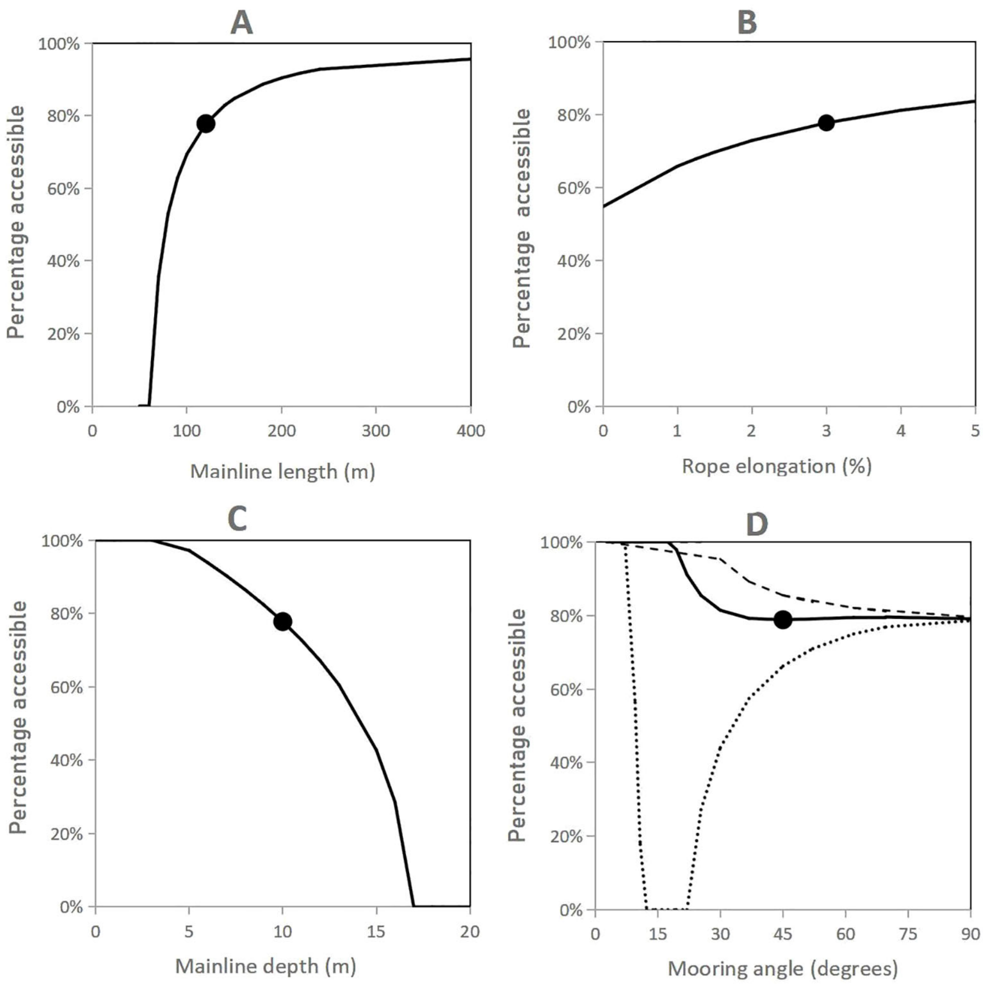

FIGURE 7
Effect on the percentage of the mainline accessible from the surface of changing **(A)** mainline length, **(B)** rope elongation, **(C)** mainline depth, and **(D)** mooring angle. The black dot is the standard longline (Table 3). In **(D)**, results are for a rope elongation of 1% (dotted line), 3% (full line) and 5% (dashed line).

To sum up the above, ML depth control for surface and semi-submerged LLs is relatively easy because there are many supports with reserve buoyancy along the mainline (small sag), these serve as direct visual clues on the need to adjust the buoyancy and, in the case of surface LLs and kelp LLs, there is relatively easy access to the ML to make this adjustment. It is more difficult for fully-submerged LLs (no direct visual clues and limited access to ML) and it is critical for those without legs because there is no place to install any buoyancy reserve along the ML and, consequently, the buoyancy must be adjusted frequently to limit the sag in the ML. If the ropes have a reasonable stretch under safe lifting forces and these can be higher than 10 kN, increasing the mooring line length (increasing the scope) will increase the accessibility of the ML from the sea surface, increase the pretension in the mainline and decrease the potential sag in the ML. However this will be at the expense of a larger LL footprint. A compromise will likely be necessary if space is limited in the leased area.

4.2 Tidal sea surface elevation

On surface and semi-submerged LLs, variations in sea surface elevation (SSE) caused by tides produces large variations of the tension in the lines. This is caused by variations in the submergence of the surface buoys. Plew (2005), Plew et al. (2005), Stevens et al. (2007), Nguyen et al. (2019), Zhu et al. (2019) and Moscicki et al. (2024) observed that the mean forces generated on this type of LL in mesotidal sites were mostly due to tidal SSE. In macrotidal sites the tension in the ML may become high enough at high tide to render lifting operations difficult and low enough at low tide that the ML becomes slack with large sags and increased wave effect on the suspensions (Bompais, 1991). One way of reducing the effect of SSE is the use surface spar (pencil) buoys. Indeed, for the same nominal buoyancy and SSE, the increase of the effective buoyancy of spar buoys is much less than that of spherical and elliptical buoys. Another way is to add tensioner buoys on the mooring lines. In the case of fully submerged LLs the effect of SSE is negligible because it does not increase the effective buoyancy of the floats (Gagnon and Bergeron, 2017).

4.3 Steady currents

Steady currents are generally assumed to be purely horizontal. They exert on LL components a horizontal force in the direction of the current (hereafter called the “drag”) and a vertical force directed towards the sea surface (“uplift”) or towards the sea bottom (“downlift”). On a typical LL, the cultured biomass and the structures to which it is attached or in which it is contained represent up to 90% of the total LL drag area, volume and mass. Consequently, forces acting on the LLs mainly depend on those exerted on the suspensions. The latter are reviewed first before reviewing the effect on whole LLs in the next section.

4.3.1 Effect on LL suspensions

In the cases of the mussel dropper and scallop lantern net, an analytical numerical model developed by Raman Nair et al. (2008) was used to simulate the effect of steady currents on these two types of suspensions (Figure 8). Both suspensions gradually incline with increasing current velocity. The mussel dropper attains a 45° inclination from vertical at a current velocity of 0.53 m/s (Figure 8A) and this produces an uplift (Figure 8C) corresponding to 40% of the buoyant weight of the dropper (Figure 8D). In the case of the lantern net, a 45° inclination is attained at 0.37 m/s and the uplift corresponds to 43% of the lantern net's buoyant weight.

In the case of the horizontal kelp-line, the results presented in Figure 8 come from the relationship established by Endresen et al. (2019) between the drag force, plant length, kelp weight and current velocity for full-scale live 3 m long kelp-line segments in perpendicular currents and from Lei et al. (2021) observations on the inclination and reconfiguration in steady currents of full-scale live kelp-line segments similar to the case study. The kelp blades attain a nearly horizontal posture in steady currents of more than 0.1–0.2 m/s. Above this threshold, in a cross-sectional view, the kelp-line resembles a streamlined body whose upstream (frontal) part is formed by the stipes that bend around the rope in the current direction and the downstream (distal) part is formed by the blades oriented parallel to the current direction. With increasing current velocity, the height of the stipe bundle decreases and the blades adopt a more streamlined shape. Due to this reconfiguration, the drag force on the kelp-line is not proportional to the current velocity squared (U^2) as in the case of a flat plate but rather to roughly $U^{1.4}$. In this example, the uplift corresponds to more than 85% of the kelp's buoyant weight at velocities > 0.3 m/s. The fact that the current exerts a drag force of similar magnitude on all three study cases (Figure 8B) is a coincidence in the choice of the suspension characteristics. Steady currents exert on kelp-lines a much smaller lift force than on heavy suspensions (mussel droppers and lantern nets; Figure 8C). In response to the lift force the buoyant weight of mussel droppers and lantern nets do not allow full reorientation parallel to the current direction seen with the kelp-line. This force changes the delicate balance between the installed buoyancy and the buoyant weight of the cultured biomass and fouling (see Section 4.3.3).

In the case of the floating vertical kelp-line at rest it resembles a wide and rough cylinder with the blades hanging downward parallel to the kelp-line axis (Bak et al., 2020). As the current velocity increases to 0.1–0.2 m/s, the kelp biomass adopts the same posture and streamlined shape around the rope as described above for the horizontal kelp-line and the kelp-line itself adopts a curved posture due to the presence of a float at the top end (Lona et al., 2020). As in the case of the mussel dropper and lantern net, the mean inclination of the kelp-line increases with increasing current velocity, but this time the inclination is towards the bottom and, if the buoyancy of the float is just enough to compensate the buoyant weight of the kelp at harvest, the kelp-line at that time will tend to be horizontal (at the depth of the mainline) at current velocities > 1.0 m/s.

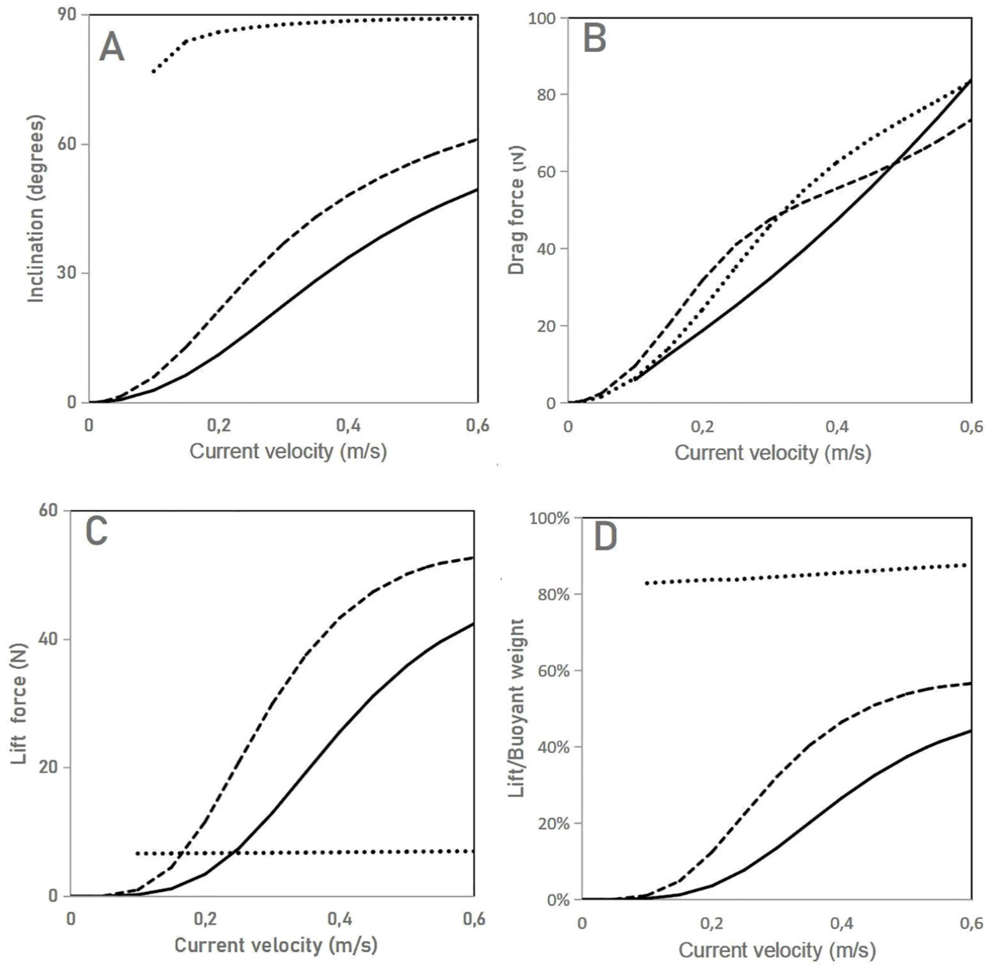

FIGURE 8
Effect of steady currents on individual suspensions. **(A)** Inclination of the suspensions; **(B)** drag force on the suspensions; **(C)** lift force on the suspensions; **(D)** lilt force on the suspensions as a percentage of their buoyant weight. Full line: mussel dropper; dashed line: scallop lantern net; dotted line: horizontal kelp line.

4.3.2 Effect on complete longlines

The force exerted by steady currents on isolated LLs depends on their angle of attack (0° when parallel to the anchor axis). In the case of the force transmitted to the mooring lines and anchors, two factors are in play: the shielding effect and the LL deflection effect.

4.3.2.1 Shielding effect

In currents parallel to the LL, the bulk drag force on the ML is usually lower than the sum of the forces on the individual isolated suspensions because there is a strong fluid-suspension interaction that reduces the velocity of the current acting on downstream suspensions (Plew, 2005; Plew et al., 2005; Gagnon and Bergeron, 2017). The importance of this shielding (sheltering, shadowing) effect depends on the angle of attack (minimum when the current is perpendicular and maximum when parallel) and the suspension spacing ratio (distance between the suspensions divided by their diameter). This effect is very difficult to measure *in-situ* due to many confounding factors (Gagnon and Bergeron, 2017) or on large scale physical models in current flumes because the latter are not wide enough. With a few exceptions (Lopez et al., 2017), published numerical simulations ignore this effect.

To illustrate the complexity and importance of the shielding effect for LLs with mussel droppers and lantern nets I use here the results of flume tests on rows of rigid fixed smooth cylinders carried out by Plew (2005) and Fredheim (2005). A spacing ratio of 2.2 representative of a LL with the fouled lantern nets was used in the case of Plew's tests and of 5.0 representative of a LL with mussel droppers was used in Fredheim's tests. The results of these tests are presented in Figure 9A where the shielding effect is given as a function of the current angle of attack and is expressed as the ratio of the measured bulk drag force on the row of cylinders to the maximum drag force (F_{bk}/F_{max}; %) that would be exerted if there was no shielding (drag on a single isolated cylinder multiplied by the number of cylinders in the row). For the closely spaced cylinders, the relationship adopts the form of a sine curve where the shielding effect gradually decreases as the angle of attack increases. In the case of the larger spacing the shielding effect is lower in a parallel current than in the case of the closely spaced

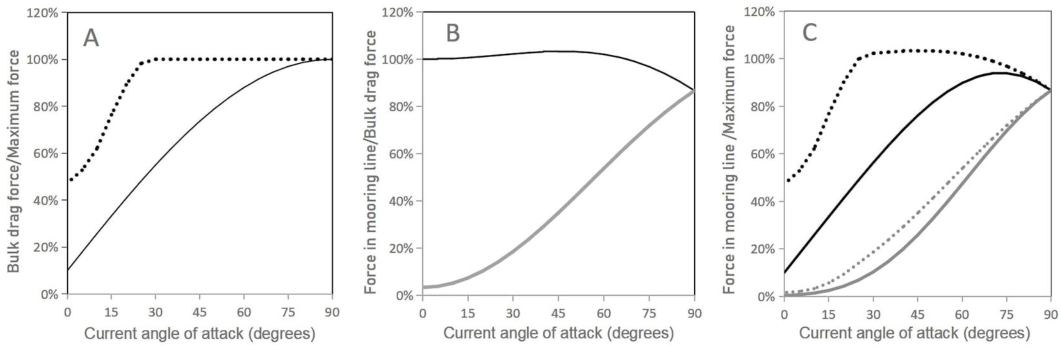

FIGURE 9
(A) Shielding effect: measured bulk drag force on the mainline (F_{bk}) as a percentage of the force that would be exerted if there was no shielding effect (F_{max}) as a function of the current angle of attack (0° when parallel to the anchor axis). **(B)** LL deflection effect: percentage of the bulk drag force on the ML (F_{bk}) that is transmitted to each mooring line (F_{mo}) as a function of the current angle of attack. **(C)** Combined effect: measured drag force transmitted to each mooring line (F_{mo}) as a percentage of the force that would be exerted on the ML if there was no shielding effect (F_{max}) as a function of the current angle of attack. In **(A)** and **(C)**: full lines: suspension spacing ratio = 2.2; dashed lines: suspension spacing ratio = 5. In **(B)** and **(C)**: black lines: upstream mooring line; gray lines: downstream mooring line.

cylinders and decreases with increasing angle of attack up to 30° then remains nil up to 90°. According to these exploratory results, there would be a strong shielding effect on mussel LLs only for small angles of attack while the shielding effect would be much stronger on LLs with lantern nets spaced 1 m apart.

The case of the horizontal kelp-line in a perpendicular current was covered in Section 4.3.1. When parallel to a current stronger than 0.1–0.2 m/s, the kelp mass in a side view of the kelp-line likely resembles a thick and rough cable the diameter of which decreases as the current velocity increases (Lei et al., 2021). Since the drag area of the kelp mass in this posture is much smaller than when the current is perpendicular, it is also likely that there is a large shielding effect on horizontal kelp-lines. In the case of fully grown floating vertical kelp-lines (Bak et al., 2018) in a parallel current higher than 0.1–0.2 m/s, the kelp mass in a side view of the kelp-line resembles in-line flags. The wetted area of the kelp mass in this posture is not significantly different than when the current is perpendicular but the pressure drag on the frontal part of the kelp-lines is likely less for low angles of attack as in the case of mussel droppers.

4.3.2.2 Longline deflection effect

When a LL without legs is parallel to the current all the bulk drag force on the ML is transmitted to the upstream anchor and when it is perpendicular it is split evenly between the two anchors. However, the perpendicular current causes a horizontal deflection of the center of the LL in the direction of the current and the total force on each anchor is larger than half the bulk drag force on the ML. Contrary the the shielding effect, this effect is well captured by numerical simulations (Fredheim and Lien, 2001; Buck et al., 2017; Dewhurst, 2019; Cheng et al., 2020). It is illustrated in Figure 9B for a longline with a deflection ratio of 0.19 (deflection distance/distance between anchors) as a function of the current angle of attack. It is expressed as the ratio (%) of the force in each mooring line to the bulk drag force on the ML (F_{mo}/F_{bk}; %). The force on the upstream anchor is higher than the bulk drag force on the ML for angles of attack between 15° and 67° and, when the current is perpendicular to the anchor axis, the force on both anchors is the same but is more than half (87%) the bulk drag force.

4.3.2.3 Combined effect of the current angle of attack

Figure 9C combines the shielding and deflection effects as a function of the current angle of attack for a deflection ratio of 0.19 and is expressed as the ratio of the force in each mooring line to the maximum force (F_{mo}/F_{max}; %). It shows that in currents parallel to the anchor axis the force on the upstream anchor for the LL with closely spaced suspensions is only 10% of what the force would be if there was no shielding and that the maximum force on this anchor is attained at an angle of attack of 75°. For the LL with more spaced suspensions, the force on the upstream anchor is much higher at all angles of attack and is maximum at a 45° angle of attack.

The presence of legs on the mainline completely changes the relationships shown in Figure 9. Indeed, in oblique and perpendicular currents the legs limit the horizontal deflection of the mainline and resist a large part of the bulk drag force (Gagnon and Bergeron, 2017). Although the relationships in Figure 9 are just approximations, they show that orienting LLs parallel to the main current axis will reduce the probability that they experience large hydrodynamic forces. This is currently the practice adopted in most commercial farms (Gagnon, 2024).

4.3.3 Effect on mainline depth

One of the main objectives of LL design and husbandry operations is to maintain the ML depth within a narrow window (design depth). Steady currents affect the depth of the ML in several ways, depending on the type of LL, its orientation relative to the current direction and the type of suspension. In the case of LLs without legs in a current parallel to the anchor axis, the tension in the mainline increases from the downstream end towards the upstream end of the ML. This tends to deflect the ML downstream, decreases the mooring angle at the upstream end of the ML and increase it at the downstream end and creates a positive slope in the ML from the upstream to the downstream end. If the corner buoys are at the surface, the submergence of the upstream one will increase and that of the downstream one will decrease. The reserve buoyancy of the upstream buoy will limit the slope in the ML. If the corner buoys are submerged, the depth of the upstream buoy will increase and that of the downstream buoy will decrease and the slope in the ML will be more pronounced than with surface buoys. If the mooring lines are longer than the water depth, the downstream corner buoy will reach the sea surface. Furthermore, the uplift exerted by currents on mussel droppers and lantern nets (see Section 4.3.1) may lift the downstream part of the ML up to the sea surface if the submerged buoyancy on it is too high (Langan et al., 2010; Dewhurst, 2019; Boo et al., 2023). These situations must be avoided for many reasons including increased risks of navigational and marine mammal entanglement and increased wave forces on the downstream part of the ML. To eliminate this problem the total buoyancy of the submerged compensation buoys must not exceed the total buoyancy (surface + submerged) required to compensate the total buoyant weight on the ML minus the expected uplift force on the suspensions for the design current velocity. In the case of the semi-submerged mussel longline studied by Dewhurst (2019), the submerged buoyancy not to exceed corresponded to 67% of the total required buoyancy, with a minimum of 33% of the required buoyancy placed in the surface buoys. On fully submerged LLs without legs where 100% of the buoyancy is submerged, ML uplifting by currents cannot be avoided for LLs with mussel droppers or lantern nets (Langan et al., 2010; Dewhurst, 2019). However, if legs are added along the ML with sufficient buoyant weight of the sinkers (Raman Nair et al., 2008), the slope in the mainline will be limited to the upstream part of the mainline while the rest of the mainline will stay at the design depth (Figure 10A).

In a current perpendicular to the anchor axis, the ML is deflected horizontally in the direction of the current and adopts the shape of a catenary in a top view (Grosenbaugh et al., 2002; Fredheim and Lien, 2001). The tension in the ML increases from the center towards both ends. The increased tension at both ends reduces the mooring angle and increases the depth of both ends of the ML unless there are surface corner buoys with sufficient reserve buoyancy to counteract this effect. The uplift on the suspensions tends to lift the middle part of the ML towards the surface unless there are legs on the ML as shown in Figure 10B. In the case of LLs with floating vertical kelp-lines in parallel and perpendicular currents, the downlift on the suspensions prevents the lifting of the ML to the surface and tends to incline the suspensions towards the bottom (Lona et al., 2020).

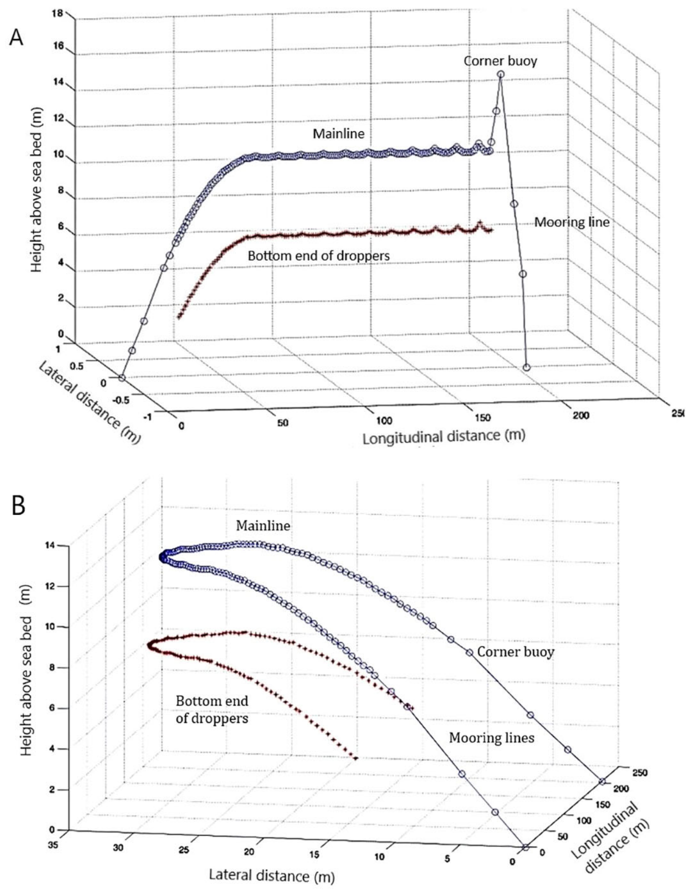

FIGURE 10
Three-dimensional posture of a typical fully submerged mussel longline with 11 m long legs in a steady current parallel to the anchor axis **(A)** and perpendicular to the anchor axis **(B)**. Site depth is 21 m. Only the mooring lines, mainline and bottom end of the mussel droppers are represented. Not to scale.

4.3.4 Interactions with whole farms

The interaction between steady currents and LL farms has been the object of several studies (Supplementary Table S1C). Generally, the velocity of an unidirectional steady current will be reduced at its passes through the farm as part of the flow is redirected above, below and/or on both sides of the farm. For a given type of suspension, the importance of this reduction depends on the areal density (number/ha) and vertical distribution in the water column of the suspensions and on LL orientation relative to the current. Shellfish farms in exposed sites have a relatively low density; they are arranged in rows of several in-line LLs, with 25 to 50 m between parallel rows (Gagnon, 2024). Orienting the rows perpendicularly to the flow results in a greater attenuation of currents inside the farm and therefore a greater reduction of seston and nutrient supply to the farm as a whole than orienting them parallel to the flow. However, in the latter case the flow is concentrated in the channels between the rows of LLs while the shielding effect between the droppers locally reduces the flow around the droppers. In most farm sites currents are tidal and reverse every 6 hours and they are seldom uni-directional in exposed sites (Gagnon and Bergeron, 2017; Dewhurst, 2019). According to Plew (2005), the natural variability of flow direction is likely to be sufficient to ensure an adequate supply to all suspensions when placing LLs parallel to the main current axis. For a large and low density farm, the advantages of aligning the LLs at low angles to the dominant currents, reducing the interference between LLs, should outweigh any shielding effect between individual droppers on individual LLs. However, more research is required to confirm this statement.

5 Dynamic analysis

5.1 Effect of wind seas and swells on isolated longlines

Wind seas are generated locally and their energy depends on the fetch of the site in the direction from which the wind is blowing while large swells are generated by storms that pass far from the site. The effect of wind seas and swells on LLs is very complex due to the confounding effect of several factors including the wave type (regular or irregular), wave height, wavelength and orientation and the presence or absence of currents and their orientation relative to the waves. Furthermore, waves exert not only a drag force but also an inertia force cause by the acceleration of the fluid around the LL components. In this section I review the effects of LL design and buoyancy management on the loading of the windward mooring line and the motion of the buoys and suspensions. But first, the wave shielding effect must be addressed.

5.1.1 Longline orientation and wave shielding

Tests on a surface LL model parallel to wave propagation in a wave flume by Cheng et al. (2023) show that there is a significant wave shielding effect that depends on the wavelength; it is small for low frequency waves (swells) and large for high frequency waves (wind seas). These authors did not test other angles of attack. To my knowledge, *in-situ* observations and physical model tests in wave tanks have not addressed the effect of LL orientation on wave loading. However, this effect was studied using numerical simulations by Deng et al. (2010), Zhang et al. (2015), Lopez et al. (2017), Cheng et al. (2020), Davonski (2020) and Feng et al. (2021). Contradictory results were obtained where the maximum tension on the windward mooring line increases or decreases with increasing angle of attack or is maximum in oblique waves. This is likely due to the fact that the numerical models used do not include a wave shielding effect. Plew (2005) and Plew et al. (2005) observed that the attenuation of waves as they propagated perpendicularly to the LLs in a large (650 m wide; 22 LLs across) low density (600 droppers/ha) farm depended on their wavelength: small waves (period< 5 s) were more attenuated than large waves for which attenuation was less than 10%. Zhu et al. (2020) came to the same conclusion using numerical simulations of a 200 m wide and more dense (1,250 droppers/ha) mussel farm during a large storm; the farm reduced the incident wave energy by more than 60% for 3 s period waves and by less than 15% for 20 s period waves.

The above indicates that high frequency waves interact more with the LLs than swells. It can only be speculated that, in the case of an isolated LL, there is a significant wave shielding effect that depends on dropper spacing when it is placed parallel to the prevailing direction of fetch-limited waves and that this effect is minimal for a 90° angle of attack. For a block of several LLs there would be a shielding effect for high frequency waves at all orientations while for large swells the shielding effect would be small for all orientations. If this proves correct, the orientation of LLs relative to waves in exposed sites would be less important than their orientation to storm generated currents.

5.1.2 Effect of mainline depth

Generally, the force exerted by waves on LL components decreases with increasing depth. For example, for waves of 2 m height and 40 m wavelength in 25 m water depth, the forces on a bluff body at 10 m will be 25-fold less than at the surface (Bompais, 1991). This reduction was verified by numerical simulations for semi-submerged scallop and mussel LLs and a kelp submersible array (Lopez et al., 2017; Dewhurst, 2019; Lian et al., 2023) and mussel semi-submerged and fully submerged LLs (Smeaton, 2019). The comparison of *in-situ* observations of surface and fully submerged mussel LLs (Gagnon and Bergeron, 2017) shows that the maximum vertical acceleration of the droppers in the latter case is one order of magnitude less than for surface LLs. Thus, to minimize wave forces, ML depth on shellfish LLs should be maximized while in the case of kelp-lines that must remain in the photic zone, the floating vertical kelp-line is the design that will minimize wave forcing.

5.1.3 Effect of mainline length

Tests on physical LL models in wave flumes (Matsubara et al., 1985, 1990; Zhao et al., 2019; Cheng et al., 2023; Wang et al., 2023) show that the loading and motion of LLs parallel to wave propagation depend on the ratio of the ML length to wavelength

(L_m/λ). Maximum tension in the windward mooring line increases with increasing wave height but the relationship with the wavelength (period) is complex and not fully understood. Cheng et al. (2023) tested L_m/λ ratios between 0.59 and 1.93. Incorporating the shielding effect in their numerical model simulations, the maximum tension in the windward mooring line was largest for L_m/λ ratios between 1.15 and 1.35. It was concluded that to minimize the loading of the windward mooring line in waves parallel to the LL, a ML length between 1.15 and 1.35 times the wavelength of the design wave should be avoided. This result is likely due to how the forces along the ML act in the same or opposite directions as suggested by Stevens et al. (2007). According to Cheng et al. (2023) most part of the force transmitted to the windward mooring line is caused by the submersion of the surface buoys. In the case of a fully submerged LL without legs (Matsubara et al., 1990), tension in the mainline did not vary significantly for a L_m/λ range of 0.4 to 2.0. This is likely because the effective buoyancy of submerged buoys is not affected by waves.

The tests carried-out by Zhao et al. (2019) and Wang et al. (2023) on surface and semi-submerged LLs parallel to wave propagation and in ranges of the L_m/λ ratio of 0.8 to 1.25 and 1.7 to 5.0, respectively, show that the amplitude of the horizontal and vertical displacement of the surface buoys and lantern nets decreases with increasing L_m/λ ratio and is lower than the wave height for ratios > 1.0. They explain this result by the fact that the tension in the lines increases with increasing L_m/λ ratio and high tension in the ML constrains the displacement of the suspensions (Boo et al., 2023). Finally, in tests on a fully submerged LL without legs parallel to wave propagation with a range of L_m/λ ratios between 0.4 and 2.0 Matsubara et al. (1985) found that the maximum vertical displacement of the buoys was highest (and higher than wave height) for ratios of 0.8 to 1.4. To sum up the above, in order to minimize the loading of the mooring lines and the vertical displacements of the suspensions on a LL parallel to wave propagation, the length of the ML should be at least 1.4 times the wavelength of the design waves.

5.1.4 Effect of buoy size, shape and placement

Lee et al. (2014) have studied in a wave flume the effect of steady currents and waves on tethered surface buoys of various shapes. Steady currents exerted more tension in the tether line in the case of long cylinders moored vertically (pencil floats, spar buoys) than for spherical floats. However, the contrary was observed for the forces exerted by waves. This is because spherical floats ride the waves while pencil floats are less sensitive to sea surface elevation (Bompais, 1991). The worst shape tested by Lee et al. (2014) was a low-aspect cylindrical buoy moored horizontally similar to the buoys used on double backbone surface LL (Plew et al., 2005).

Lien and Fredheim (2001) compared with numerical simulations two types of surface mussel growing structures: a conventional LL with pencil floats and a horizontal longtube. In waves parallel to the LLs, there were snap loads in the dropper lines of the conventional LL while in those attached to the longtube the tension was much less variable and no zero tensions were recorded. In small waves, snap loads were seen in droppers directly under the buoys while in large waves they were seen in the droppers placed in the middle of the span between the buoys. In waves perpendicular to the LL, the span between the floats and the droppers attached to it show large accelerations as the ML stretches and un-stretches at each passing wave while this effect is not possible with the longtube. This shows that, for the same total buoyancy, placing several small buoys on the ML is a better approach for surface LLs than a few large floats (Bompais, 1991).

Snap loads in the suspensions are responsible for mussel drop-off from fully grown mussel droppers and reduced growth and survival of scallops grown in lantern nets. These are caused by the out of phase motion of the buoys and suspensions. At each passing wave, the tension in the dropper line can go down to zero as the wave through passes and suddenly increase in the ascending phase of the wave (Bompais, 1991). For surface and semi-submerged LLs, the risk of snap loads can be reduced by 1) increasing the tension in the ML, 2) preventing surface buoys from having too much reserve buoyancy (by frequent buoyancy adjustments), 3) limiting the span between the buoys (many small floats better than smaller number of large floats) and 4) using pencil floats rather than spherical ones (Bompais, 1991; Lien et al., 2001). In the case of fully submerged LLs snap loads are less likely due to the reduced wave loading and absence of forces caused by buoy submergence.

5.1.5 Effect of adding legs

The only study on the effect of adding legs on wave loading of fully submerged LLs is that of Knysh et al. (2020). They simulated the effect of adding three legs to a fully submerged mussel LL in extreme waves and currents perpendicular to the anchor axis. When compared to the LL with the same geometry without the legs, the maximum vertical acceleration of the droppers increased by 24%. According to Loste and Cazin (1993) adding legs to a LL decreases its structural flexibility and increases the risk of snap loads in the suspensions.

5.1.6 Effect of mooring configuration and angle

Mooring lines can be designed in many different configurations. For a thorough review of those most often used on LLs see Bompais (1991) and Priour (1995). Most of the commercial farms that are currently operating in exposed sites use the most simple configuration: a single taut rope (Gagnon, 2024). Some use a tensioner mooring with one submerged buoy attached to the mooring line at some distance between the anchor and corner buoy. The disadvantage of the single-leg mooring is that it is less effective in damping wave energy than the chain catenary mooring and the tensioner mooring. The chain catenary mooring is more expensive and requires a much larger distance between the anchors than the other mooring configurations and are not used when lease space is limiting. The latter reduces the dynamic range of the mooring force on the condition that the tensioner buoy remains submerged in all conditions (Palm and Eskilsson, 2020).

Cheng et al. (2023) studied the effect of increasing the mooring line angle from 19° to 45° (decreasing mooring line length, scope) on a surface LL with a simple taut mooring line in waves parallel to the LL. This caused a decrease of the maximum tension in the windward mooring line. This is likely because the pretension in the mainline decreased with increasing mooring angle.

6 Discussion and conclusion

Although LLs are relatively simple and inexpensive structures, their interaction with currents and waves is complex and they should be carefully designed before deployment in high energy environments. The simple analytical models presented in this paper were used only to illustrate this complexity and the many compromises that must be made. Site surveys to collect metocean data and more complex and suitable models based on finite element analysis (FEA) must be used to properly design LLs for exposed sites. However, simulations that ignore the current and wave shielding effects provide over-estimations of the loading and motion of LLs in many situations.

While it is standard practice to multiply by safety factors the estimated maximum forces to determine the dimensions of LL components such as anchors and ropes, this is not applicable to buoys/floats. Buoyancy management requires to maintain a delicate balance between the buoyancy of the floats and the time varying buoyant weight of the cultured biomass and fouling. Over-sizing buoys compromises the survivability of the structure and the survival (retention), growth and quality of the cultured biomass. The best way to reduce the hydrodynamic loading and agitation of LLs by waves is to maintain the ML at the largest depth possible. That depth can be considerable for bivalves but not for kelp which must remain in the surface illuminated layer at least during day time. In the case of the floating giant kelp (*Macrocystis* sp.) the ML can serve as the kelp-line and the plants float naturally above it (Tullberg et al., 2022) while in the case of kelp species with negative buoyancy (*S. latissima* and *S. japonica*), a promising method consists of growing then on vertical lines fitted with a small float at the top end. This way the ML can be lower in the water column and the downlift exerted by currents on the kelp-lines will push the kelp biomass out of the surface layer during storms.

Lowering the ML in the water column comes at the expense of reducing the percentage of the ML accessible from the surface (or increasing the size of the lines, the holding power of the anchors and the size of the vessels required for this operation). It also complicates considerably buoyancy management in the case of fully submerged LLs. Buoyancy management becomes problematic on fully submerged LLs without legs because there is no place to install a buoyancy reserve on the ML. To maintain the ML at the design depth frequent buoyancy adjustments are required and these may be costly and impossible for considerable periods of time. Lifting frequently the ML can also affect the survival (retention) and growth of the cultured biomass. An interesting design is to install all the buoyancy required until harvest at the beginning of the grow-out cycle so that adjustments are not required (i.e. the “set and forget” approach). This is possible by adding legs on fully submerged LLs but this increases considerably the forces required to lift the ML to the surface at harvest. A new concept developed in New Zealand eliminates this problem by clamping the ML to fixed legs with a special device that releases it on command from the surface for servicing and harvesting (Goseberg et al., 2017). Other concepts being tested are based on depth cycling using variable buoyancy components (submersible buoys). This cycling can be diurnal (for kelp), occasional (lowering at the approach of a storm, lifting for husbandry and harvesting operations), seasonal (lowering during winter or predatory duck migration). It is likely that this approach can eventually become economically feasible only for large arrays of LLs (Bale, 2017; Goseberg et al., 2017; Capron et al., 2018; Godsiff, 2020; Navarette et al., 2021; Kite-Powell et al., 2022; Lian et al., 2023, 2024).

LL orientation relative to currents and waves determines in large part the intensity of their loading and motion and the seston or nutrient flux through the farms. It is also important for determining the area efficiency of the farm within an allocated lease. In sheltered sites, LL loading by currents is larger than by waves and, in most commercial sites, LLs are oriented parallel to the tidal current axis to minimize the drag forces. However, there is presently no consensus on what should be their orientation in exposed sites where current and wave loading are both important and multi-directional. In some exposed farms the LLs are oriented parallel to the prevailing direction of swell propagation and in others they are parallel to the main axis of the currents as determined from long-term recordings (Gagnon, 2024). Up to now, *in-situ* measurements, physical models tested in current and wave flumes and numerical models have not been able to resolve this important question. In the former case, there are many confounding factors that mask the effect the current and wave angle of attack. In the case of flume tests, the flumes are not wide enough to test LLs in oblique and perpendicular currents and waves. Finally, numerical models do not incorporate current and wave shielding as a function of suspension spacing and current/wave angle of attack because these relationships are unknown; the simulations ignore these effects or apply estimated reduction coefficients to the current velocity field or drag coefficients. It is likely that the loading and motion of LLs are very sensitive to their orientation relative to steady currents and small waves and much less sensitive to their orientation relative to large waves (swells) but more research is required to confirm this. If confirmed, it would mean that the LLs should be oriented parallel to the main direction of storm generated currents, hence the need for reliable metocean data for each site.

LL design and farm layout are not conditioned only by mechanical considerations. Other important economic, environmental and social considerations come into play including scalability (Solvang et al., 2021; St-Gelais et al., 2022), ease of mechanization and automation of seeding and harvesting operations (Chung et al., 2015; Choi, 2020; Capron et al., 2018; Solvang et al., 2021), co-location with renewable energy infrastructure (Buck and Langan, 2017), remote sensing (Myamoto et al., 2020; Peres da Silva, 2021), marine mammal entanglement (NOAA, 2015; Bath et al., 2023; ICES, 2023) and human health & safety (Yang et al., 2020). Several research and development programs currently underway around the world to test new LL design and operation (see a listing in Gagnon, 2024) will increase considerably the knowledge base supporting aquaculture expansion to exposed sites.

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Supplementary material

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Status of off-bottom mariculture in wave-exposed environments. Part 1. Global inventory of extractive species commercial farms in temperate waters

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There is currently a strong drive to expand aquaculture further offshore co-occurring with a rapid change of the conditions under which this activity will be practiced due to climate change. At the dawn of these profound changes a global review of the current status of technologies used commercially to grow extractive species in wave exposed environments can serve as a benchmark for future developments. Part 1 of this paper presents a systematic inventory of commercial farms in temperate exposed waters. The study area includes 5 regions in the northern hemisphere and 3 regions in the southern hemisphere and covers entirely or part of 48 countries and territories. The inventory is based on 80+ high resolution aquaculture lease maps, most of them available as Internet Web-GIS applications, that cover the entire study area with the exception of a few countries. Exposed sites are first identified from these maps using simple wave fetch criteria and this preselection is then validated using climatological data on wave height and power density (energy flux). The number of sites and the leased area are tallied by region, country, species group and production method. The longline is the production method used in more than 99% of the sites inventoried. Longline design and farm layout in 28 of these sites are reviewed. With a few exceptions, semi-submerged or fully submerged designs are used (in some cases they have been for more than 30 years) while the information on farm layout is patchy. A review of structural damage and loss of cultured biomass due to hydrodynamic forces in commercial and experimental farms confirms that surface and semi-submerged longlines are more vulnerable to large storms than fully-submerged designs.

KEYWORDS

aquaculture, offshore, open ocean, exposed, temperate, extractive species, global, status

1 Introduction

In 2013 global aquaculture production (including algae) exceeded global capture fisheries for the first time (FAO, 2022). This remarkable milestone is the result of two major long-term trends: the stagnation of capture fisheries since the mid-1990s and the 24-fold increase of eastern Asia aquaculture production from 1980 to 2020. However, the growth rate of aquaculture production peaked in 1996 and has considerably decreased since (Sumaila et al., 2022). In some cases, production has actually decreased since the mid-1990s such as bivalves in Europe (Avdelas et al., 2021), bivalves and seaweed in Japan (Watanabe and Sakami, 2021) and scallops in Chile (von Brand et al., 2016). Kelp (order Laminariales) aquaculture production is presently insignificant outside of Asia (< 1,000 t total; FAO, 2023a) despite recent developments in northern Europe and North America. The World Bank (2013) estimated that global demand for fish and seafood for human consumption would increase by 36% from 2006 to 2030 and that aquaculture needs to fill the 40 million tonnes gap. As for seaweeds, there is a global 12 billion US$ potential for new markets including biofuels and bioplastics (World Bank, 2023).

In 2013, the FAO introduced the Blue Growth Initiative to promote sustainable mariculture development in response to the growing demand for seafood and seaweed and ensure global food security. This agenda has been adopted by the European Union, OECD and World Bank (Massa et al., 2017). Several countries have implemented this initiative through marine spatial planning and the creation of allocated zones for aquaculture (AZAs) with the objectives of reserving space for mariculture, reducing user conflicts and environmental impacts and speeding-up the leasing/permitting process (FAO, 2013; Sanchez-Jerez et al., 2016; Macias et al., 2019; Morris et al., 2021; Wang et al., 2022). In temperate waters, most of the space available for mariculture in sheltered areas (estuaries, lagoons, fjords and enclosed bays) is already occupied. Expansion is only possible in more exposed sites. Moreover, in several sheltered areas the carrying capacity has been exceeded and part of the production is moving farther offshore to reduce the density of farming operations (Mille and Blachier, 2009; Komatsu et al., 2016; Wang et al., 2022). There is also increasing pressure from other coastal users and regulators to move existing nearshore farms farther offshore (Wang et al., 2022). For these reasons, newly created AZAs are mostly situated in exposed sites away from conflicting uses. Another important opportunity for mariculture expansion is its co-location with marine renewable energy farms which are, by definition, situated in high energy environments. For example, it is projected that the installed capacity of offshore wind farms will increase 15- to 24-fold between 2018 and 2040 and that these farms will occupy 47,000 to 73,000 km^2 of exposed waters, mainly in China, Europe and northeastern USA (IEA, 2019).

Co-occurring with this strong drive for exposed waters, climate change will have a significant impact on the conditions in which mariculture will develop in the coming decades (Cubillo et al., 2021; Hu et al., 2021; Liu et al., 2024). More specifically, the IPCC (2022) predicts for the second half of the 21st century an increase of the average sea temperature and of the frequency, duration and intensity of marine heat waves in all regions as well as an increase of the mean wave energy and extreme wave heights in several regions. At the dawn of these profound changes, a global review of the technologies currently used by commercial farms in high energy environments can be useful for the industry and the R&D community and serve as a benchmark for future development.

There is no consensus on the definition of "open-ocean", "offshore", "off-the-coast" or "exposed" mariculture (Kapetsky and Aguilar-Manjarrez, 2007; Lovatelli et al., 2013; Froehlich et al., 2017; Bak et al., 2020; Howarth et al., 2022; ICES, 2023). The criteria used to classify sites are usually a combination of the distance to nearest coastline or port, water depth, current velocity, wave height and wind speed with various thresholds. Consequently, the published lists of such sites (Cheney et al., 2010; Ögmundarson et al., 2011; Buck and Langan, 2017; Galparsoro et al., 2020; Howarth et al., 2022; ICES, 2012, 2023; Fujita et al., 2023) vary considerably. Several reviews of the technological aspects of offshore/exposed extractive species aquaculture have been published since 2010 (Cheney et al., 2010; Ögmundarson et al., 2011; Fernand et al., 2017; Buck et al., 2017, 2018; Goseberg et al., 2017; Bak et al., 2020; Heasman et al., 2020; Tullberg et al., 2022; Saether et al., 2024). Most of these reviews focus on case studies or on experimental/pilot technology as opposed to commercial practice.

Extractive species are those that do not require nutrient/feed input during the at-sea grow-out phase. In temperate waters almost 100% of mariculture production of these non-fed species is for the following three groups: kelps (order Laminariales), bivalve molluscs (mussels, oysters and scallops) and tunicates (FAO, 2023a). They are prime candidates for offshore expansion and their grow-out has much lower adverse effects on the environment than fish farms (Buck et al., 2017; Mascorda Cabre et al., 2021; Fujita et al., 2023). Clawson et al. (2022) carried out a global inventory of commercial mariculture farms. They estimated the number of farms per country based on aquaculture lease maps or, when not available, by dividing the national production by the estimated average production per farm. This study excluded kelp and tunicate farms and made no distinction between sheltered and exposed farms and the production methods used. Harvey et al. (2024) compared the density of longline and raft farming (presumably bivalves and macroalgae) between parts of China, Chile, Japan, South Korea and Vietnam based on the random sampling of Google Earth imagery. This study was limited to nearshore areas with a water depth of less than 15 m. At the national and sub-national levels, aquaculture geographic information systems (Supplementary Table S3) make no distinction between sheltered and exposed sites. This is also the case for China-wide mariculture mapping exercises based on satellite imagery recently published (Liu et al., 2022a; Jin et al., 2023).

In this paper, I carry-out a systematic global inventory of extractive species commercial farms in exposed temperate waters based on high resolution aquaculture lease maps (HRALMs). The inventory is limited to temperate marine waters for the following reasons: there is no aquaculture in polar/sub-polar regions (Oyinlola et al., 2018; Clawson et al., 2022); temperate open waters are characterized by much higher wave energy than tropical/subtropical waters (Arinaga and Cheung, 2012); and information on the exact location of farms in the tropical/subtropical regions is lacking for most countries (Clawson et al., 2022) while, as we will see below, coverage is almost complete in temperate waters. I then review longline design and farm layout for the exposed sites for which the information is available. Finally, I review the information available on structural damage and cultured biomass loss in longline farms caused by hydrodynamic forces.

2 Methodology

2.1 Study area

The study area is limited to brackish and marine waters where the mean annual sea surface temperature (SST) is between 5 and 20°C. These limits correspond roughly to the global distribution of blue mussels (*Mytilus* sp.; Gaitan-Espitia et al., 2016; Hilbish et al., 2000) and kelps (order Laminariales; Steneck et al., 2002). The study area was subdivided into eight large regions (Figure 1): Atlantic Northeast (ANE), Atlantic Northwest (ANW), Mediterranean and Black seas (MBS), Pacific Northeast (PNE), Pacific Northwest (PNW), Temperate South America (TSAM), Temperate South Africa (TSAF) and Temperate Australasia (TAA). The list of countries and country subdivisions included in each region is given in Supplementary Table S1. The sources of the SST climatologies used to delimit the study area and of other global oceanic variables used to characterize each region are given in Supplementary Table S2.

2.2 Exposed farm identification

Identification of exposed farms was based on high-resolution interactive or static aquaculture lease maps (HRALMs) available on the Internet. The extended list of the 80+ HRALMs which cover roughly 95% of the study area is provided in Supplementary Table S3. A large majority of the HRALMs are interactive Web-GIS applications or KML files readable on Google Earth that provide more or less details on individual leases. The criteria used to screen the thousands of aquaculture leases appearing on these HRALMs are 1) the type of lease (commercial and active), 2) the cultured species (extractive, non-fed), 3) the culture method (suspended, off-bottom) and 4) wave exposure (exposed sites). Inactive, proposed, under review, experimental and pilot leases were not retained. The main mariculture extractive species in temperate waters are listed in Table 1. Abalone, sea cucumbers and urchins farms were excluded from this category. Intertidal, pole, trestle, table and on-bottom (sea ranching) farms were not retained.

Wave exposure was the only criteria used to distinguish between exposed and sheltered sites. This selection was made in two steps. In a first step, the following fetch criteria were used to preselect sites: 1) the maximum fetch of the site is longer than 150 km; and 2) the window of continuous fetch longer than 20 km is wider than 45° and includes the maximum fetch direction. This was easily evaluated and, for sites near the thresholds, measured directly on the maps. The fetch criteria used above provide only a rough estimate of wave exposure because they do not take into account the direction of the prevailing winds and swells. In a second step, wave

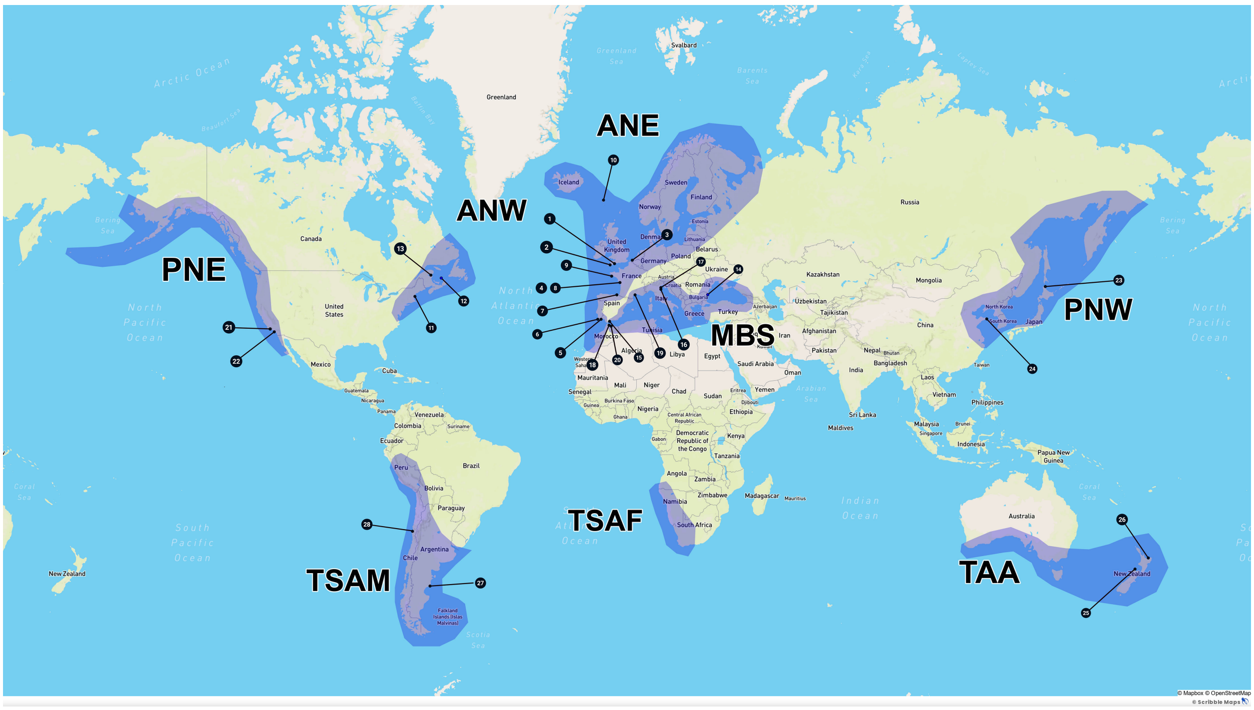

FIGURE 1
Limits of the eight large regions (shaded areas) which make up the study area and position of the 28 exposed sites for which detailed information on longline design and farm layout is available.

TABLE 1 Main temperate marine extractive species cultured off-bottom (FAO, 2023a).

Group	Sub-group	Species	Region	Study area production, 2021 (10^3 t)
Kelps	not applicable	*Saccharina japonica*	PNW	15,829
		Undaria pinnafitida	PNW, ANE	
		Saccharina latissima	ANW, ANE, PNE	
Bivalves	Mussels	*Mytilus* sp.	All	1,890
		Perna canaliculus	TAA	
Bivalves	Oysters	*Maganella (Crasssostrea) gigas*	PNW, ANE, TSAM	1,639
		Crassostrea virginica	ANW	
Bivalves	Scallops	*Mizuhopecten (Patinopecten) yessoensis*	PNW, PNE	889
		Chlamys farreri	PNW	
		Argopecten purpuratus	TSAM	
		Placopecten magellanicus	ANW	
Tunicates	not applicable	*Halocynthia roretzi*	PNW	32
		Styela sp.	PNW	

climatologies (Supplementary Table S4) were used to validate the preselection. Examination of these maps indicated that the above fetch thresholds corresponded with one or more of the following wave thresholds: 1) annual mean significant wave height (SWH) > 0.5 m; 2) 99th percentile of SWH > 2.2 m; 3) 50-year-return-period SWH > 4.0 m; and 4) annual mean wave power density (WPD; synonym: wave energy flux) > 1.5 kW/m. The 50-year-return-period SWH is the standard extreme wave height used to design floating aquaculture facilities (Norway NS9415 Standard, 2009). The hourly WPD is proportional to SWH^{2}T (where T is the wave period). For a given site, when the classification given by the four variables was contradictory, the one given by the variable with the highest spatial resolution was retained. For a small number of preselected sites the wave exposure thresholds were not exceeded and these sites were deleted from the compilation (e.g. Thermaikos Gulf, Greece and northeastern Adriatic Sea, Italy). One well documented site in the Faroe Islands where the maximum fetch is only 10 km was not preselected but was added to the final tally because the 50-year-return-period SWH exceeds 4 m. Preselected sites that could not be confirmed for lack of high-resolution wave climatologies were kept in the compilation.

Countries or country subdivisions for which comprehensive HRALMs were not available are: Albania, China, Falkland Islands, Georgia, Monaco, North Korea, Romania, Russian Black Sea, Tunisia, Turkey and Ukraine (outside Crimea). In addition, the Russian Far East presented a special case discussed in Section 3.2.1. In all other cases the identification of exposed sites was carried out using the following approach. First, the FishStatJ database (FAO, 2023a) was consulted and countries/country subdivisions with less than 50 t of bivalve, tunicate and kelp production were eliminated (Falkland Islands, Georgia, Monaco, Romania and Ukraine, outside Crimea). Secondly, for the remaining countries and country subdivisions, National Aquaculture Sector Overviews (NASO; FAO, 2023b) were consulted and those where all kelp, bivalve or tunicate farms were determined as sheltered after checking the wave fetch criteria on Google Earth and wave climatologies where eliminated (Albania and Tunisia). For the remaining countries/subdivisions, governmental documents and technical and academic literature that relate to the geographic position of existing farms were consulted. This allowed an estimation of the number of exposed farms in Krasnodar Krai (Russia) and Turkey. At this stage, information was missing for China and North Korea. The method used to estimate the extent (km^2) of exposed farms in these two countries is described in Section 3.2.1.

2.3 Inventory metrics

Results are summarized per country or territory in each of the 8 regions of the study area using three metrics: 1) number of sites (total and per species group), 2) total leased area (ha), and 3) percentage of sites that use longlines. A "site" refers to a single isolated lease or a group of several active leases in an allocated zone for aquaculture (AZA). The leased area includes the actual space occupied by the production structures, navigational channels and buffer zones around the structures and any undeveloped part of the lease. When more than one species group was listed for a site, the site was assigned to the first group listed. Bivalve sub-groups (oysters, mussels and scallops) were not distinguished because many sites grow more than one sub-group. Longlines consist of long horizontal ropes supported by buoys (floats) individually anchored to the sea bed at both ends or in arrays of several parallel ropes anchored by a grid of anchors.

2.4 Longline design and farm layout characterization

Details on longline (LL) design and farm layout was available for some of the exposed sites inventoried. The environment of each site was characterized by the following variables: region, location, water body, year established, leased area, distance to nearest coastline, water depth and wave exposure. For the latter, the criteria and thresholds presented in Table 2 were used to classify each site as moderately exposed, fully exposed or very exposed. The variables used to characterize LL design and farm layout are: LL type, mainline length and depth, mooring and anchoring configuration, LL (for bivalves) or kelp-line (for kelps) orientation relative to currents and waves, and farm density. Farm density (m of mainline/ha) was calculated as the planned/allowed maximum number of LLs multiplied by average mainline length (m) and divided by leased area (ha). Description of LL design is limited to those used for the grow-out phase; spat catching LLs are not covered. The terminology used in this part and the rest of the paper is given in Tables 3–5 and, in the cases of Tables 3 and 4, illustrated in Figure 2. The major sources of information are leasing or permitting documents, technical reports, academic literature and company websites (Supplementary Table S5). For more details on the various LL components and designs, see Bompais (1991), Langan et al. (2010), Ögmundarson et al. (2011), Bonardelli (2013), Flavin et al. (2013), Goseberg et al. (2017) and Bonardelli et al. (2019).

2.5 Structural damage and cultured biomass loss characterization

A review of available information on structural damage and cultured biomass loss due to hydrodynamic forces for commercial and experimental LLs was carried-out in order to compare the actual suitability of the various types of LLS relative to their level of exposure. The sources of this type of information were technical reports, academic literature and the media.

3 Results

3.1 Regional oceanic conditions

Large marginal seas in the PNW (Bohai, Yellow, Japan and Okhotsk seas), ANW (Gulf of St. Lawrence), ANE (White, North, Baltic, Irish and Celtic seas) and the MBS Region have relatively reduced wave exposure compared to areas were the coasts overlook directly the Pacific, Atlantic or Indian oceans. The pole-ward part of all regions except MBS is situated in the global extra-tropical storm belts where wave energy is at its maximum. The west facing coasts in these belts (e.g. Alaska, Ireland, southern Chile, Tasmania and New Zealand) are the most exposed areas to winter storms in the world. Late summer tropical cyclones (typhoons and hurricanes) are more frequent in the southern part of the PNW and ANW regions. All the Pacific Ocean coasts (PNW, PNE, Peru, Chile and New Zealand) are vulnerable to tsunamis.

The tidal range does not exceed 4 m except in limited macro-tidal areas in the PNW (Jiangsu, China and western Korea), PNE (Alaska), ANW (Bay of Fundy), ANE (White, Celtic and Irish seas, English Channel and Brittany) and TSAM (southern Argentina). The largest micro-tidal areas (tidal range < 2m) are the Sea of Japan (PNW) and the MBS Region. Maximum tidal currents do not exceed 0.6 m/s except in the macro-tidal areas listed above and in straits (e.g. Gibraltar, (Spain and Morocco), Cook, (NZ)). There is no sea ice present in the PNE, TSAM, TSAF and TAA regions but it is usually present during winter in the Bohai Sea, northern Sea of Japan and the Sea of Okhotsk (PNW), Gulf of St. Lawrence and northern Newfoundland (ANW), White and Baltic seas (ANE) and northern Black Sea (MBS). The four major global coastal upwelling systems (CUS) are situated in the study area: along the southern coast of PNE (California Current) and ANE (Canary-Iberia CUS), the Pacific coast of the TSAM region (Peruvian-Chilean CUS) and in the TSAF Region (Benguela Current).

3.2 Global inventory

A summary of the global inventory is presented in Table 6. Information is missing for North Korea, Russian Far East and Russian Black Sea and only a rough estimate of the exposed farmed area was possible for China. Excluding these four countries and country subdivisions, a total of 392 kelp, 299 bivalve and 172 tunicate sites were inventoried. In the case of sites for which the culture method is known, 99.4% use longlines, only 3 sites use surface rigid rafts and one site uses surface long-tubes. There are currently no exposed farms in countries, states or provinces where hundreds of sheltered farms exist. These include Ireland, Scotland (UK), western Sweden, Norway, Tasmania (Australia), southern Chile, Alaska and Maine (USA), British Columbia, Newfoundland, Nova Scotia and Prince Edward Island (Canada). Each region is reviewed separately below.

3.2.1 Northwest Pacific

At least 74% of the total farming area (ha) inventoried are situated in the PNW region. The overwhelming importance of this region is not surprising knowing that it accounts for over 99% of the kelp, 72% of the bivalve and 100% of the tunicate production (sheltered + exposed) of all temperate countries (FAO, 2023a). Due to this overwhelming importance, each country is examined separately below.

In the case of China, HRALMs at the national or provincial levels are not available. The Chinese Statistical Fishery Yearbook provides the area farmed by species and province but does not distinguish between sheltered and exposed sites (Wang et al., 2022). For these reasons, it was not possible to obtain a precise estimate of the total area of exposed farms in temperate China. An indirect approach was used for the country subdivisions included in the study area. Almost 100% of the kelp production in China comes

TABLE 2 Wave exposure classification. A site is assigned to the highest wave exposure class for which at least one of the four criteria is met.

Class	Mean annual SWH (m)	99th percentile SWH (m)	50y-return-period SWH (m)	Mean annual WPD (kW/m)[1]
Sheltered (S)	< 0.5	< 2.2	< 4	< 1.5
Moderately exposed (ME)	0.5–1.0	2.2–3.8	4–7	1.5–8
Fully exposed (FE)	1.0–2.0	3.8–6.0	7–14	8–20
Very exposed (VE)	>2.0	>6.0	>14	>20

1. WPD, wave power density (energy flux).

TABLE 3 Longline component definitions.

LL component	Description
Mainline (ML)	horizontal line to which the compensation buoys and suspensions are attached. Synonym: backbone
Mooring line	line between each end of the ML and the anchors
Anchor	device on or in the sea bottom at each end of the LL to which the mooring line is attached
Corner buoy	buoy at the junction of the ML and mooring line
Compensation buoy	buoys attached along the ML to compensate the weight of the suspensions
Suspension	dropper, net or cage attached along the ML that hold or contain the cultured biomass
Kelp-line	vertical or horizontal rope to which the kelp is attached
Leg	vertical line attached to the ML with a sinker (leg sinker) at the bottom end that rests on the sea bottom and a buoy (leg float) at the top end attached to the ML

from the culture of kombu (*S. japonica*) and wakame (*U. pinnatifida*). The total area occupied by farms in China in 2015 for these two species was 436 km^2 and 69 km^2, respectively (Zheng et al., 2019). Liu et al. (2019) estimates that 30% of the kombu farming area (133 km^2 in 2015) is located more than 11 km from the coastline in more than 20 m water depth, mostly in the following three counties: Rongcheng and Shangdao (Shandong) and Lushun (Liaoning). According to Zheng et al. (2019) almost all the wakame production in China comes from the study area. Rongcheng County at the eastern tip of the Shandong Peninsula is the only zone in the Chinese part of the study area where the thresholds for wave height and wave power are exceeded within 10 km of the coast (He and Xu, 2016; Jiang et al., 2016; Dong et al., 2020). This 300 km long peninsula juts into the center of the Yellow Sea. In Rongcheng County there is a succession of open bays (Rongcheng, Yangyuchi, Ailian, Heini) and the semi-enclosed Sanggou Bay that constitute the epicenter of kombu longline farming in China (Liu et al., 2022a; Jin et al., 2023). The total area of exposed farming in these open bays and in the area offshore Sanggou Bay can be estimated at roughly 200 km^2. It is likely that 100% of this area is used solely for longline kombu farming from fall to following spring. The high-density longline fields clearly visible on Google Earth extend up to 14.5 km from the inner bay shore into the Yellow Sea. In the southern half of Rongcheng County including Sanggou Bay, remote sensing based mapping shows that the exposed culture area increased roughly eight-fold between 1990 and 2018 (Wang et al., 2022).

In Japan the estimated total area of exposed sites amounts to over 1,500 km^2 which is by far the largest area of any country. It is likely that nearly 100% of these sites use LLs. Three exposed zones can be distinguished based on the main cultured species: 1) Hokkaido dominated by scallop culture (*M. yessoensis*), 2) Aomori Prefecture dominated by tunicate culture (*H. roretzi*), and 3) the rest of northern Honshu dominated by wakame (*U. pinnatifida*) and kombu (*S. japonica*) cultivation. In the case of scallop culture around Hokkaido, there are two exposed sub-zones based on the scallop culture technique: 1a) Sea of Okhotsk where longlines are used for spat catching and the intermediate culture in large leases before juveniles are sowed on the bottom and harvested by dredges (bottom culture areas are not included in the inventory) and 1b) the rest of Hokkaido where scallops are grown on LLs for all phases (Andrews et al., 2013).

In South Korea exposed sites are concentrated along the eastern coast (Sea of Japan). The average size of the farms is quite small. In

TABLE 4 Longline type definitions.

Longline Type	Mainline depth	Corner buoy depth	Compensation buoy depth	Legs
Surface (S)	surface	surface	surface	no
Semi-submerged without legs (SS)	submerged	surface	all or partly at surface	no
Semi-submerged with legs (SS-L)	submerged	surface	all or partly at surface	yes
Fully submerged without legs (FS)	submerged	surface or submerged	submerged	no
Fully submerged with legs (FS-L)	submerged	surface or submerged	submerged	yes

TABLE 5 Mooring and anchoring definitions.

Configuration		Definition
Mooring mode	Single individual (SI)	LL composed of a single ML individually anchored at both ends
	Double individual (DI)	LL composed of two parallel MLs anchored together at both ends
	Array (AR)	Several parallel MLs with or without cross-connections between them held in place by a grid of mooring lines
Nb of mooring lines	2-point (2P)	One mooring line at each end on the LL
	4-point (4P)	Two mooring lines at each end of the LL
	Grid (G)	Multiple mooring lines arranged in a grid (for arrays)
Mooring type	Single rope (R)	Single rope between the anchor and the corner buoy without tension buoy and/or sinker
	Tensioner buoy (T1)	Submerged buoy attached to the mooring rope at some distance from the anchor
	Tensioner buoy and sinker (T2)	Submerged buoy and sinker attached to the mooring rope at two distances from the anchor
	Chain catenary (CC)	Mooring line with the lower portion composed of a heavy chain resting on the bottom
Anchor type	Deadweight (DW)	Concrete block(s) resting on bottom
	Drag embedment (DEA)	Anchor embedded into the top sediments by pulling on it
	Screw anchor (SA)	Metal pile screwed deep into the sediments
	Pile (PI)	Wooden pile driven into the sediments

terms of total area occupied, they are dominated by scallops (northeast), tunicates (central) and kelp (southeast).

HRALMs are not available for North Korea and other information on the location of aquaculture farms is very scarce. Available statistics on production (FAO, 2023a) are unreliable estimates but they indicate that extractive species culture in this country is only a very small fraction of that of South Korea, Japan and China. It is likely that the number and area of exposed farms is negligible in this country.

In the Russian Far East, according to the aquaculture leasing web application Aquavostok (2023), over 700 km^2 of exposed aquaculture space have been leased and is "in use". Most of this space was leased after 2015 and is located along the coasts of the Primorsky Krai (Sea of Japan). As a result, the total production of kelp, mollusks, echinoderms and salmon in this zone increased ten-fold between 2015 and 2021 (FAO, 2023a). Information on the cultured species and production method is not available for individual sites. Since these sites can be used to grow non-extractive species (salmon, abalone, sea urchin) and for on-bottom scallop culture, it was not possible to obtain a reliable estimate of the number and extent of sites in this sub-region.

3.2.2 Northeast Pacific

The farms are situated in the Southern California Bight (USA) and along the Pacific coast of the state of Baja California (Mexico). These farms grow the Mediterranean mussel (*M. galloprovincialis*) and the giant kelp (*Macrocystis* sp.) on longlines and were established after 2004.

3.2.3 Northwest Atlantic

The farms are situated in the Gulf of St. Lawrence (Canada) and along the New England coast (USA). These are used to cultivate the blue mussel (*M. edulis*) and the sugar kelp (*S. latissima*) on LLs and were established after 2005.

3.2.4 Northeast Atlantic

The farms are dispersed from the North Sea to Algarve, Portugal. The main species cultured are the blue mussel (*Mytilus* sp.), the Pacific oyster (*M. gigas*) and the sugar kelp (*S. latissima*) on LLs. The oldest farm was established in the Pertuis Breton (France) in 1991 while most of the others were established after 2006.

3.2.5 Mediterranean and Black Seas

Exposed farms in this region grow the Mediterranean mussel (*M. galloprovincialis*) on LLs. Some also grow or condition oysters. There are no tunicate and kelp farms in the region. The farms in France and Italy were established in the mid-1980s, those in Spain and Bulgaria in the late 1990s and 2000s and those in Crimea (Ukraine), Krasnodar Krai (Russia), Turkey and Morocco after 2015. Four AZAs (total area: 4,200 ha) were created in the 1980s for mussel culture in the exposed waters off the Occitanie coast (France). In the early 1990s there were over 2,000 ha leased producing 8,000 t of mussels annually using LLs (Danioux et al., 2000). Due to heavy spat predation by fishes, many of the leases were abandoned or used to condition oysters grown in coastal lagoons (Cepralmar, 2017). HRALMs were not available for Turkey. The only extractive species cultured in this country is the Mediterranean mussel (FAO, 2023a). Mussel production increased from virtually zero to 4,500 t between 2015 and 2021. The farms are all situated in the sheltered waters of the Aegean and Marmara seas (Balci Akova, 2015; Yildirim, 2021) except for two new LL farms established in 2022 off the exposed Black Sea coast (Gucukluoglu, 2022). HRALMs are not available for the Krasnodar

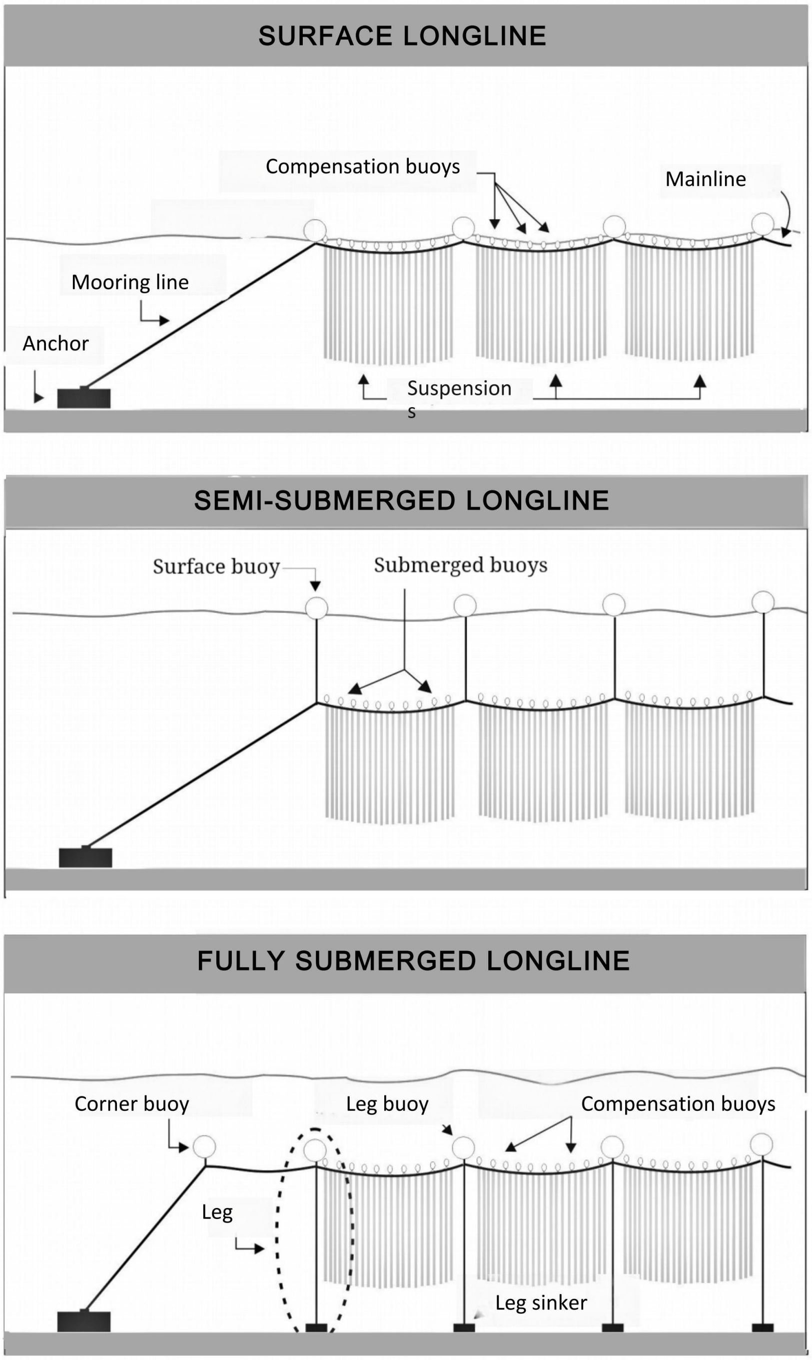

FIGURE 2
Schematic presentation of the three main types of longlines and their components (not to scale).

Krai (Russia). Other sources indicate that there are at least 14 exposed mussel *(M. galloprovincialis*) and oyster (*M. gigas*) farms along the Russian Black Sea coast, most of them established after 2019.

3.2.6 Temperate South America

Except for one site used for giant kelp culture (*Macrocystis* sp.), the exposed sites in Chile and Peru are used to grow the purple scallop (*A. purpuratus*) on LLs. In Chile, all sites are along the northern coast. The oldest farms were established in the 1980s. In Argentina, two sites were established after 2009 and are used to grow blue mussels (*Mytilus* sp.) on LLs.

3.2.7 Temperate South Africa

All shellfish farms are located in sheltered sites and there are no kelp and tunicate farms in this region.

TABLE 6 Total area and number of exposed sites in the study area and percentage of sites using longlines (% LL) per region and country.

Region	Country	Area (ha)	Number of sites				% LL	Remarks
			Bivalves	Tunicates	Kelps	Total		
ANE	Belgium	454	1	0	0	1	100	
	Faroe Islands	40	0	0	1	1	100	
	France	1,465	5	0	2	7	100	
	Morocco	470	1	0	1	2	100	
	Portugal	1,500	5	0	0	5	100	
	Spain	43	2	0	1	3	100	
	UK	1,661	6	0	1	7	100	
	Other countries	0	0	0	0	0	-	
ANW	Canada	327	3	0	1	4	100	
	USA	80	2	0	0	2	100	
	Other countries	0	0	0	0	0	-	
MBS	Algeria	450	31	0	0	31	100	
	Bulgaria	1,230	35	0	0	35	94	
	France	560	2	0	0	2	100	
	Italy	5,646	21	0	0	21	100	
	Morocco	45	3	0	0	3	100	
	Russia	?	14^{E}	0	0	14^{E}	100^{E}	
	Spain	375	9	0	0	9	67	
	Turkey	10^{E}	2	0	0	2	100	See text
	Ukraine (Crimea)	169^{E}	4^{E}	0	0	4^{E}	100	
	Other countries	0	0	0	0	0	-	
PNE	Canada	0	0	0	0	0	-	
	Mexico	43	3	0	2	5	100	
	USA	70	2	0	0	2	100	
PNW	China	$20,000^{E}$	?	?	?	?	100^{E}	See text
	Japan	152,590	55	8	218	281	100	See text
	North Korea	0^{E}	0^{E}	0^{E}	0^{E}	0^{E}	-	See text
	Russia	?	?	?	?	?	?	See text
	South Korea	2,982	71	164	164	399	100	See text
TAA	Australia	125	1	0	0	1	100	
	New Zealand	17,626	16	0	0	16	100	See text
TSAF	All	0	0	0	0	0	-	
TSAM	Argentina	12	2	0	0	2	100	
	Chile	565	11	0	1	12	100	
	Falkland Isles	0	0	0	0	0	-	
	Peru	330	6	0	0	6	100	

E, estimate.

3.2.8 Temperate Australasia

The main species cultured are the blue mussel (*Mytilus* sp.) in Australia and the green-lipped mussel (*P. canaliculus*) in New Zealand. All farms were established after 2000 and use LLs. In New Zealand, more than 60% of the 176 km^2 of exposed area consist of very large leases (400 to 3,800 ha each) that are partly or not yet developed. Another 25% are only used for bivalve spat catching during summer on a rotational basis (TDC, 2019).

3.3 Longline design and farm layout

Detailed information on LL design and farm layout was available for only 28 of the exposed sites inventoried and in several of these cases information on farm layout is lacking. Tables 7 and 8 present a summary for these sites listed by region and by the main species cultured, respectively. The sites cover a wide range of locations (7 of the 8 regions), year of establishment

TABLE 7 Situation of the 28 exposed sites for which details on longline design and farm layout are available.

Site #	Region	Location	Water Body	Year establish.	Leased Area (ha)	Water Depth (m)	Distance to coast (km)	Wave expos. (1)
1	ANE	Brixham, UK	Lyme Bay	2014	1540	20–25	4–10	ME
2	ANE	St. Austell, UK	St. Austel Bay	2010	105	8–15	0.9–1.5	ME
3	ANE	Nieuwpoort, Belgium	North Sea	2022	454	10–12	4.5	ME
4	ANE	La Rochelle, France	Pertuis Breton	1991	800	10–15	3.8	ME
5	ANE	Olhao, Portugal	Atlantic Ocean	2011	112	25	6	ME
6	ANE	Sagres, Portugal	Atlantic Ocean	2012	161	20–30	2.4	ME
7	ANE	Andarroa, Spain	Atlantic Ocean	2018	8	40	1	FE
8	ANE	La Rochelle, France	Pertuis Breton	2007	350	15–20	4.8	ME
9	ANE	Loctudy, France	Atlantic Ocean	2013	150	15–25	2–4	FE
10	ANE	Faroe Islands	Funnigsfjord	2018	40	25–70	0.4–1.1	ME
11	ANW	Rye Beach, NH, USA	Atlantic Ocean	2006	60	40	5	FE
12	ANW	Magdalen Isles, Canada	Gulf of St. Lawrence	2007	196	20–24	4	ME
13	ANW	Paspébiac, Canada	Gulf of St. Lawrence	2018	84	15–20	2–4	ME
14	MBS	Kavarna, Bulgaria	Black Sea	2004	200	<15	0.8	ME
15	MBS	Marbella, Spain	Mediterranean Sea	1999	13	20	0.8	ME
16	MBS	Sacca di Goro, Italy	Adriatic Sea	1980's	116	25	4.8	ME
17	MBS	Chioggia, Italy	Adriatic Sea	1991	200	20–24	6	ME
18	MBS	Ras-el-Ma, Morocco	Alboran Sea	2023	30	20–50	0.5	ME
19	MBS	Sète, France	Gulf of Lion	1987	504	20–30	0.5–5	ME
20	MBS	Cala Iris, Morocco	Mediterranean Sea	2023	15	25	1.3	ME
21	PNE	Santa Barbara, CA, USA	S. California Bight	2005	29	24–27	1.2	ME
22	PNE	Huntington Beach, CA, USA	S. California Bight	2016	40	30–46	9.5	ME
23	PNW	Sarufutsu, Japan	Sea of Hokhotsk	1980	7500	40	3–5	ME
24	PNW	Rongcheng, China	Yellow Sea	1990's	7000	10–30	5–8	ME
25	TAA	Collingwood, NZ	Golden Bay	2000s	159	9–12	2.5	ME
26	TAA	Opotiki, New Zealand	Bay of Plenty	2010	3800	30–50	8–10.5	FE
27	TSAm	Camarones, Argentina	Bahia Camarones	2010	12	20	0.4	ME
28	TSAm	Tongoy, Chile	Bahia Tongoy	1980s	300	20–40	1–3	ME

1. ME, moderately exposed; FE, fully exposed.

TABLE 8 Longline design and farm layout of the 28 exposed sites of Table 7.

Site #	Main species	LL type (1)	Mainline length (m)	Mainline depth (m)	Mooring mode (2)	Nb of anchors (2)	Mooring line type (2)	Anchor type (2)	Farm density (m of ML/ha)	LL (kelp-line) orientation (parallel to)
1	Mussel	SS	150	3	SI	2P	R	SA	60	current
2	Mussel	SS	200	2-3	SI/DI	2P	CC	DW		
3	Mussel	SS	100-120	1-2	SI	2P	R	SA	231	current
4	Mussel	SS	100	2	SI	2P	T1	DW	30	current & swell
5	Mussel	SS	400	5	SI	2P	R	DW		
6	Mussel	SS	420	2	AR	2P	R	DW	140	
7	Mussel	FS	120	10	SI	2P	R	DW + SA	65	
11	Mussel	FS	183	15	SI	2P	R	DW		
12	Mussel	FS-L	100	9-13	SI	2P	R	SA	96	current
14	Mussel	S	220	0-1	DI	2P	R	DW		coast
15	Mussel	SS	200	2	SI	2P	R	DW	153	
16	Mussel	SS-L	1000	2-3	SI	2P	R	DW	156	current
17	Mussel	SS	250	6	SI	2P	R	DW		
18	Mussel	FS	200	3	SI	2P	T1	DW	127	coast
19	Mussel	FS-L	250	5	SI	2P	T1	DW + PI	10–34	swell
20	Mussel	FS-L	250	3	SI	2P	T1	DW	94	swell
21	Mussel	SS	138	6-9	SI	2P	R	HA	189	coast
22	Mussel	SS	210	7.5	SI	2P	R	SA	208	coast
25	Mussel	S	120	0-1	DI	2P	R	SA	170	current
26	Mussel	SS	150	5	SI	2P	R	DW or SA	20	swell
27	Mussel	FS-L	188	8	SI	2P	T1	DW		coast
8	Oyster	SS-L	100	2	SI	2P	T1	DW + SA	55	current & swell
23	Scallop	FS-L	200	20	SI	2P	R	SA		
28	Scallop	SS	40-200	5-10	SI	2P	R	DW		
9	Kelp	SS	700	1	SI	2P	T2	DW	980	current & swell
10	Kelp	FS	500	10	SI	4P	R	DEA	114	
13	Kelp	FS-L	100	4-7	SI	2P	R	DW		
24	Kelp	S	70	0-1	AR	G	R	PI or DW	4,000	current

1. See Table 4 for signification of abbreviations.
2. See Table 5 for signification of abbreviations.

(1980–2023) and size (8–7,500 ha). Roughly 75% are situated less than 5 km from the coast and in water depths of less than 30 m and all are situated less than 11 km from the coast in water depths of less than 70 m. Twenty-four sites are classified as moderately exposed, 4 as fully exposed and none as very exposed. The fully exposed sites are # 7 (Basque Country, Spain), # 9 (southern Brittany, France), # 11 (New Hampshire, USA) and # 26 (Bay of Plenty, NZ). Twenty-one sites mainly grow mussels, 4 grow kelp, two grow scallops and one grows oysters. The information on LL design and farm layout is summarized below by cultured species.

3.3.1 Mussel and oyster farms

Most mussel and oyster farms use individually anchored semi-submerged or fully submerged LLs. ML length varies between 100 and 1,000 m and its depth varies between 1 and 15 m, the deepest in the fully exposed sites. The 1,000 m semi-submerged LLs in Site

16 are fitted with legs every 75 m along the ML. In most sites the simplest mooring and anchoring system is used: 2-point, single rope and deadweight anchors. Farm density (m of ML/ha) decreases with increasing lease area mainly because large leases are subdivided into blocks of LLs separated by wide navigational channels and buffer zones. In most of the moderately exposed sites, LLs are oriented parallel to the currents or the coast (and presumably to the currents). In four moderately exposed sites and two fully exposed sites (# 9 and # 26), they are oriented parallel to swell propagation.

3.3.2 Scallop farms

The two scallop sites are situated in northern Hokkaido (Sea of Okhostk) for spat catching and intermediate culture of the Japanese scallop (*M. yessoensis*) and northern Chile for all phases of culture of the purple scallop (*A. purpuratus*). There are several published descriptions of the scallop LLs used in Japan but most of these focus on sheltered areas (Taguchi, 1977; Ventilla, 1982; Beal, 1999; Kosaka, 2016). There are no standard LL design and farm layout; they depend on the culture phase (spat collection, intermediate culture or final grow-out), available lease area and degree of exposure to waves, currents and drifting sea ice. Longlines may be anchored individually or in arrays of several LLs as large as 16 ha. Along the exposed coast of the Sea of Okhotsk the Sarufutsu cooperative (Site # 23) uses fully-submerged LLs for the intermediate culture phase. The ML is maintained 20 m below the sea surface by a combination of surface floats and legs spaced at 25–50 m intervals (Lucien-Brun and Lachaux, 1983). Tongoy Bay (Site # 28) is the main scallop culture site in Chile. The LLs used there are semi-submerged with the ML maintained between 5 and 10 m below the sea surface depending on the water depth.

3.3.3 Kelp farms

The four kelp farms in Table 8 show that there is currently no standard design to grow this species group in exposed sites. Arrays are used in the moderately exposed area offshore Sanggou Bay, China (Site # 24). Each array is composed of 4 or 5, 70–100 m long surface LLs individually anchored 4 m apart with kelp-lines attached horizontally between two adjacent LLs at 1–2 m intervals. The use of surface LLs in this moderately exposed site is likely possible because of wave attenuation by the very high farm density (Liu and Zhang, 2022). In the moderately exposed Quebec farm (Site # 13), individually anchored fully submerged LLs with legs are used. The ML is maintained 7 m below the sea surface in winter because of drift ice and is raised to a depth of 4 m, below the surface freshet, in spring. The kelp-line is attached parallel to the ML and 1 m below it. In the fully exposed farm in southern Brittany (Site # 9), semi-submerged LLs 700 m long with legs attached at 100 m intervals are used. The density of this farm is also very high due to the small distance between LLs (10 m). In the Faroe Islands moderately exposed farm (Site # 10), individually anchored fully-submerged LLs without legs are used and the 500 m long ML is maintained 10 m below the surface. The kelp-lines are 10 m long vertical ropes attached at 1–2 m intervals to the ML and fitted with a small buoy at their free end that maintains the kelp floating above the ML in the surface water layer.

3.3.4 Tunicate farms

No detailed information was found for individual tunicate farms. Generally, tunicates (*H. roretzi* and *Styela clava*) are grown on LLs similar to those used for mussels. The tunicates attach to ropes and form vertically hanging droppers similar in shape and size to mussel droppers (Lambert et al., 2016).

3.4 Structural damage and loss of cultured biomass

3.4.1 Structural damage

LLs in sheltered sites are vulnerable to extreme storms. For example, an extreme post-tropical storm (Fiona) severely damaged LL farms in sheltered sites in the Gulf of St. Lawrence, Canada in 2022 (CBC, 2022). In the main sheltered mussel farming area in New Zealand (Marlborough Sounds), between 500 and 1,500 buoys are lost every year due to rough weather (MPI, 2021). In moderately exposed sites, large extra-tropical storms caused severe damage to semi-submerged LLs along the northwestern Adriatic coast, Italy, in 2010 and 2017 (Vianello, 2013; Mistri and Munari, 2019), in the Pertuis Breton, France, in 2008 (Site # 8; Mille and Blachier, 2009), in Tongoy Bay, Chile, in 2015 (Site # 28; Bakit et al., 2022), in Tasman Bay, New Zealand, in 2021 (Gee, 2021) and to surface kelp LLs in Rongcheng County (Site # 24), China (Liu et al., 2019). Eyrolles et al. (2018) report structural damage to semi-submerged LLS in a Brittany fully exposed farm (site # 9) due to waves and vessels. In November 2023 an extreme storm destroyed most of the semi-submerged farms along the moderately exposed Crimean and Russian Black Sea coast (PROyugAgro, 2024). However, I found no report of structural damage in the case of fully submerged LLs in commercial farms except for the Occitanie AZA (Site # 19), France where deadweight anchors slipped during a 1990 winter storm (Bompais, 1991). In most areas the response to hydrodynamic damage was to increase the pressure resistance of the buoys, the strength of buoy attachments, the size of the ropes and the holding capacity of the anchors with various combinations: screw anchors, multiple in-line deadweights, deadweight plus drag embedment anchors or piles (Ensor, 2011; Bompais, 1991; Blachier, 2011; Mille and Le Moine, 2011; Lee et al., 2015).

In the case of experimental LLs, their performance in exposed sites depended on their type. Long-tubes and surface longlines failed completely and were deemed unsuitable for exposed sites (Mueller-Fuega and Bompais, 1989; Buck and Buchholz, 2004; Daly, 2007; Minnhagen et al., 2019). Semi-submerged and fully submerged LLs without legs performed well except when the submerged buoys did not resist the hydrostatic pressure and imploded and when buoyancy adjustments could not be made in time before they collapsed to the sea bottom. Some were destroyed by a hurricane, fishing vessels or an unknown cause (Pajot, 1989; Paul and Grosenbaugh, 2000; Langan (2002); Langan and Horton, 2003;

Buck, 2007; Lindell, 2015; Minnhagen et al., 2019; Bonardelli et al., 2019; Lona et al., 2020). Fully submerged LLs with legs had no major problems (Karayücel et al., 2015; Bourque and Myrand, 2014; Id Halla et al., 2017) except for a poorly designed configuration in Sweden (Bonardelli et al., 2019). Metal connections (shackles, thimbles, swivels, rings) are often the weak point of the design and they should be avoided (Buck, 2007; Bonardelli et al., 2019; Bak et al., 2020).

Although large tsunamis have a return period of several decades, some of them have been responsible for severe or catastrophic damage to longlines recently in Japan, Chile and New Zealand. Farms in sheltered bays along the Pacific coast of northern Honshu, Japan, were severely damaged by a tsunami in 2010 (Kato et al., 2010) and completely destroyed by the Great Eastern Japan (Tohuku) tsunami of March 2011 (Suppasri et al., 2018). In Tongoy Bay, Chile (Site # 28), scallop farms were severely damaged by the 2011 Japanese tsunami and again in 2015 (Bakit et al., 2022). Farms in some sheltered sites in New Zealand were damaged by tsunamis in 2004 and 2010 (Ensor, 2011). After the large tsunamis of 1960, 2010 and 2011 on the Pacific coast of Japan, the level of damage to LLs was much higher in sheltered areas than in open ocean sites and was not related to sea surface elevation but rather to current velocity; LLs were destroyed when it exceeded 1.0-1.2 m/s (Kato et al., 2010; Suppasri et al., 2018). On the open coast this velocity is rarely attained during a tsunami in areas where the water is deeper than 65 m and consequently open deep waters are a refuge from tsunamis for surface structures (Lynett et al., 2014).

3.4.2 Loss of cultured biomass caused by hydrodynamic forcing

Several mechanical interactions may cause significant losses of the cultured biomass on LLs, mainly in the case of mussels and kelps that grow attached to ropes without containment. The attachment strength of individual *S. latissima* blades to ropes depends on the origin of the seedlings; those coming from exposed sites are strong enough to withstand high drag forces and the sheltering effect between kelp blades on a LL further reduces the probability of being dislodged (Buck and Buchholz, 2005; Chen et al., 2023). This species is cultivated at high densities (hundreds of plants per m of kelp-line) and the losses due to hydrodynamic forces are masked by the natural self-thinning process that considerably reduces plant density during the grow-out cycle (Kerrison et al., 2017). In the case of *S. japonica* in Sanggou Bay, China (Site # 24), which is cultivated at low densities (20 plants/m), Zhang et al. (2011) report that 16% of the kelp plants were dislodged mostly during winter and 4% of the blades were broken mostly at the end of the grow-out cycle while Liu et al. (2019; 2022b) report a high level of seedling fall-off (up to 50%) and blade breakage (up to 70%) in the outermost exposed areas off Sanggou Bay because the cultivars used were not developed for high energy environments. In late Spring or mid-Summer depending on the latitude, heavy fouling of the kelp blade starts, kelp tissue deteriorates and breakage increases rapidly; biomass loss can reach 50% by late summer and almost 100% in late fall (Gendron and Tamigneaux, 2008; Fieler et al., 2021; Skjermo et al., 2020). This is why in most areas kelp is harvested in late spring before heavy fouling starts.

In the case of mussel droppers, the important variable appears to be the bulk force with which the mussel matrix attaches to the rope rather than the attachment strength of individual mussels (Gagnon, 2019). This force decreases (or does not increase enough) as the mussels grow and fully grown droppers are prone to sloughing (fall-off) if there are snap loads in the dropper line. Wu et al. (2021 and 2024) report severe mussel sloughing near harvest time on surface LLs in Shengsi County, China, due to passing tropical storms. In some farming areas, sloughing is mitigated by inserting short vertical pegs through the dropper line at roughly 20 cm intervals (Çelik et al., 2015). Friction between adjacent droppers because their linear weight varies along the ML may cause erosion of the mussel matrix (Bompais, 1991). The use of continuous droppers where the dropper forms loops under the ML reduces the likelihood of this happening. When the distance between the LLs is small (< 10 m) and the pretension is not the same in all MLs, friction between the MLs erodes the kelp (Flavin et al., 2013) and mussel matrix (Bompais, 1991). In large waves perpendicular or oblique to the ML, kelp blades attached directly to the ML (Zhu, 2020) and mussel droppers (Lien and Fredheim, 2001) may roll-over the ML. This may reduce the attachment strength of the kelp and mussel matrix.

When contained in pearl nets and lantern nets, oysters and particularly scallops are very sensitive to the acceleration and inclination of their enclosures by currents and waves (Oshino, 2010; Natsuike et al., 2022; Goseberg et al., 2017; Campbell and Gray, 2023). Scallop mortality may increase by 25% and growth decrease by 20% in enclosures coupled with a surface buoy compared to those coupled with a buoy submerged 6.5 m below the sea surface (Freites et al., 1999). Similarly, survival may increase by 34% and growth by 50% when the scallops are artificially attached to the lantern net compared to when they are free to move inside (Ventilla, 1982). In the case of the ear-hanging method, where the scallops are not enclosed but rather tied by a hole drilled through their shell to dropper lines, it is mostly limited to sheltered sites (Ventilla, 1982).

4 Discussion and conclusion

The two main constraints to the expansion of mariculture in wave exposed environments is the distance between the farm and the servicing port and the intensity of the hydrodynamic forces acting on the aquaculture structures and servicing vessel. The first constraint is mainly economic (operational costs increase with distance to port and remote operations and monitoring are expensive) while the second one has economic (capital costs), technological (structure design), logistical (operational window), biological (survival, retention, growth and quality of the cultured biomass) and human health & safety aspects. The ICES Working Group on Open Ocean Aquaculture (ICES, 2023) has recently developed hydrodynamic exposure indices to standardize the characterization of existing and future aquaculture sites based on metocean data relative to current and wave energy. These indices will be published soon.

Considering that several thousands of aquaculture sites had to be classified as sheltered or exposed for the systematic inventory carried-out in this paper, simple wave fetch criteria easy to apply on HRALMs were used to preselect exposed sites. Wave climatological data, when available, were then used to finalize the selection. Climatological data based on *in situ* measurements (i.e. wave buoys) in or close to commercial farms are very scarce. The final selection was mostly based on maps (Supplementary Table S4) produced from wind-wave models applied at intermediate (0.02–0.2°) to high (50–500 m) spatial resolution (Guillou et al., 2020). These maps do not cover completely the study area and each source maps only one or two of the four variables retained for the selection. For several sites they provided contradictory results as to whether they are sheltered or exposed. More weight was given to high resolution maps in the determination of the exposure level of such sites. These sites are also likely to experience intense currents (> 1.0 m/s) and winds (> 25 m/s) during large storms. This approach is less complex than that used by Lader et al. (2017) to classify the 1,070 salmon farms registered in Norway with respect to their exposure to wind seas (swells excluded). Their 3-step methodology includes for each site, 1) a detailed fetch analysis, 2) construction of time series of wave height and period estimates based on wind and fetch data, and 3) extremal analysis. Their results show that only 1.1% of the salmon farms have a continuous 40-km-fetch window wider than 45° and none of the sites has a 50-year-return-period wave height larger than 4 m. This is consistent with the fact that with the approach I used, all the 230 bivalve and kelp farms in Norway were classified as sheltered.

The number of exposed bivalve sites in the study area (excluding China, Russia and North Korea) represents 2% of the total number of farms (sheltered + exposed) that Clawson et al. (2022) estimated for the same area. In the case of kelp sites, the total number of farms (sheltered + exposed) in the study area is unknown. The area of exposed kelp farming I estimated for temperate China (200 km^2) corresponds to 43% of the total area of kelp farming in the same provinces (Jin et al., 2023). There are some caveats regarding the interpretation of the results of this inventory. Since the selected sites cover a very wide range of sizes (8 to 7000 ha), the total leased area gives a better idea of the contribution of each country to global production than the total number of sites. However, the relative importance of each country in terms of leased area can also be misleading as the proportion of the leased area occupied by LLs decreases with increasing lease area and the development of very large leases is staged over several years. Currently, non-fed off-bottom mariculture in exposed sites is concentrated in the PNW Region, mainly in Japan and China. In the former country LLs have been used for more than fifty years to grow scallops while in China, exposed sites are used to grow kelp in very high density LL fields since the 1990s. Outside the PNW, exposed farms are currently very scarce in countries or country subdivisions benefiting from extensive areas of sheltered sites like Ireland, Scotland, Tasmania, Canada, Alaska, Maine and southern Chile. Exposed farms exist since the 1980s in France, Italy and northern Chile. Several exposed farms have been established after 2010 in all regions except Temperate South Africa.

Predicting how mariculture in exposed sites will evolve in the future is out of the scope of the present paper. It will depend on several factors including technological and biological (genetic) developments, economical feasibility, market demand, government policy and climate change. In the case of the latter factor it should be possible to model how much suitable areas will be gained or lost for each cultured species using future sea state conditions based on IPCC scenarios. For instance, will mussel culture still be possible in the MBS Region in 2050 (Cubillo et al., 2021). Given that things are currently changing quite rapidly due to climate change and the strong momentum for offshore expansion, this inventory should be considered a snapshot of the early 2020s that can eventually be used later as a benchmark to measure what has actually been gained or lost. Climate change will have a significant effect on the extent of the temperate regions and exposed areas as defined in this paper. More specifically, the IPCC (2022) predicts for the second half of 21th century a pole-ward migration of the 5° and 20° SST isotherms used in this paper to delimit the study area and it is likely that some of the sites not included in this inventory will exceed the wave height and power density thresholds used to identify exposed sites.

With a few exceptions, the exposed farms in the present inventory are located in environments that are less energetic than where offshore wind and wave farms are or will be established in the

TABLE 9 List of R&D programs focusing on kelp and bivalve farming in high energy environments (terminated or initiated between 2014 and 2024).

Program	Country	Main objective	Web site/Reference
BALTIC BLUE GROWTH	Sweden, Latvia, Poland	Growing mussels in the Baltic Sea	https://interreg-baltic.eu/project/baltic-blue-growth/
EDULIS	Belgium	Growing mussels in wind farms	https://bluegent.ugent.be/edulis
EOOA[1] and AOOF[2]	New Zealand	Growing bivalves in high energy environments	Heasman et al. (2020); https://openocean.cawthron.org.nz/
GENIALG	Norway	Growing kelp in exposed sites	https://genialgproject.eu/
MACROSEA	Norway	Industrial kelp production	https://www.sintef.no/projectweb/macrosea/
MARINER	USA	Industrial kelp production	https://arpa-e.energy.gov/technologies/programs/mariner
UNITED and ULTFARMS	Germany, Netherlands, Belgium	Growing kelp and bivalves in wind farms	https://www.h2020united.eu/; https://ultfarms.eu/
WEIR & WIND	Netherlands	Growing kelp in high energy environments	https://www.northseafarmers.org/sector/wier-en-wind

1. Enabling Open Ocean Aquaculture.
2. Anchoring Our Open Ocean Future (Ngā Punga o te Moana).

next decade (4C Offshore, 2023). For example, the average annual wave power density in the North Sea wind farms varies between 4 kW/m off Belgium and 33 kW/m off Norway (Beels et al., 2007; Rusu and Rusu, 2021).

The best sources of information on LL design and farm layout are leasing/permitting documents produced by governmental authorities and applicants, but these documents are very scarce on the Internet. Peer-reviewed articles and company websites rarely provide complete information on specific farms, likely to protect sensitive commercial information. For most of those for which the information is available, semi-submerged or fully submerged LL designs were adopted. These were first developed in Japan in the 1970s and adapted commercially in the 1980s or early 1990s in France (Bompais, 1991; Mille and Blachier, 2009), eastern Canada (Bonardelli, 1996) and Italy (Danioux et al., 2000) using a trial and error approach. Fully submerged LLs were successfully experimented in exposed sites for up to five years (Paul and Grosenbaugh, 2000; Langan and Horton, 2003; Karayücel et al., 2015; Bourque and Myrand, 2014; Id Halla et al., 2017; Mizuta and Wikfors, 2019). Although it is vulnerable to extreme storms like any marine structure, this technology has proven its suitability for farming in fully exposed environments for more than 30 years. The question remains whether it is suitable for very exposed environments where there are plans to co-locate them with marine renewable energy farms. In the past 10 years, several R&D programs have terminated or been initiated to determine the feasibility of bivalve and kelp farming in wind and wave farms and other very exposed sites (Table 9). Currently used designs, new designs based on the basic longline and other technologies have or will be tested. In Part 2 of this article (Gagnon, 2024), I review the loading and motion of LLs in currents and waves and during husbandry operations and I compare the advantages and disadvantages of the various LL types.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MG: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/faquc.2024.1411749/full#supplementary-material

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The social science of offshore aquaculture: uncertainties, challenges and solution-oriented governance needs

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Aquaculture technology is on the move, enabling production in more open and exposed ocean environments around the world. These new systems offer solutions to environmental challenges facing conventional aquaculture, yet new technologies also create new social challenges while potentially exacerbating, or at minimum recreating, others. Offshore aquaculture research and governance are still in early stages, as is our understanding of the social repercussions and challenges associated with development. This paper provides an evaluation and reflection on offshore aquaculture from a social science perspective and is based on findings from a modified World Café group discussion method including the thoughts and experiences of social science experts. Key challenges and uncertainties including a lack of an appropriate regulatory framework, societal perceptions of offshore aquaculture, and offshore aquaculture's contribution to society were identified. The governance implications of these challenges are discussed as well as the need for social sciences to address these challenges through transformative and transdisciplinary approaches that bridge science and society.

KEYWORDS

governance, inter- and transdisciplinarity, systems perspective, social dimensions, offshore aquaculture

Introduction

In recent years, "offshore" aquaculture has gained increased attention as a major avenue for the expansion of aquaculture, especially for commercially important finfish species such as Atlantic salmon (Morro et al., 2022), but also for various species of shellfish (Barillé et al., 2020; Heasman et al., 2020). We hereby follow the definition given in Buck et al., 2024, in which it is suggest that the definition of "offshore" versus "nearshore" and "exposed" versus "sheltered" be defined exclusively according to the distance from shore based on visibility and the wave and current conditions respectively, creating discrete categories for each term. By and large, the discourses on offshore aquaculture have been driven mainly by biological and technological considerations. In contrast, social science perspectives are, as of yet, rather under-researched areas that require more attention (Krause et al., 2015), a trend that is present throughout ocean sustainability research (Partelow et al., 2023). Indeed, while there has been a recent proliferation of social science research on aquaculture (Budhathoki et al., 2024), most has been focused on near-shore coastal aquaculture contexts; thus, nuanced understandings of societal concerns about offshore aquaculture is greatly lacking in the aquaculture literature. This is however urgently needed, as climate change, biodiversity loss and food security are central challenges humanity is facing (Krause et al., 2022; FAO, 2021). These challenges call for novel research approaches that lead to interventions, actions and change to encourage more sustainable pathways. For instance, to limit compromising the integrity of the planet, a shift is needed toward marine food production with low environmental impacts and low carbon footprint (Krause et al., 2022). Hence, while knowledge-oriented basic research is required for the development of long-term innovations, research should also adopt a more immediate and solution-oriented focus directed at the most vulnerable and support associated regulatory and policy needs (Drakvik et al., 2020).

The management of aquaculture has previously been described as a "wicked problem" due to uncertainty around its impacts on the environment and society and the rapidly changing nature of the industry (Osmundsen et al., 2017). Wicked problems are characterized by being difficult to solve due to their complexity and interdependencies including linkages between social, economic, and policy issues and outcomes (Weber and Khademian, 2008). Understanding these issues and outcomes as well as their implications for policy and regulation have been approached through the social sciences, their subfields, and associated methodologies including economics (e.g. Anderson et al., 2019; Asche et al., 2022), geography (e.g. Belton and Bush, 2014; Vandergeest and Unno, 2012), sociology (e.g. Safford et al., 2019), and political science (e.g. Young et al., 2019; Martin et al., 2021; Wiber et al., 2021). Many of these approaches highlight the need for a place-based and spatial understanding of the impacts and outcomes of aquaculture, and the interactions between them. Therefore, the wicked problem of aquaculture management, policy, and governance can be expected to be replicated, accentuated, and changed as aquaculture moves offshore, creating new linkages between social and ecological systems while changing the nature of others. Managing these emerging challenges will necessitate new and evolving policies and regulations. Social science research approaches, like those already employed toward understanding the current and previous state of aquaculture systems, need to be expanded. In addition, the integration of these approaches and emerging transdisciplinary research will be needed to understand changing aquaculture social-ecological systems and inform policy and regulation as infrastructure moves offshore.

In this pursuit, we argue that there is a risk that offshore aquaculture is treated as a "one-type-only" type of aquaculture, disregarding the different modes of offshore aquaculture operations that entail discriminating uncertainties and challenges. Next to the type of species cultivated, the interplay between water depth, distance from dock, people time, vessel efficiency and sea conditions all play an important role to the commercial viability of an offshore aquaculture farm (Buck et al., 2024). Furthermore, governance issues range from fish welfare, security of workforce, liability of technical structures as well as ownership issues pertaining the offshore aquaculture structure as such, as well as on the fish production therein. From a social science stance, these result in different types of societal concerns and related governance needs, where governance includes the policies, processes, and practices that are used to manage coastal and ocean resources in ways that reflect societal expectations (Jolly et al., 2023). Accordingly, an informed differentiation between different types of offshore aquaculture is crucial (see Froehlich et al., 2017; Buck et al., 2024). In recognition of the need to clarify definitions related to the term "offshore" (Watson et al., 2022), which are also described through terms such as "exposed", and "open ocean" aquaculture (Buck et al., 2024), this paper deals primarily with definitions distinguished by distance, since most of the social implications and considerations resonate around the challenges and uncertainties of moving operations further from shore. Accordingly, the discussions around the challenges and considerations will focus on offshore aquaculture, as this term better represents the farm's geographical distance from the shore.

Based on summarizing key insights of experts, the objective of this paper is to reflect on the state of current knowledge in understanding anticipated social repercussions and challenges of entering a new aquaculture landscape. Thus, this paper offers a critical social science examination of the current state of offshore aquaculture research. In addition, it discusses the opportunities for social science to increase solution-oriented governance that addresses in an adequate manner the pivotal role that societal concerns play in the decision for, and development of, sustainable offshore aquaculture systems. Therefore, this reflection on the state of knowledge regarding the social implications of offshore aquaculture and opportunities for social science also serves as a call to natural scientists and policymakers to more strongly engage social scientists and social science methodologies in addressing the challenges that lie ahead.

Methodological approach

To endorse the topic of offshore aquaculture from a social science perspective, this paper presents reflections that emerged through discussions by social science experts. These discussions follow from evidence that the sustainability outcomes of offshore aquaculture differ across social dimensions and scale, and are dependent on farm scale and location (Krause et al., 2020). To this end, and working under the assumption that offshore aquaculture and its social dimensions are highly site-specific, we collated the findings of a modified World Café session during the annual European Aquaculture Society (EAS) meeting in Rimini, Italy in September 2022. Generally, the World Café is a large group method, which contains a sequence of discussions at tables with 4 to 7 people seated at each table (Brown and Isaacs, 2005). Such sessions can last from a couple of hours up to one to two days. In our case, an adapted version of the World Café method took place during one full-day at the EAS conference that focused on "Socio-economic challenges for sustainable aquaculture in a changing environment". Participants included 14 expert presenters from European and North American institutions who provided in-depth research talks, as well as an audience of approximately 50 conference attendees with a diverse background, ranging from natural to social sciences. Since most of the experts and participants were from countries from the Global North, the focus of the deliberations were biased toward high-tech offshore salmon aquaculture systems. That said, the following sections recognize this potential bias by carving out the very central issues of social science engagements in this research field in a more generic manner. To foster social science perspectives on the challenges and opportunities for offshore aquaculture, experts were asked to provide their thoughts and experiences on the following research questions:

(1) What emerging trajectories and related uncertainties can be observed that need to be considered from a social science perspective to foster innovative solutions of sustainable offshore aquaculture?
(2) What challenges or constraints can be identified that relate to the broader context of this development?
(3) What other thematic areas can be identified that need to be addressed to foster solution-oriented governance outcomes?

Given the venue and conference format constraints prevented a typical World Café with multiple tables, we organized the conference session into different thematic sub-sections. These were (a) emerging trajectories, (b) approaches and tools, and (c) governance. Under each of these thematic headings, presenters provided an overview of their cutting-edge research and provided their thoughts on the three questions listed above. During the three subsequent World Café breakout sessions (~25 min each) the thoughts and personal experiences of experts and audience on the three questions were discussed in plenary. One central focus of this exercise concerned the main uncertainties, challenges and the identification of under-researched topics that relate specifically to offshore aquaculture from a social science epistemology.

In the following sections, we present central themes and findings that emerged in the discussions. These results reflect themes emerging from experts present at the World Café session, and further reflections and references to the social science literature. The first section describes the key challenges and uncertainties identified by experts. The next section provides a reflection on the governance implications of these challenges. In the final section, these are synthesized to identify opportunities for social science research to contribute knowledge and inform governance of offshore aquaculture. Given this approach and the diversity of expertise, theoretical foundations, and methodological approaches of experts who participated in the World Café, this discussion focuses on broad thematic points of discussion. Although this approach may neglect some of the nuance of the discussion that took place among experts, we hope that this broader perspective provides a practical overview for natural scientists and policymakers, and that it may inspire social scientists to address the challenges of offshore aquaculture from specific theoretical perspectives and methodologies.

Challenges and uncertainties to offshore aquaculture governance

New production systems such as offshore aquaculture have their own challenges and uncertainties that warrant attention e.g., infrastructure, financial needs and risks, fish welfare, and societal/consumer perceptions, among others. The following section describes participants' insights into key social challenges and uncertainties related to offshore aquaculture, and the repercussions they might have on society and governance. Many of the identified challenges and uncertainties coincide with long-standing challenges of conventional aquaculture. This section describes the additional challenges, highlighting that often those existing challenges are exacerbated due to distance and/or exposure.

Unfolding regulatory frameworks

As of today, ongoing processes for developing technology for offshore aquaculture are in motion (Moe Føre et al., 2022). Yet, participants regularly discussed that a major obstacle in establishing offshore aquaculture has been the difficulty of navigating present regulatory frameworks (Watson et al., 2022). There is a lack of streamlined, consistent and predictable policy frameworks that support permitting processes for offshore aquaculture (Morro et al., 2022). In recent years, few jurisdictions have begun to explore and implement offshore aquaculture policies, including the United States of America (NOAA, 2016; Upton, 2019), New Zealand (The New Zealand Government, 2019), Panama[1] and Norway[2]. Beyond these notable exceptions, many aquaculture jurisdictions lack dedicated regulatory frameworks for offshore aquaculture (Davies et al., 2019), often taking a largely "one size fits all" approach to culture practices. For instance, although there is an Aquaculture Act regulating all aquaculture activities in Norway (Norwegian Ministry of Fisheries and Coastal Affairs, 2005), there is a need for additions and adjustments to adequately address aspects

1 https://thefishsite.com/articles/offshore-farmer-reveals-global-seafood-ambitions-forever-oceans-bill-bien-

2 https://www.intrafish.com/aquaculture/norway-updates-rules-for-offshore-aquaculture-but-plenty-of-work-still-lies-ahead/2-1-1347935

of offshore aquaculture. For example, tax regulations are only valid in certain (nearshore) areas, creating a need for more specific tax regulations for offshore aquaculture. Public authorities may have jurisdiction only within specific distances from the coast, prompting decisions to be made for new jurisdictional areas, or the substitution of other regulatory bodies to oversee aquaculture production. While jurisdictions are working to accommodate offshore aquaculture, the frameworks are not expedient and are complicated by existing fragmented and complex regulatory frameworks that are often composed of regulations across various agencies and spatial scales (Osmundsen et al., 2022). Based on these insights, the participants of the World Café discussed how the complexity of existing frameworks and uncertainty of creating effective governance structures designed to meet the unique challenges of offshore aquaculture are not only challenging for government, but may also hinder the willingness of investors to develop offshore aquaculture in jurisdictions that lack clear regulatory regimes (Knapp and Rubino, 2016).

Offshore aquaculture production systems are driven by a plethora of diverging considerations and decision-making aspects that have implications for effective planning, licensing and management decisions. From our discussions, participants reflected on shared experiences that current governance mechanisms, management approaches and monitoring requirements in many areas are designed to account for environmental and production features of the nearshore environment. However, offshore systems have variable considerations that can range from decisions on infrastructure in relation to the type of product produced, the variable welfare and disease aspects, and potentially drastically different environmental conditions, all of which experts felt would have repercussions on the respective probable governance regime. Additionally, decisions on technology are also interlinked with site specifications and the needs for operational safety, manpower/presence of staff, emergency preparedness, energy needs, equipment liability needs, etc. For example, environmental conditions in more exposed, offshore areas means workers are likely more susceptible to high wind and waves, having important considerations for worker health and safety (Holmen, 2022; Neis et al., 2023). As a result, these needs require tailoring the respective technological designs for specific sites and conditions to a larger extent than is common for conventional aquaculture technologies in nearshore sheltered areas. Therefore, participants reflected that siting and planning considerations and criteria would likely be variable, given the variable underlying biophysical and social considerations of more offshore and exposed aquaculture. In sum, contextual differences between offshore and nearshore aquaculture, as well as the site-specific context of offshore developments will affect strategic decisions related to licensing, site and technology use, and tactical planning and operational decisions that consider type of system and key decision makers.

Understanding societal perceptions

Underlying much of the discussion in breakout sessions were the influence and repercussions of societal perceptions, and how the introduction of an emerging technology may influence the space of public trust and legitimacy. Experts reflected on how in many areas, public perceptions of aquaculture and its regulations are a factor driving regulatory change, and have been recognized as a barrier to effective governance and growth of aquaculture worldwide (Young et al., 2019). Societal concerns are affected by the relationship between nature and humans, and specific contextual societal values, perceptions and priorities evolve and can rapidly change, all of which can affect the social license to operate offshore aquaculture (Mather and Fanning, 2019; Krause et al., 2020). Participants felt that these considerations are particularly relevant in new production systems as technologies and practices are still evolving, which could trigger unexpected sustainability challenges. More often than not, societal interests and values concerning offshore aquaculture are anticipated to be linked with prior experience with, and expectations toward conventional nearshore aquaculture, even if new production methods arise. As an emerging sector in aquaculture, offshore aquaculture may also have unique characteristics that mediate public opinion and acceptance of the technologies.

Participants also discussed how existing conflicts related to aquaculture and societal expectations may become emphasized as industry production enters new areas further away from coastal communities and uncertainties concerning potential conflicts with societal actors/communities increase. That said, the utilization of novel offshore areas for aquaculture hosts the creation of new conflicts, e.g. related to other industries, diverging power-relations and interests, demanding authorities to handle potential conflicts and trade-offs previously unknown. For example, offshore aquaculture may occur in areas of interest for offshore wind development, which may create new conflicts, or conversely identify new opportunities for synergies (Billing et al., 2022).

Furthermore, the current trajectories toward offshore aquaculture face the challenge that social equity outcomes are not yet well understood. Next to the unresolved issue of the ocean as a common to all, this also relates to legitimacy beyond the aquaculture sector as conflicts and concerns about aquaculture span multiple time and space scales. Experiences from sectors beyond aquaculture that have recent technological shifts, such as offshore wind and renewable energy, illustrate that society can exhibit a renewed sense of uncertainty and caution toward new technology sectors (Kermagoret et al., 2016; Batel, 2020). The public may be, to greater degrees, uncertain about accepting a new technology, regardless of site or design specific considerations. However, exploring how the public may respond to emerging offshore technologies has yet to be realized (Guthrie et al., 2024).

Offshore aquaculture's contribution to society

Recent experience has been gained in understanding how offshore aquaculture relates to the larger themes of sustainable development. The United Nations Sustainable Development Goals (SDGs) were adopted in 2016, but to date there is little sector-specific work done to link offshore aquaculture to the broad social, political and ecological expectations of the SDGs. However, marine aquaculture is clearly linked to SDGs: In a pilot project financed by the Research Council of Norway in 2021[3], the Norwegian organization representing over 40 small- and medium-sized salmon farms, Salmon Group AS (https://salmongroup.no/), worked with interdisciplinary social scientists at the University of Bergen to assess which of the 169 targets of the UN SDGs were relevant to salmon aquaculture in Norway. The result was that 103 targets over all of the 17 Sustainable Development Goals were deemed either directly or indirectly relevant for salmon production in Norway. These surprising results revealed the power of understanding the underlying value chains of marine aquaculture, and that the sourcing of ingredients for salmon feed, for example, have direct links to labor rights, gender equality, data access, political representation and ecological preservation that reflect the complexities of the social-ecological system. These value chain components and linkages to SDGs can also be expected for offshore aquaculture; therefore, the role of social science in sustainable development of offshore aquaculture is crystal clear, considering the direct social and political links of offshore aquaculture to the global normative guidance toward sustainability.

All of these potential contributions need to be assessed to determine whether emerging offshore aquaculture systems can provide sustainable production by advancing the analysis of the social effects of different types of resource management regimes, supply chains and logistics. Furthermore, the uncertainties of new production systems are exacerbated by the anticipated potential mitigation of environmental impacts, which is one of the most prominent aspects driving public opinion in traditional nearshore aquaculture (Olsen et al., 2023). This is strongly linked to trade-offs of sustainability outcomes that can be further differentiated between long- and short term effects (Krause et al., under review)[4].

In addition, new technologies often require substantial capital investment and incur financial uncertainty and risks to producers. The cost factor in offshore aquaculture is an essential uncertainty in this regard. Most operational costs will increase (related to investments, operations, transports etc.), the structures are expected to be replaced more often than traditional farms, and license costs are still highly uncertain since there are to date few examples of governments with established license regimes for offshore aquaculture (Morro et al., 2022). Furthermore, higher costs and uncertainties regarding production will also affect the possible economic gains for society at large and thus the distribution of these. Combined, the increased costs and risks to establish offshore operations create a form of barrier to entry for small-scale producers, as those establishing these technologies are likely well-funded large corporations. Indeed, there is already a high degree of horizontal integration and increasing firm size in salmon aquaculture (Asche et al., 2013) and the potential dominance of the offshore sector by large multinational corporations could have distributive justice implications and considerations for equitable distribution of benefits to hosting areas and jurisdictions.

It may be tempting to address these challenges and uncertainties on a case-by-case basis, with new research and development, new assessments and public campaigns and the like. However, we believe these are short-term and temporary fixes. Instead, we argue that taking a systematic social science perspective on offshore aquaculture is needed to understand these challenges and uncertainties in their societal context and identify long-lasting sustainable pathways to societal change.

A social science reflection on offshore aquaculture governance

Reflecting on the challenges and uncertainties that accompany offshore aquaculture systems and technologies reinforces critical opportunities for social science perspectives to advance effective governance of the emerging sector. Yet, the question of how we can integrate the social perspective in the current development toward offshore aquaculture is not an “easy fit”. Indeed, it is challenging to integrate the (often not easily measurable) social perspectives, since it requires consideration of a very diverse public. In addition, there are many remaining uncertainties in the operation, maintenance, and interconnectedness of production within the respective social-ecological system at large. These challenges are exacerbated by the largely ineffective ways that social perspectives are incorporated for conventional aquaculture, thus highlighting a lack of effective frameworks from which to model (Osmundsen et al., 2020a). The following section reflects on the thematic points of World Café discussions surrounding the considerations of incorporating a social perspective to offshore aquaculture governance, and the critical discourses and issues that social sciences can help inform. These key themes set the boundaries around which a social science agenda for offshore aquaculture can be discussed.

Governing public and private interests

Any kind of governance regime needs to consider the role of access to capital, cross-sectional dialogue forms and collaboration arenas between private and public stakeholders, all of which need to be tailored to novel licensing regimes of offshore aquaculture. In conventional aquaculture, emergency preparedness based on collaboration between private and public stakeholders from multiple sectors in the coastal zone still have potential for improvement (Osmundsen et al., 2020b). This aspect of collaboration is also highly relevant for offshore sites. Regulating a multi-technology aquaculture sector requires fundamental changes in current regulatory frameworks and must avoid merely adapting and extending current regulatory designs to include new production concepts. Layered, complex and fragmented regulatory frameworks for aquaculture already exist in many aquaculture

3 https://prosjektbanken.forskningsradet.no/en/project/FORISS/323913?Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=score&sortOrder=desc&resultCount=30&offset=0&Fritekst=sdg+wizard

4 Krause, G., Filgueira, R., Ahmed, N., Alexander, K., Fanning, L., Ferse, S., et al. (under review). Regionalisation alone will not make marine aquaculture more sustainable. *Rev. Aquaculture*.

producing countries due to continuous adaptation of existing frameworks (McDaniels et al., 2005; Osmundsen et al., 2022; Sandersen and Kvalvik, 2014). New offshore production areas entail different characteristics than coastal areas where farms are already established, thus existing regulations may not be appropriate but must be made relevant for species, environment and production methods (Morro et al., 2022; Watson et al., 2022). For example, licenses for offshore production in Norway represent a new form of regulation of aquaculture, connecting site (geographical location), installation (production technology) and volume (allowable biomass) per each license. In the case of Norway, offshore aquaculture is defined by the Norwegian government beingoutside the existing geographical jurisdictional areas for existing regulations as well as beyond the sectoral authorities' responsibility in terms of control and management of the industry. Consequently, development of new licenses must be accompanied by processes and establishment of jurisdictions, collaborations, and clarifications of roles and responsibilities of the involved public authorities. Adherent to this, governments must make decisions upon which public authorities are relevant and what possible new roles and laws are needed in securing good governance of offshore aquaculture production.

The Norwegian example demonstrates a central mainstay of research needs for offshore aquaculture: How to tackle current licensing schemes under adaptive and cross-sectional governance regimes. To date, licensing procedures are commonly customized for conventional aquaculture, not for new production systems such as offshore aquaculture (Davies et al., 2019), but even sector-specific approaches may disregard the many attitudes toward the legitimacy of offshore aquaculture that are beyond the aquaculture sector and revolve around broader environmental, social, and governance issues. As such, governance structures need to involve many actors, who are all responsible for "different pieces of the same pie" and range from local, regional, national as well as international institutions.

Acknowledging the complexity of production and political interests

The complexities of aquaculture production and political interests and values that range from nation specific interests to the current global economic and political environment all shape the potential governance of emerging technologies on a site-specific scale. This is extremely challenging, as there are yet manifold knowledge gaps and uncertainties related to causal effects in offshore aquaculture operations. However, it is clear that policy design will have different impacts on industry development as well as repercussions for society at large. From this stance, the World Café highlighted the need to include assessments of societal impact, e.g. changes in value creation, economic benefits and distribution, and if/how these are sought and accounted for in governance measures during the process of developing new regulatory frameworks for offshore aquaculture. This would be an important factor which should be included in the debate about licenses and their costs, representing a possible trade-off in balancing necessary risk relief for industry on one hand and important revenues for society/communities on the other hand.

First research results show that geographical conditions, to a limited extent, determine the importance of various social impacts and involvement of different stakeholders. Operations further offshore imply that the production has relevance for multiple adjacent communities, stakeholders, and interests. Perceived benefits and impacts are beyond direct visual impacts as stakeholders are equally concerned about indirect impacts including equity, collective choice rights, and the distribution of impacts (Suryanata and Umemoto, 2005). In this sense, a shift in focus to community wellbeing is necessary to realize the potential social benefits of marine aquaculture expansion (Campbell et al., 2021). The classification of various types of offshore aquaculture can shed some light on the differences in social acceptance. However, as pointed out in the discussion among the participants of the World Café, this should not be used in a deterministic manner as some social impacts, and concerns, transcend the boundaries of geographical distance. Ultimately, the question remains however, who should make the choice?

Social supply-chain perspective

Offshore aquaculture can be viewed as new production systems that offer solutions for more sustainable development of the industry. However, new production systems also have their own challenges in terms of infrastructure needs, risks, and fish welfare and societal/consumer perceptions (Wever et al., 2015, Morro et al., 2022). New farming technologies for offshore aquaculture necessitate larger and more expensive structures which will rely on the labor supply and competence of supplier industries, hence different ripple effects from aquaculture can be expected. The discussants agreed that additionally, the development of new value chains for new production systems that include offshore aquaculture are in nascent stages and thus much still needs to be researched. Under this light, the whole supply chain must be considered. This includes production costs and benefits, infrastructure and competence needs, enabling environment and management, and environmental and social risks and resilience. For example, vulnerabilities and resilience to supply chain disruption that will have implications for sustainable livelihoods are untested. Life Cycle Analysis (LCA) is needed to demonstrate sustainable production, vis à vis the real-world application of spatial scale modeling will be needed to understand trade-offs across geographic scales associated with emerging value chains. Further, social acceptance and consumer receptivity in aquaculture are intertwined and engage with broader social change movements reflecting a discourse extending beyond sole aquaculture issues and its local governance.

New policies and regulations as well as existing market-driven governance schemes will need to account for new production systems for offshore aquaculture while also considering cascading impacts, vulnerabilities, and risks across the supply chain. Novel policy design and the shaping of regulatory frameworks need to

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acknowledge their impact on industry development. This relates to the direct production volumes, number of jobs, but also to the rather indirect societal development that relate to the questions of where should people live, and who should live there. Furthermore social norms that revolve around the relationship between nature and humans, i.e.how do we interact with nature, and what are the limits for human actions, need to be considered.

Legitimacy and democratic decision-making

A key under-researched theme identified in the discussions of the World Café in the context of social science engagement with offshore aquaculture relate to the questions of the limits of democratic processes in decision-making, addressing societal expectations, and regulatory needs for securing social acceptance and sustainable outcomes of new production methods and areas for offshore aquaculture. By virtue, democratic decision-making infers the need for decisions that affect society to reflect those societal values, priorities, and expectations. Those decisions, and the subsequent outcomes (e.g. industry development) should ideally be viewed as fair and legitimate. Recently, the legitimacy of aquaculture has been a key factor in understanding the societal acceptance of aquaculture (Bjørkan and Eilertsen, 2020; Sønvisen and Vik, 2021; Olsen et al., 2023; Weitzman et al., 2023). These findings emphasize the need to understand societal perceptions and expectations and how aquaculture aligns with them. Despite the recent advances in this area, participants discussed the challenge of what is felt to be a substantial knowledge gap in social perceptions, attitudes, and understanding the factors that drive them. Indeed, only recently these have begun to be investigated in conventional aquaculture systems in nearshore environments. These challenges become exacerbated due to the noteworthy limit of social science research on the specific needs and considerations for governance of offshore aquaculture.

Although offshore aquaculture involves major changes in production, participants reflected on how it could be anticipated that the expectations from society may still be positive in terms of sustainability, industry contributions to society, and regulatory demands. Offshore aquaculture systems may offer solutions to current environmental challenges facing nearshore aquaculture (Fairbanks, 2016; Jansen et al., 2016; Lester et al., 2018), which are often viewed as a key element for a sustainable development of the industry and a recurring societal concern. Yet, participants also acknowledged that there may also be trade-offs in the environmental and social costs of offshore production systems, and reinforced the importance of understanding the specific societal perceptions and responses to offshore aquaculture for specific areas, species, and policy contexts.

Ensuring legitimacy for offshore aquaculture production is dependent on societal expectations being met by industry proceedings and governmental regulation. Recent evidence from nearshore aquaculture systems illustrates that public trust in government and transparency of regulatory processes as a key component in the legitimacy of aquaculture within communities (Weitzman et al., 2023). As such, governments' arguments and policies supporting offshore aquaculture as a solution for targeting sustainability goals must be deemed acceptable from societal stakeholders as well. For conventional aquaculture and industry activities in general, an important factor for acceptance is the distribution of economic benefits from industry, or distributive justice that pertain to industry contributions in local communities and for the wider public (Ertör and Ortega-Cerdà, 2015; Misund et al., 2023). With offshore aquaculture however, there is great uncertainty to how such production and adherent regulations will affect the benefits and distribution of these to society, and therefore the legitimacy of offshore aquaculture.

Adding to calamity, participants highlighted that social acceptance in aquaculture is always embedded in broader social change movements. Politics, perceptions and social expectations can change rapidly and often. Moreover, the relationships between nature and humans are fluid. Appropriately presenting and accounting for this fluidity and dynamic state of these considerations is an enduring challenge for effective coastal governance and MSP (Jones et al., 2016). This may be especially notable with the accompaniment of the rapid technological and governance changes of an emerging offshore aquaculture sector. This underlines the importance of not only continued, up to date co-produced social science knowledge generation on these aspects, but also that governance responses to the emergence of this novel sector need to be adaptive and flexible to effectively ensure legitimacy of policies and practices.

A social science agenda for offshore aquaculture governance

Capturing social dimensions of offshore aquaculture in support for solution-oriented research approaches can be viewed as "wicked problems" in that all parameters cannot be specified, there is no single optimum to be attained and "…there is no criterion system nor rule which would tell you what is correct or false" (Rittel, 1977; Osmundsen et al., 2017). Indeed, the above compilation of under-researched trajectories, challenges and solution-oriented governance needs that were identified by the participants of the World Café exercise and mirrored by literature review leads to asking two questions at once: What should social science do? And what should be done with the social science knowledge created? In other words, *how* should the scientific arena shift toward urgently needed solution-oriented research outcomes and what are the identified specific under-researched social science arenas therein? In this section, we highlight that there are significant opportunities for social science to provide co-produced knowledge and insights to better understand the social repercussions and considerations of offshore aquaculture systems. This knowledge could ultimately inform more legitimate and effective governance to promote an emerging sector sustainably.

What can social science do?

We have identified several topical areas of concern that can be addressed by social science approaches (Figure 1). These include, among others, the need to identify areas of conflict between marine users, understanding the social impacts of offshore aquaculture, and assessing the economic costs and risks thereof. Successful and sustainable governance processes and practices that lead to appropriate regulatory frameworks will only be possible via understanding of societal concerns as they intersect across the offshore aquaculture value chain. Recent social science research efforts have sought to understand, quantify, and explore social repercussions and perceptions of aquaculture. This demonstrates the value of social science methods and knowledge for the aquaculture industry and society. For example, Marine Spatial Planning (MSP) has been suggested by several authors (Ehler and Douvere, 2009; Foley et al., 2010; White et al., 2012) as a suitable tool for reducing conflicts and fostering synergies between maritime uses under a sustainability lens. Public surveys, media analysis, and ethnographic methods have been used to improve understanding of social acceptance of aquaculture (e.g. Kraly et al., 2022; Aanesen et al., 2023; Olsen et al., 2023; Weitzman et al., 2023). Critical analyses of policy, regulations, and other governance practices have been applied to better understand governance processes and outcomes, and reveal the limitations of current public and private governance (Anderson et al., 2019; Falconer et al., 2023; Osmundsen et al., 2022; Jonell et al., 2013; Rector et al., 2024). Economic modeling has been used to understand the impacts of aquaculture in rural and developing economies (Filipski and Belton, 2018; Grealis et al., 2017). Each of these social science approaches will be valuable in developing an improved social understanding of offshore aquaculture that can inform governance and associated regulatory frameworks. However, the integration of social and ecological knowledge and research that engages with industry and citizen tacit knowledge and perspectives via co-productive research methods is urgently needed. Such transdisciplinary engagements hold the promise to deliver feasible and effective pathways beneficial for societal well-being and the sustainability of offshore aquaculture production.

The case for inter- and transdisciplinarity

We have identified several areas of concern that warrant concerted inter- and transdisciplinary research approaches. Interdisciplinarity describes the integration of disciplines toward a common goal and shared research question, while transdisciplinarity describes the integration of both disciplines and non-academic participants toward shared processes that results in actionable knowledge that benefits society (Tress et al., 2005). As a general principle, most of the identified under-researched topics are related to processes and therefore require novel transdisciplinary approaches to tackle these complex questions. However, the current composition of research in offshore aquaculture is yet in nascent stages in terms of how and in what ways to combine the different knowledge realms and evidence from cross-cutting disciplines and experts in the field. By and large, the identification of "who holds a stake" in the system is the mainstay of most of social science research on offshore aquaculture, while being at the same time the principal stage in any solution-oriented governance initiative (Reed et al., 2009; Prell, 2012; Krause et al., 2015).

In the case of offshore aquaculture, it is evident that industry actors and coastal communities are stakeholders, though interests

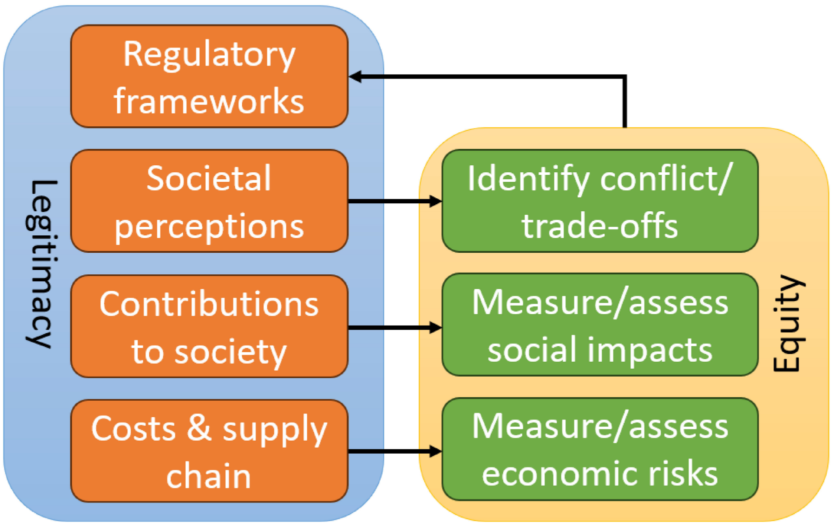

FIGURE 1
What can social science do? Orange boxes represent challenges and areas of uncertainty related to offshore aquaculture. These competing and overlapping challenges create what is known as a "wicked problem". Green boxes represent some of what social science can do to understand and address these challenges. Integration of these approaches through interdisciplinary research, and the inclusion of industry and societal knowledge and experience through transdisciplinary research is needed to address this wicked problem in ways that benefit society through the equitable distribution of benefits and the legitimacy of policy that governs offshore aquaculture.

likely extend to additional groups and institutions. Industrial actors aiming for the offshores do so because these geographical areas offer benefits not attainable in coastal waters. These relate to e.g. access to production sites that are scarce closer to shore, economies of scale since production may be largely increased, longer distance to nearby sites and greater water exchange protecting against sea lice and infection pressures, and perhaps closer distance to markets. Also, exemptions from local and regional jurisdictions and taxation regimes may, in theory, be a motivation to move further from the coast. For coastal communities, reduced geographical presence of aquaculture may allow for increased activities in other sectors, but may also very likely reduce access to direct employment benefits, ripple effects from aquaculture operations, and revenues. In contrast for societies at large, offshore aquaculture may positively contribute to global food security issues. However, it must be acknowledged that it relies on shared resources resulting in governance problems that require institutional solutions aligned with collective interests (Partelow, et al., 2022; Krause et al., under review)[4].

That said, the management of human activities is complex and broad touching on many facets of wellbeing and affecting multiple actors and institutions (Reed, 2008). Hence, from a planning perspective of offshore aquaculture, it is crucial to have a full understanding of the stakeholders and their relations and characteristics that may influence decisions through their power, or support the initiative promoting cooperation and knowledge exchange during engagement (Prell et al., 2008). This makes the decision-making process transparent and contributes to democratic and holistic decision-making process (Reed, 2008), while acknowledging social processes such as knowledge transfer, information sharing and power relations. It is essential to identify the key actors or stakeholders in a respective offshore aquaculture system arrangement and to understand their behavior, intentions, interrelations and interests, as well as their respective sustainability outcomes (Krause et al., under review)[4]. The assessment of influence and resources they bring for implementation of the process is important (Grimble and Wellard, 1997; Brugha and Varvasovszky, 2000). However, societal values, perceptions, and priorities are constantly changing and evolving. As thus politics and perceptions (and social expectations) can change rapidly and often, these uncertainties and their impact are not easy to measure or specify. As of yet, there remains a substantial knowledge gap in social perceptions, attitudes, and understanding the factors that drive them.

Methodological challenges to a holistic social perspective

In a holistic approach, the social science perspective will point out contradictions and inherent trade-offs, even though this view alone will rarely provide applicable solutions for this. Thus, the challenge remains of how to integrate societal perspectives that cover the need to recognize the tension between individual expression and longing for social recognition for particular communities (Fukuyama, 2018). Methods in transdisciplinary research are still emerging. For instance, Fuzzy Cognitive Mapping is a well-known method for mapping inherent interactions of the social-ecological system in smaller diverse groups (Tiller et al., 2016), but there is no experience of up-scaling this method to larger groups. Next, on a global scale the sustainable development of offshore aquaculture is constrained by nation specific interests, but also by the current unsettled global economic and political environments of our time. Contextual changes can lead to shifting priorities and conflictual goals, increasing the necessity of trade-offs. All of this influences the respective social license to operate offshore aquaculture. As the latter spans across multiple time and space scales, it is challenging to create effective transdisciplinary research methods that foster sustainable responses for societally acceptable aquaculture.

Despite these difficulties, there are potential solutions within reach. For example, social licenses depend on authentic dialogues among the public, industry, and authorities. Dialogues that respond to concerns of a diverse public, and which are perceived as genuine, trustworthy and transparent, may move public sentiments in a positive direction. Experiences from virtual round tables in Scotland demonstrate that the inclusion of a diverse public with industry representatives, researchers and authorities in a transdisciplinary research setting are capable of fostering such dialogue, even though such events include a fairly large number of participants (SSAC, 2023). Other approaches to investigate community concerns and possible measures for reducing conflicts and establish social license is exemplified by Condie et al. (2022). By looking into submissions to two governmental inquiries in Tasmania, they identified stakeholder groups, and co-explored prominent issues of concern by the community, such as environmental sustainability, regional economic growth, governance, communication, and the role of science. Similar approaches could be useful for other governments and science as well, and could provide important knowledge related to emerging issues concerning offshore aquaculture and its possible implications.

When it comes to governance complexities, e.g., overlapping regulations and/or regulatory gaps, the optimal approaches for social-ecological data collection remains a challenge as input and output data are limited by location and time. In addition, the systems being analyzed are dynamic, as well as time and resource dependent while being driven by system uncertainty. The development of new offshore aquaculture provides opportunities to both study social dimensions and incorporate social perspectives in the development of the industry and governance approaches. Integration experts and methods will be needed to facilitate inter- and transdisciplinary approaches, but these experts and the costs of truly integrative solutions-oriented research are not well-supported or facilitated by institutional and academic structures (Hoffmann et al., 2017, 2022). The challenge remains to work cost- and time-efficiently while also producing thorough in-depth data and analyses of social-ecological systems in order to create knowledge that can be harnessed for sustainable development pathways of further offshore aquaculture expansion.

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TABLE 1 The most salient challenges, risks, and solutions for offshore aquaculture development.

Challenges	Risks	Solutions
Lack of dedicated regulatory frameworks; fragmented regulatory frameworks across multiple agencies and spatial scales	Scaffolding offshore aquaculture permitting onto existing regulatory frameworks designed for nearshore environments could lead to inefficiencies or ineffective governance; investors are unwilling to develop offshore aquaculture in jurisdictions that lack clear regulatory regimes	Develop and implement context-specific, streamlined, consistent, and predictable policy frameworks that support offshore aquaculture permitting
Understanding public perception, opinion, and acceptance of emerging offshore aquaculture technologies	Creation of new conflicts with relevant actors and communities; negative impacts on the legitimacy of offshore aquaculture	Use of participatory and transdisciplinary research approaches to identify potential societal conflicts, trade-offs, and understand acceptance of and opposition to offshore aquaculture
Potential conflict with offshore industries and other marine uses	Competition for offshore space and development of one offshore industry at the expense of others	Inclusive Marine Spatial Planning process that recognizes stake- and rightsholders
Understanding and predicting impacts of offshore aquaculture on society across the supply chain at relevant spatial scales	Creating undesirable trade-offs between social and environmental sustainability	Assess social, environmental, and economic risks and identify trade-offs at local, regional, and global scales
Increase in capital and operational costs	Barrier to entry for small-scale producers and dominance of multinational corporations result in inequitable distribution of risks and benefits of offshore aquaculture development	Equitable distribution of benefits of offshore aquaculture through mechanisms that benefit host communities

Conclusion

This paper offers a critical social science reflection on an emerging offshore aquaculture sector, based on discussions among aquaculture experts and researchers raised in a one-day World Café session. The discussion revolves around the most salient social challenges and risks that offshore aquaculture could face and the role of social science in mediating those challenges (Table 1). While many of the observations and discussions draw on experiences and research from nearshore aquaculture environments, this reflection offers a renewed perspective that can be valuable for industry and decision-makers to foster an equitable, sustainable offshore aquaculture sector. While this paper offers general reflections on the social repercussions and policy implications of offshore aquaculture, specific societal consequences, perceptions, and policy strategies warrant more contextualized research and discussions to consider the needs and implications for different areas, species, and production systems.

Based on our discussions, we observe that the technological changes in offshore aquaculture challenge conventional governance and require transformed and disrupted solutions that intersect not only science and society, but also different scientific bodies and disciplines. Indeed, many of the solutions, challenges, and social science reflections on governance for offshore aquaculture revolve around resolving aspects of legitimacy. This highlights the need to consider aspects of procedural justice, equity, and well-being in aquaculture. These dimensions reinforce the need to "humanize" aquaculture governance (Brugere et al., 2023) through an emphasized social framing of challenges (Krause et al., 2015) that embraces intersectionality and promotes cross-disciplinary knowledge systems. The development of offshore aquaculture is both a challenge and an opportunity for the application of this transformed mode of research and knowledge generation. In this regard, transdisciplinary research approaches are warranted. However, how to put such transformative change toward sustainable food production while ensuring food security into practice remains a challenge and will require transdisciplinary approaches to find societal appropriate solutions (Markus et al., 2017; Krause et al., 2020; Franke et al., 2022; Krause et al., 2022; Partelow et al., 2023). These solutions need to be implemented, and this may require profound changes, including ethical and philosophical considerations regarding the relationship and responsibility of humans to nature (Huss et al., 2022). It implies a different orientation of science and its role in governance in the 21st century. The character of this new (transformative) orientation of science is only now beginning to emerge, but will need to accommodate new opportunities for science in tandem with society. Only then can we forge a collective meaning on how to manage the complex challenges for offshore aquaculture.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

GK: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. JW: Investigation, Writing – original draft, Writing – review & editing. MR: Investigation, Writing – original draft, Writing – review & editing. RF: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. SB: Investigation, Writing – original draft, Writing – review &

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Hydrodynamic exposure – on the quest to deriving quantitative metrics for mariculture sites

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This work attempts to define metrics for hydrodynamic exposure, using known oceanographic variables to provide a universal site assessment method for mariculture structures. Understanding environmental conditions driving open-ocean mariculture siting is crucial in establishing consistent ocean governance, minimizing adverse environmental impacts, and facilitating economically sustainable farm operations. To provide a metric of oceanic conditions and associated requirements for structural design and operation of aquaculture systems, six Exposure Indices (EI) are proposed that consider physical energy levels related to hydrodynamic forces at a site. Four of the proposed indices consider only environmental conditions, while the other two also consider the dimensions of the gear that is exposed to the external loads. These indices are: Exposure Velocity (EV), Exposure Velocity at Reference Depth (EVRD), Specific Exposure Energy (SEE), Depth-integrated Energy Flux (DEF), Structure-centered Depth-integrated Energy (SDE), and a Structure-centered Drag-to-Buoyancy Ratio (SDBR). While these indices are derived with a focus on aquaculture structures, they may also have applications for estimating biological stressors and operational challenges. The proposed exposure indices were evaluated for a range of known aquaculture sites around the world. A sensitivity analysis was conducted that quantified the relationship between the exposure indices and storm event return period. At a regional scale, hindcast numerical data for the German Bight combined with calculations of 50-year extreme values were used to calculate and map each proposed index spatially. Resulting maps showed that exposure is not simply a function of distance from shore. The six indices show plausible performance regarding the objective assessment of aquaculture sites. The authors herein present the indices to the aquaculture and ocean engineering communities for discussion, application, and potential adoption of one or more of the proposed indices.

KEYWORDS

aquaculture siting, degree of exposure, hydrodynamic loading, aquaculture technology, aquaculture engineering, quantitative assessment, operation, maintenance

1 Introduction

The United Nations sustainable development goals (SDG) clearly set out the world's ambition to reduce hunger (SDG #2), while simultaneously advocating sustainable production and consumption (SDG #12) (United Nations, 2020; FAO, 2020). As the global population is projected to increase over the next decades to reach 9.8 billion by 2050 and 11.2 billion by 2100 (United Nations, 2022; Chao et al., 2021), so is the demand for food projected to increase in an attempt to reduce hunger and poverty. Low- and middle-income countries have shown a considerable increase in demands for animal proteins (Tilman et al., 2011), in turn driving the dynamics in utilizing formerly unused land or sea plots for farming practices around the globe affecting over 30% of the landmass in just six decades (van Vliet et al., 2015; Winkler et al., 2021). Poore and Nemecek (2018) indicate that the production of animal protein has a disproportionally higher environmental impact per calorie than plant-based proteins. Foods farmed in aquatic water bodies have far lower carbon footprints (CF) than land-based production of protein (MacLeod et al., 2020). Large seaweed farms have the potential to sequestrate carbon efficiently (Krause-Jensen and Duarte, 2016), though the economics are still challenging (Coleman et al., 2022a, 2022b; Sulaiman and Abdul Raship, 2013). Salmon farming studies in various countries reaffirm that the CF of most aquaculture systems is lower than the footprint of any other form of animal protein production systems (Nijdam et al., 2012; MacLeod et al., 2020), the largest part being production and transport of feed. Mariculture hence appears to be a very promising alternative to land-based food production (Costa-Pierce et al., 2021; Costa-Pierce, 2016). Recent technological developments in allowing mariculture production in more exposed conditions indicate opportunities to further minimize CF while improving productivity (Boyd et al., 2020). Examples of novel production systems or new concepts bringing aquaculture into more exposed waters are the shellfish tower (Heasman et al., 2021; Landmann et al., 2021), multi-use concepts (Buck et al., 2004), shellfish longlines (Stevens et al., 2008; Goseberg et al., 2017 or open ocean fish cage systems (Moe Føre et al., 2022; Fredriksson et al., 2004).

Understanding the potential for, and the conditions driving mariculture siting, is crucial in establishing sustainable ocean governance, minimizing environmental impact, and facilitating economically sustainable farm operations. A recent mapping study by Clawson et al. (2022) has provided a database for existing and potential mariculture sites at a global scale. In absence of more accurate information, siting potential has been defined by criteria such as distance from port and from coast as well as number of known sites; their siting algorithm then was validated based on known aquaculture sites. However, this approach is not taking into account site-specific oceanographic conditions which in real mariculture operations often supersede mere distance-based criteria. Therefore, a need exists to define and eventually establish an exposure index (EI) that represents both oceanic conditions and associated requirements for structural design and operation of aquaculture systems. Such an index would assist potential farmers, equipment developers, policy developers, regulators, and insurers alike. In the past, such a definition has been difficult to determine due to the multitude of unassociated users with different needs. Oceanic exposure is notoriously difficult to describe and hence various terms touch on these conditions, e.g. 'offshore', 'nearshore', 'sheltered' or 'exposed' (cp. also Froehlich et al., 2017). These terms are used to help characterize the site-specific level of engineering required to ensure structural mariculture system integrity. In Buck et al. (2024), considerable variations and ambiguities in the definitions of offshore aquaculture were found, but all implied distance from shore. The authors agree, however, that it is not the distance from the coast but primarily the exposure to waves and currents that is the more important factor in classification of an aquaculture site.

This work consequently attempts to define a set of metrics for hydrodynamic exposure, using standard oceanographic variables to provide a universally valid site assessment method for mariculture structures. These possible indices we present are essentially considering physical energy levels or hydrodynamic forces at a site, with a two-pronged view: a first view is purely considering external loads while a second view is additionally considering the dimensions of the gear that is exposed to the external loads. An EI provides a quantified continuum of increasing environmental intensity (and resultant energy tolerant structures and considerations) with increasing exposure. The rationale behind the EI is that the intensity of the hydrodynamic conditions at a site will dictate or heavily impact: the equipment required; the species that can be cultivated at the site; the vessels required to service the site and species; the operation and maintenance methods; the logistics including management/frequency of delivery of feeds (if finfish); aspects of the environmental impacts; the degree of risk mitigation required (to the farmer, the environment, to the financier and to the insurer). Quantifying these parameters in a single metric will assist regulators to issue permits/licenses, assist developers in selecting gear types, assist farmers in considering operational logistics, and generally be useful to all investigators. A suitably defined EI will also help to fill in data gaps for and about mariculture identified by Froehlich et al. (2022), as such indices would provide spatial information about farming potential that can be directly used in digital assessment systems.

Three primary factors, which influence the intensity of a site, were identified in Buck et al. (2024): Waves (height and period/length), ocean currents (speed) and water depth. It is understood that there are variables within these primary factors such as the depth-variable current profile that also influence levels of energy. To accommodate such natural variations and investigate the usefulness of a range of approaches, a number of methods to describe exposure were developed. All are potentially useful, but they emphasize different considerations and exhibit varying degrees of sensitivity. The authors acknowledge that no single method exists that considers all fluctuations, variations and nuances. However, quantifying various index results may yield insightful information to investors, insurers, businesses, ventures, and regulators. Normalized results readily render multiple facets of aquatic site conditions assessable with one standardized metric. This will enable stakeholders to gain a sophisticated perspective on the suitability and limitations of a potential aquaculture site. The benefit of the EI is that it combines the numerous independent environmental factors into a single generally applicable metric.

More specifically, the work which overall aims to quantitatively describe hydrodynamic exposure of mariculture sites has the following objectives:

- To provide a broad perspective on potential formulations of hydrodynamic exposure and lay out their basic meaning.
- To apply the formulated indices to known aquaculture sites worldwide to compare their exposure on a global scale.
- To map the indices to understand spatial variations on a basin scale.
- To provide a thorough discussion on advantages and disadvantages of the suggested hydrodynamic exposure indices.

The remainder of this work is organized as follows: Section 2 gives an overview of the various developed EIs, explains the normalization across the indices and introduces oceanographic data used. Section 3 showcases exemplary results obtained with different EIs for select sites around the globe as well as a high-resolution index map of the North Sea. Section 4 discusses the advantages and disadvantages of the introduced EIs, while Section 5 draws a conclusion and gives an outlook of work to do.

2 Materials and methods

2.1 Quantitative metrics to measure hydrodynamic exposure

In the design of aquaculture structures, perhaps the most critical component of the process is the quantification of the environmental parameters specific to a potential mariculture site, which are usually summarized in a site selection criteria catalogue (Aguilar-Manjarrez et al., 2017; Benetti et al., 2010; Gentry et al., 2017; Helsley, 1997; Oyinlola et al., 2018; Longdill et al., 2008; Kapetsky et al., 2013; Buck and Grote, 2018). From the land-dwelling, human perspective, it may be natural to define a site by distance from shore. Of course, distance is relevant for the operation of aquaculture farms, but it is not the primary factor governing exposure to environmental loads. Therefore, from the ocean engineering viewpoint, it is logical to define the location by the magnitude of interaction between the ocean environment and the aquaculture structure. The intensity of oceanographic conditions, typically in the form of waves and currents, impose forces on the aquaculture structures which generally increase with increasing fluid velocities and accelerations. Wind loads should also be considered in structural design, but wave and current loads generally dominate because most aquaculture structures have considerably more volume below the waterline than above. The dimensions of aquaculture system components, range from small diameter twine (millimeters) (Loverich and Forster, 2000; Loverich and Gace, 1997; Føre et al., 2022) of fish containment net to farms that cover hectares of sea area (Gray, 2019; Goseberg et al., 2017). Aquaculture system components are often the products themselves composing of shellfish droppers or thickly grown macroalgae with scales from one to 100s of meters (Chopin and Sawhney, 2009).

The approach described here considers the relative size of individual aquaculture system components to distinguish it from other "offshore" industry structures used for oil/gas, wind and hydrokinetics. This was done to identify the relevant types of forces (drag/inertia) and therefore the variables used in the development of the index.

2.1.1 Definition of variables to formulate exposure indices

The parameters that have been identified as the dominant parameters of the hydrodynamic energy at the aquatic site are: significant wave height (H_s), peak wave period (T_p), water current speed (U_c), wave induced current or orbital velocity (u) in the horizontal direction, and the depth of water at a site (d). Here, the current speed is the complement to the wave induced orbital velocity; U_c encompasses currents driven by tides, winds, buoyancy, and wave-driven mean flows while u is only the orbital velocity. By considering these environmental characteristics, several mathematical formulations were considered. It is important to note that *EI*s require that the hydrodynamic parameters of the site under consideration must be known (either from measurements or numerical modeling) to inform the index calculation. Since waves attenuate and current velocities can vary with depth, both are a function of vertical position in the water column (z). The corresponding hydrodynamic loads acting on the aquaculture structure may change with submergence at the same site due to decreased wave-induced fluid velocities (u_w) as shown on Figure 1.

The exposure index must also be defined according to a desired probability function and return period (e.g., 50-year storm condition). These parameters can be obtained from model results, field datasets, hind-/forecasts or other acceptable methods. Once this condition has been identified, the corresponding design values for H_s, T_p, and depth-dependent U_c can be determined for a site. For instance, with the wave period and depth, the wavelength (L) can be defined with linear wave theory (e.g. Dean and Dalrymple, 1991; USACE, 2002), by the dispersion relation:

$$L = \frac{gT_p^2}{2\pi} tanh(kd) \tag{1}$$

with g being the gravitational acceleration and where k is the wave number:

$$k = \frac{2\pi}{L} \tag{2}$$

The dispersion relation requires a numerical solution to obtain the wavelength, as a function of depth at the site, since it is found both inside and outside of the hyperbolic tangent function. With the wavelength, the relative depth is defined as:

$$Relative \ \ Depth = \frac{d}{L}. \tag{3}$$

As a wave propagates from deep to shallow water the wave period remains constant, but the wavelength decreases and

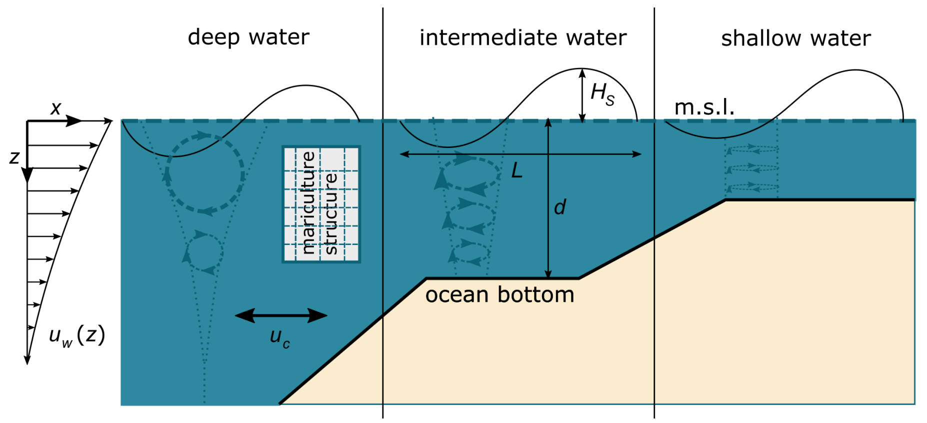

FIGURE 1
Waves and currents are site specific with parameters a function of vertical location in the water column (z). As waves propagate from deep to shallow water, wave height and length change as a function of (x).

therefore the wave heights shoal (increase) until they become steep enough to break. For a fixed wave period, increasing wave heights increase the horizontal wave velocities (u) and accelerations (du/dt, t time) and the forces on the structure.

Wave and current forces on aquaculture structures that consist of cylinders with a diameter (D) can be approximately calculated using a per unit length form of Morison's equation (Morison et al., 1950):

$$f_x = C_D D \frac{1}{2} \rho (u + U_c)|u + U_c| + C_m \rho \frac{\pi D^2}{4} \frac{\partial u}{\partial t} \quad (4)$$

assuming that the size of diameter (D) is small compared to the wavelength (L). In Equation 4, C_D is the drag coefficient, ρ is the mass density of the fluid, C_m is the mass coefficient and u is the instantaneous horizontal wave particle velocity:

$$u(x, z, t) = \frac{\pi H}{T} \frac{\cosh k(z + d)}{\sinh (kd)} cos(kx - \omega t) \quad (5)$$

The horizontal wave particle velocity oscillates as a function of the cosine term and therefore in Equation 5 the absolute value sign maintains the direction of u. The magnitude of the wave-induced fluid velocity can be written as:

$$u_w(z) = \frac{\pi H}{T} \frac{\cosh k(z + d)}{\sinh (kd)}, \quad (6)$$

showing attenuation with vertical position in the water column (z). The velocity term in Equation 4 also includes a steady component, $U_c(z)$, also shown on Figure 1. Aside from the depth-dependent velocity induced by waves when acting on a slender cylindrical body, as shown in Equation 4, acceleration components also exist. These acceleration-dependent forces, related to the inertia of the water oscillating around the cylinder, are represented by the function of $\frac{\partial u}{\partial t}$. The dominance of wave drag over wave inertia forcing on a structure is characterized by the Keulegan-Carpenter number (Keulegan and Carpenter, 1958) expressed as:

$$KC = \frac{u \cdot T_P}{D} \quad (7)$$

The KC number is typically calculated using particle orbital velocities u (Sarpkaya, 2014).

As discussed in McCormick (2010), (wave) drag dominates for small diameter cylinders if the KC number is on the order of 100, which could represent a KC number threshold. This would be the case if $u_w = 1\frac{m}{s}$, $T_p = 10$ s and $D = 0.1$ m. Inertia force dominance would increase as the submerged diameter (or volume) of the structure becomes larger, decreasing KC to level of ≈ 10. In this context, it is assumed that aquaculture structures like mussel droppers, kelp-lines, rope, net and buoys are all slender as compared to wave height H_s and length L. The drag dominance would increase the wave velocities is combined with the steady current velocities.

2.1.2 Hydrodynamic exposure indices

This work proposes and examines six hydrodynamic exposure indices that are based on the variable definitions described in Equation 8 to Equation 19. The first four indices were developed based on the environmental loading variables wave length, water depth, wave- and current-induced velocities, while the fifth and sixth index also include geometric and other characteristic information of some aquaculture technology, such as the structure's diameter. The indices take as input the defined hydrodynamic oceanographic variables, all of which are typically derived using extreme value analysis based on measurements or hind-cast simulations. Therefore, when using the indices, it is important to recognize that these values are probabilistic by nature. Input variables should generally be design values, e.g., using return periods (occurrences) of 50 years. The following candidate indices are proposed and examined:

1. Exposure Velocity (EV)
2. Exposure Velocity at Reference Depth (EVRD)
3. Specific Exposure Energy (SEE)
4. Depth-integrated Energy Flux (DEF)
5. Structure-centered Depth-integrated Energy (SDE)
6. Structure-centered Drag-to-Buoyancy Ratio (SDBR)

The benefits, challenges and specific reasoning in defining each index are presented next.

2.1.2.1 Exposure velocity

Drag forces on aquaculture structures in oceanic conditions are strongly tied to the combined current- and wave-induced velocity field at some depth measured from the sea surface. In accordance with Equation 5, the total fluid velocity takes into account the depth-dependent orbital velocities (see Figure 1) and the water currents; the latter are typically an intricate state of e.g., tidal and circulation oceanic currents. This definition of exposure velocity incorporates the nonlinear wave-current interaction. That is,

$$Exposure\ \ Velocity\ \ (EV) = \sqrt{u_w(z)^2 + 2u_w(z)U_c(z) + \ U_c(z)^2} = U_c(z) + u_w(z) \qquad (8)$$

Equation 9 can be applied for a given depth, wave height, wave period and position in the water column. Where not otherwise specified, the analyses presented here surface values, which generally correspond to the highest exposure level over the water depth.

2.1.2.2 Exposure velocity at reference depth

Aquaculture structures can be deployed at various depths below the water surface. Many extend down from near the surface such as seaweed (extending 0 - 10 m) and mussel farming lines (extending 0 - 20 m) or fish nets (extending 20 - 50 m) (Heasman et al., 2021; Stevens et al., 2008). In addition, submerged structures may become highly relevant in exposed sites. To achieve a common measure of exposure velocity for a specific site independent of types of structures, a reference depth of 10 m has been proposed for this special case of the EV index. Considering a structure with a depth of 10 m, the suggested exposure velocity is given as the average horizontal current velocity plus the average maximum particle velocity over this depth in a given direction. To simplify further (avoiding integration over a certain water depth), current velocity design values at 5 m (U_{c5}) and the horizontal particle velocity (Equation 5) at 5 m (u=u_{w5_max}) is assumed to represent the average current and wave particle velocities respectively over the reference depth. This gives the following mathematical expression of the Exposure Velocity at Reference Depth (EVRD):

$$Exposure\ \ Velocity\ \ at\ \ Reference\ \ Depth\ \ (EVRD) = \ U_E = U_{c5} + u_{w5} \qquad (9)$$

where the indices ‘c’ and ‘w’ represent the current- and wave-induced velocities, respectively. Alternative depth definitions are possible, when applied to actual mariculture operations.

2.1.2.3 Specific exposure energy

The intensity of extreme conditions at aquaculture sites may be related to the energy in the moving seawater. For a moving mass of uniform fluid, the kinetic energy can be described as,

$$E = \frac{1}{2}\ m\ \ U^2 \qquad (10)$$

where m is the mass of fluid and U is its instantaneous velocity. Current and wave-induced fluid velocities can be incorporated by defining U as the exposure velocity derived above, which is the sum of a steady and a wave-induced fluid velocity for the point of interest,

$$U(z) \ = \ U_c(z) \ + \ u_w(z) \qquad (11)$$

Dividing kinetic energy by m yields kinetic energy per unit mass, which can be described as the *Specific Exposure Energy (SEE)*. That is,

$$\text{Specific Exposure Energy (SEE)} = \ 1/2 \ \ (U_c(z) \ + \ u_w(z))^2 \qquad (12)$$

This index has SI units of J/kg. Since drag force on any gear is nominally proportional to fluid velocity squared, drag forces will also be proportional to the Specific Exposure Energy.

This exposure index can also be extended to a structure-centric index by multiplying a site’s SEE (e.g., in J/kg) by the mass of the displacement water of the aquaculture structure (in kg), to yield a structure-centric exposure energy with SI units of Joules.

2.1.2.4 Depth-integrated energy flux

Another proposed quantitative metric is called the energy flux (DEF) index and is the sum of energy flux due to both waves and currents integrated over the water depth. Wave energy flux is equivalent to units of power, and is often quantified in energy flux per unit width (e.g., W/m, in SI). One motivation for using the Specific Exposure Energy, is that it provides a relevant and quantified metric for kinetic energy. Furthermore, wave energy flux at many coastal locations has been quantified and mapped in wave and marine current renewable energy production (Drew et al., 2009; Jin et al., 2022). For deep water waves, the wave energy flux (power) per unit width, W/m, due to wave action in a given sea state is defined as:

$$Wave - based\ \ Energy\ \ Flux = \frac{\rho g^2 (H_s^2) T_E}{64\pi} \qquad (13)$$

In Equation 13, T_E is the ‘energy period’ of the sea state in seconds. For simplicity, the energy period can be estimated to be proportional to the peak period, using the empirical relationship such as $T_E = 0.9T_P$ (c.f., Ahn, 2021). The expression defined here is derived for deep water integrating wave energy flux vertically over the entire water column depth. This technique also incorporates a variance spectrum approach proportional to energy with the use of H_s in m.

The energy flux through a vertical plane normal to the current velocity is proportional to U^3. Integrated over depth, the energy flux per horizontal distance is,

$$Current - based\ \ Energy\ \ Flux\ \ (WEF)_c = \frac{1}{2}\rho d(U_c)^3 \qquad (14)$$

Thus, a combination of wave- and current-induced energy flux may be approximated by a linear superposition as:

$$Depth - integrated\ \ Energy\ \ Flux\ \ (DEF) = \frac{\rho g^2 (H_s^2) T_E}{64\pi} + \ \frac{1}{2}\rho d(U_c)^3 \qquad (15)$$

2.1.2.5 Structure-centered depth-integrated energy

While an environmental loading focus has been the guiding principle for the formulation of the above indices, the authors have opted to include indices that include characteristics related to specific mariculture components, i.e., solidity or a diameter of a hypothetical mariculture structure. Two primary factors in governing total forces of structures are their diameter and the solidity (Gansel et al., 2018, 2015; Føre et al., 2022); To that end, energy content in a unit space of the horizontal ocean domain has been approximated, using basic oceanographic formulations for the energy (in Joule J) that is contained in the water column from the surface elevation to the ocean bottom, integrated horizontally over wavelength. It is comprised of the potential and kinetic wave energy, based on linear wave theory,

$$E_{wave} = \frac{1}{8}\rho g H_s^2. \tag{16}$$

Energy of tidal or oceanic currents can be expressed in terms of kinetic energy per unit area, and may approximately reduce to:

$$E_{current} = \frac{1}{2}\rho d U^2 \quad in \quad [J/m^2]. \tag{17}$$

A simple linear combination the solidity and exposed surface area of a mariculture structure, in our case an idealized cylinder is chosen, with the sum of the wave and current energy can now become an expression for the amount of energy close to a structure, available for wave-current interaction. While higher-order, and non-linear interactions, as well as ratios of drag over inertia forces are neglected in this approach, a simple relation exists that allows to compare simpler mariculture structures independent of location. The structure-centered Depth-integrated Energy index (SDE), using Equation 16 and Equation 17, becomes:

$$Structure - centered \;\; Depth - integrated \;\; Energy \;\; (SDE) = \left(\frac{1}{8} g H_s^2 + \frac{1}{2} d U^2\right)\rho S A_{structure} \tag{18}$$

where $S = A_p/A$ defines the solidity of a mariculture structure as the ratio of the area of gear material A_p and the total area covered by a reference area A (Zhan et al., 2006; Tsukrov et al., 2011). In addition, the surface area over which the energy is integrated is $A_{structure} = \pi \cdot D^2/4$. This index can also be converted to a structure-agnostic index by simply removing the factors S and $A_{structure}$ *from* Equation 18.

2.1.2.6 Structure-centered drag-to-buoyancy ratio

To achieve an exposure index that is proportional to energy and drag forces and is non-dimensional, an alternative structure-centric index is proposed based on the ratio of drag forces to buoyant forces on an aquaculture structure. In this formulation,

$$Drag - to - buoyancy \;\; Ratio = \frac{Drag \;\; force}{Buoyancy \;\; force} = \frac{\frac{1}{2}\rho C_D A U^2}{\rho g V} \tag{19}$$

with U being the exposure velocity as calculated previously ($U = U_c(z) + u_w(z)$). The projected area, A, can be taken to be proportional to D^2 (where, as before, D is the characteristic length associated with the structure). Similarly, volume, V, is proportional to D^3. Taking a representative drag coefficient of $C_D = 1$, the equation above becomes:

$$Drag - to - buoyancy \;\; Ratio \;\; (SDBR) = \frac{U^2}{2gD} \tag{20}$$

This structure-centric index has the benefit of being a non-dimensional number. Note that the parameter D is a characteristics length of a structure, and not the local water depth in which the structure is placed; thus, the SDBR should not be confused with a Froude number squared.

2.2 Oceanographic data and exposure indices for known aquaculture sites

The proposed exposure indices were evaluated for a range of known aquaculture sites around the world. Site parameters including extreme values for wave and current magnitudes were provided via personal communication with members of the International Council for the Exploration of the Seas (ICES) Working Group on Open-Ocean Aquaculture (WGOOA) and collaborators. The derivation of site-specific extreme values is not the focus of this paper. Therefore, the extreme values listed here were accepted as provided and should not be used for design or other purposes.

2.3 Oceanographic data and exposure indices at the regional scale

2.3.1 Database EasyGSH for the German Bight North Sea

A wide range of applicable sites in various seas worldwide could have served as case studies for this study. Due to the current global developments to simultaneously use marine areas and existing infrastructures according to the multi-use concept (Buck and Langan, 2017; Schupp et al., 2019) a region is chosen, where these concepts are being intensively investigated, such as the North Sea. North Sea countries including Germany, Denmark, the Netherlands, Belgium and the UK, have been studying the multi-use of offshore wind farms (OWF) and aquaculture for two decades and provide a wide range of data. We have focused on the German Bight due to the accessibility of suitable data. Synoptic data stemming from a numerical model covering the region and spanning a simulation period of two decades serves as basis for applying different exposure indices developed throughout this work to a continuous spatial data set (Hagen et al., 2021). The model data features a spatial resolution of 100 m and presents a range of hydrodynamic and morphologic variables. From the EasyGSH database, hydrodynamic quantities were obtained in georeferenced Tagged Image File Format (geoTIFF), which are subsequently processed with open source and proprietary software (The Mathworks Inc, 2022; QGIS Development Team, 2022).

2.3.2 Extreme value analysis of hydrodynamic variables

Extreme value analysis of significant wave heights, $H_s(x,y)$, and depth averaged current speeds taken from the seabed to the free surface η, $\frac{1}{\eta+d}\int_{-d}^{\eta} U_c(x,y,z)dz$, from the EasyGSH database spanning 20 years (1996-2015) define estimates of the 50 year return values over a 100 m grid with dimensions 2141 x 2102 (n=2,789,571). The EasyGSH data repository provides bathymetry and yearly maxima significant wave heights on this 100 m grid and depth averaged currents (Δt=20 min), resampled to a 1000 m grid. Univariate extreme value analysis of significant wave heights and depth averaged current speeds was performed with series of yearly block maxima over the German Bight. This approach is conservative, as the directionality and behavior of extremes in the joint H_s-T_p-U distribution is not taken into account (e.g., 50-year u_w and U_c values are not necessarily coincident in time and direction). The authors acknowledge more robust methods exist for estimating extremes in a multivariate parameter space (Eckert-Gallup et al., 2016; Mackay and de Hauteclocque, 2023). At each node in the EasyGSH domain, series of yearly block maxima x_i, where x_i represents series of either hydrodynamic variable, were fit to the Gumbel distribution

$$F(x;\mu,\ \beta) = \exp(-e^{-(x-\mu)/\beta}), \quad -\infty < x < \infty \tag{21}$$

where μ is the location parameter and β>0 the scale parameter. The Gumbel distribution was selected after fitting at 500 random nodes to a range of distributions, and then assessing the quality of fits. The Gumbel distribution proved to fit best for 94% of the random sample.

The best fit to the Gumbel distribution was calculated through finding the least squares solution to

$$-\log(-\log(F(x;\mu,\ \beta))) = (x-\mu)/\beta. \tag{22}$$

The 50-year return values, x_{50}, were calculated from the associated fit, as:

$$x_{50} = \beta - \mu\log\left(-\log\left(1-\frac{1}{50}\right)\right). \tag{23}$$

Values of 50-year significant wave heights were assumed to have peak periods defined by wave steepness limits (DNVGL, 2010). Values of 50-year depth averaged currents were linearly interpolated to the same 100 m grid as 50-year significant wave heights and assumed to follow a power law over the depth. This resulted in current flow velocities (Equation 24) that can be used in calculation of exposure indices (Welzel et al., 2021; Lewis et al., 2017):

$$U(z) = U(0)\left(\frac{d+z}{d}\right)^{1/7}, \quad z \le 0 \tag{24}$$

The 50-year H_s and associated T_p were used to calculate the maximum wave induced horizontal velocity magnitude $u_w(z)$, for z = 0 and -5 M.S.L. Lastly, bathymetry from EasyGSH was adjusted nearshore from its mean-sea-level datum to account for depth limited wave breaking that may have occurred during periods of high water (e.g., spring tide or storm surge). In locations where the 50-year H_s/d ratio was greater than 0.55, the depth was modified such that $d = H_s/0.55$.

2.3.3 Computation of exposure indices

The exposure indices from Section 2.1.2 were then computed for the grid cells of the synoptic numerical results of the 50-year extreme values. For the maps of the German Bight, constructed, commissioned and planned offshore wind park areas are also provided (Hannemann, 2022), since there has been a considerable body of literature that discusses multi-use concepts involving offshore wind and aquaculture production (Przedrzymirska et al., 2021; Gimpel et al., 2015; Buck et al., 2008; Buck and Langan, 2017). Vertical location in the water column considered for index calculations was set to the surface at z = 0 m except for the EVRD, which used z = -5m. For the structure-centric indices (SDE and SDBR) solidity was set to S = 0.25 and the characteristic length/diameter was set to D = 1.0 m, based on typical aquaculture structures.

Computed index values were normalized to render results more intercomparable. Methodological details are given appendix A.

3 Results

Hydrodynamic exposure indices developed in this study are applied to illustrate their applicability with respect to quantifying exposure of aquaculture sites or gear. To test universal applicability, a global perspective is given through mapped known global aquaculture sites where operational research or commercial farms are active. While these locations are single positions around the globe, hydrodynamic exposure indices can also be mapped for larger regions, as long as suitable basis input variables are available (see Section 2.1.1) The authors have used publicly available synoptic oceanographic data for the North Sea part of the German Bight to showcase the robustness and usefulness of the defined indices and examine their variations over a defined region.

3.1 Index comparison based on known aquaculture locations

We applied the six different Exposure Indices to quantify the exposure of known aquaculture locations. The resulting EI values are compiled in Table 1 with their respective location and corresponding return periods. The results have been color-coded with a color intensity proportional to index value magnitude; a mapped illustration is compiled in Figure 2 for the sites. Areas clustered with sites like northern Europe or the United States Atlantic and Pacific coast feature in Figures 3A–F respectively, to make the results more accessible on a regional scale. It is noted that index values in Table 1 are a function of return period and the values provided for this analysis are for a range of return periods including 10, 50, and 100 years.

It has to be noted that mapped locations are generally close to shore or port, and the advent of aquaculture production far offshore has not yet been seen. This corroborates Clawson et al. (2022) who state that 98% of the world's ocean space has no aquaculture operations.

From Figure 2, it is evident that the SDE is much more dependent on local differences in exposure than on global trends. Generally, most of the EI exhibit similarly high values for some of the highly exposed locations, such as sites 7, 8, 18 and 24. As desired, sheltered areas appear to exhibit lower index values, whereas unsheltered areas show higher values. Milder conditions according to the index are present inside the North Sea near the German Bight (cf. Figure 3A) as well as along the Atlantic coast of Ireland (cf. Figure 3B). The Faroe Islands (Figure 3C) show fairly mild conditions across all six indices for two locations described as sheltered (sites 24 and 25), whereas the northernmost site, open to the Arctic Sea (site 26) exhibits very exposed conditions according to the developed classification.

Conditions for the chosen aquaculture sites on the Pacific coast of the United States (i.e., site 6) are milder according to the Depth-integrated energy indices (DEF and SDE) but show more severe values for EV, EVRD, SEE and SDBR (c.f. Figure 3D). The Gulf of Mexico (site 8 in Figure 3E) shows more energetic conditions probably due to the frequent appearance and landfall of hurricanes within this region (Zuzak et al., 2021). For the Gulf of Maine along the Atlantic coast of the United States (cf. Figure 3F) the velocity-based exposure indices EV, EVRD, SEE and SDBR show larger values, whereas Depth-integrated energy and energy flux indices DEF and SDE represent sites 1, 4 and 5 as milder.

3.2 Influence of return periods

The sensitivity to return period was investigated based on available data for a location in New Zealand (see Table 2). The return periods assigned to the wave data are one and fifty years respectively. A longer return period would in general result in higher exposure indices. This reflects that the exposure indices are sufficiently flexible to quantify the intensity of conditions to which aquaculture gear will be exposed in shorter periods (e.g., a typical year) and longer periods (e.g., 50 years). For the various exposure indices, the ratio between the 50-year index value and the 1-year index value ranges from 1.6 to 3.5. Higher ratios were found for the indices that are approximately proportional to fluid drag loads (SEE and SDBR).

3.3 Spatial mapping products: The German Bight case

In addition to globally distributed aquaculture sites presented in Section 2.2, a synoptic assessment based upon extreme value analysis of numerical hindcast data covering the German Bight was performed to evaluate the performance of the developed indices on a spatial level. Figure 4 shows the 50-year hydrodynamic variables H_s, u_W, *and* U_c and the depth d that define the exposure indices that are presented in the following subsection 3.3.1 In all figures, the color bar scale spans from 0 to the 99th-percentile of the exposure index.

3.3.1 Exposure velocity

The EV and EVRD for surface currents and a reference depth of 5 m are depicted in Figures 5–8 respectively. Both the EV evaluated at the surface and EVRD approach upper percentiles near the barrier islands and at the mouths of estuaries, where shoaling waves increase u_w and the convergence of tidal inlets amplifies U_c. The EV index values at the surface more noticeably exceeds EVRD in regions further from the coast (e.g., >20 km) because horizontal velocities induced by shallow water waves do not decay with depth. In the normalized maps, i.e., Figure 6 and Figure 8, it is apparent, that values of EV are generally larger than EVRD in tidal basins and behind the back-barrier islands.

3.3.2 Specific exposure energy

The SEE at the surface is quantified for z = 0 m and results compiled in Figure 9 for computed and in Figure 10 for normalized SEE values. Spatial variations are more readily observed due to the quadratic contribution of u_W and U_c. The largest SEE values are found on the exposed side of barrier islands where, where horizontal wave-induced velocities are magnified by shallow water, and near constrictions where tidal and storm-driven currents are highest. Select deep water regions with high significant wave heights and large current speeds (Figure 4C) also yield large SEE values. The SEE is significantly reduced from 7-8 J/kg to 2-4 J/kg in the back bays and the shoals of the estuaries.

3.3.3 Depth-integrated energy flux

The DEF (Figures 11, 12) presents an alternative representation of exposure in the spatial domain. At a distance of 40 km from the coast, the DEF obtains values of 120 – 160 kW/m while in shallow regions along the barrier islands and in estuaries the DEF is consistently 2-20 kW/m. This spatial variation is primarily driven by the decrease in the $\frac{1}{2}\rho\bar{U}_c^3 d$ term as d approaches 0 m in shallow waters and secondarily by the reduced 50-year sea states in protected waters.

3.3.4 Structure-centered depth-integrated energy

The SDE, evaluated with structure solidity of 0.25 and surface area $\pi/4$ in Equation 18, accentuates the energy in the deeper regions of estuarine channels and tidal inlets in the southern and south-eastern regions of the German Bight (Figures 13, 14). When water depths approach 0 m, the SDE is limited to values <50 kJ kg/m^3. In open water, the SDE obtains values of 1.5 to 23 kJ kg/m^3.

3.3.5 Structure-centered drag-to-buoyancy ratio

The SDBR at the surface is presented in Figures 15, 16, for SDBR values and its normalized version respectively. It is proportional to the SEE; it is greatest in nearshore waters exposed to 50-year sea states and amplified oceanic currents. In the leeward side of barrier islands, the SDBR is consistently less than 0.8 while it remains amplified in the center of estuarine channels.

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TABLE 1 Oceanographic data for selected aquaculture sites around the globe. The colormap identifies the relative value of the EI with respect to the selected sites. Source is personal communication with.

ID	Location	Source	Return Period	Water Depth	Sig. Wave Height	Peak Period	Oceanic Current Speed	Position in Water Column	EV	EV 5m	SEE	DEF	SDE	SDBR
			yr	m	m	s	m/s	m	m/s	m/s	J/kg	kW/m	kJ kg/m^3	–
1	Gulf of Maine, Cape Elizabeth	Dewhurst	50.0	26.0	9.6	11.4	0.5	0.0	3.90	3.44	7.63	465.56	28.08	0.78
2	Gulf of Maine, Saco Bay	Dewhurst	50.0	14.0	5.4	11.4	0.8	0.0	3.19	2.93	5.24	150.45	9.72	0.42
3	Gulf of Maine, Cape Elizabeth (submerged)	Dewhurst	50.0	26.0	9.6	11.4	0.5	-3.0	3.61	3.44	6.53	465.56	28.08	0.52
4	Gulf ofMaine, Saco Bay (submerged)	Dewhurst	50.0	14.0	5.4	11.4	0.8	-3.0	2.99	2.93	4.61	150.45	9.72	0.37
5	Gulf of Maine, Isle of Shoals	Dewhurst	50.0	52.0	10.1	12.6	0.7	0.0	3.48	3.17	6.13	576.67	33.29	0.49
6	Santa Barbara Channel	Dewhurst	50.0	33.0	5.6	7.1	0.8	0.0	3.32	2.48	5.45	106.97	11.84	0.44
7	Gulf of Mexico, Pensacola	Dewhurst	50.0	45.0	12.2	15.0	2.0	0.0	5.33	5.02	14.00	1170.29	65.82	1.12
8	Gulf of Mexico, Pensacola (submerged)	Dewhurst	50.0	45.0	12.2	15.0	2.0	-15.0	4.63	5.02	10.53	1170.29	65.82	0.84
9	North Sea, FINO1	Strothotte	50.0	30.0	7.4	14.0	1.5	0.0	3.86	3.64	7.45	390.40	24.37	0.60
9a	North Sea, FINO1	*EasyGSH*	*50.0*	*29.96*	*5.84*	*7.31*	*1.46*	*0.0*	*4.02*	*3.27*	*8.07*	*142.63*	*17.78*	*1.65*
10	North Sea, Roter Sand	Buck	1.0	12.0	3.0	10.0	1.0	0.0	2.48	2.25	3.06	45.89	4.11	0.25
10a	North Sea, Roter Sand	*EasyGSH*	*50.0*	*10.8*	*4.39*	*7.0*	*1.62*	*0.0*	*4.08*	*3.29*	*8.31*	*75.86*	*9.15*	*1.69*
11	Opotiki, Bay of Plenty, New Zealand (submerged)	Heasman	50.0	45.0	7.6	15.2	0.6	-5.0	2.48	2.48	3.07	392.64	19.06	0.25
12	Pegasus Bay, New Zealand (submerged)	Heasman	50.0	22.0	7.6	15.2	0.6	-3.0	3.13	3.11	5.06	390.09	18.06	0.40
13	Boknafjorden, Norway	Moe Føre	50.0	100.0	2.5	6.0	1.0	0.0	2.31	1.75	2.67	67.81	13.93	0.21
14	Frohavet, Norway	Moe Føre	50.0	100.0	7.0	7.0	1.2	0.0	4.34	3.28	9.42	240.01	31.90	0.75
15	Long Island, Ireland		10.0	15.0	5.4	19.6	0.9	0.0	3.10	3.05	4.94	257.96	10.10	0.40
16	Cape Clear, Ireland		10.0	35.0	11.0	19.6	0.8	0.0	3.88	3.75	7.61	1056.35	38.54	0.61
17	Bantry Bay, Ireland		10.0	20.0	2.5	19.2	0.4	0.0	1.34	1.27	0.86	53.64	2.24	0.07
18	Deenish Island, Kenmare Bay, Ireland		10.0	27.0	12.7	19.3	0.5	0.0	4.51	4.33	10.23	1376.21	48.58	0.82

(Continued)

TABLE 1 Continued

ID	Location	Source	Return Period	Water Depth	Sig. Wave Height	Peak Period	Oceanic Current Speed	Position in Water Column	EV	EV 5m	SEE	DEF	SDE	SDBR
			yr	m	m	s	m/s	m	m/s	m/s	J/kg	kW/m	kJ kg/m^3	–
19	Clare Island, Clew Bay, Ireland		10.0	21.0	3.2	19.5	0.8	0.0	1.93	1.88	1.87	93.68	4.66	0.15
20	Clew Bay, Ireland		10.0	20.0	1.9	19.1	0.6	0.0	1.30	1.26	0.83	32.66	1.94	0.07
21	Caribbean Sea, Panama	Sclodnick & Sullivan	10.0	62.0	6.0	10.0	1.6	-15.0	2.65	3.16	3.52	289.11	29.83	0.28
22	Gulf of California, Baja California Sur, Mexico	Sclodnick & Sullivan	10.0	42.0	5.0	7.0	0.6	0.0	2.85	2.09	4.06	81.92	9.23	0.32
23	Fiskaaling 1, Faroe Islands	Norði via Strand via Dewhurst	50.0	20.0	4.5	16.0	0.2	0.0	1.86	1.75	1.74	143.14	6.09	0.14
24	Fiskaaling 2, Faroe Islands		10.0	33.0	14.0	16.0	0.3	0.0	4.51	4.18	10.03	1385.14	58.40	0.80
25	Gøtuvík, Faroe Islands	Joensen via Buck	50.0	70.0	7.0	10.0	0.7	0.0	2.95	2.55	4.36	230.89	19.14	0.35
26	Luderitz, Namibia	Knoester via Dewhurst	50.0	55.0	5.3	14.5	0.7	0.0	2.08	1.94	2.11	189.51	11.57	0.17
27	Thornton Bank, North Sea, Surfaced	Nevejan and Pribadi via Dewhurst	50.0	29.0	6.3	8.3	1.1	0.0	3.55	2.99	6.56	165.24	15.99	0.52
28	Thornton Bank, North Sea, Submerged		50.0	29.0	6.3	8.3	1.1	-9.0	2.57	2.99	3.45	165.24	15.99	0.28
29	Norwegian Sea, Frohavet	(Jin et al., 2021)	100.0	150.0	5.0	11.0	0.8	0.0	2.18	2.01	2.48	160.78	19.00	0.20

1) Ocean current speed (U_c) at z=0m was used as design current speed for the developed indices due to a lack of information regarding depth resolved ocean current profiles. For site specific applications the user is strongly advised to use depth resolving information for design related questions.
2) Lines 9a and 10a are derived from statistical extrapolation of 20 year numerical simulation to 50 year return period values extracted from the areal representations given in Figures 5–16.
3) Color intensity for last six columns is based on cell value, with faded to most intense correlating to smallest to largest value.

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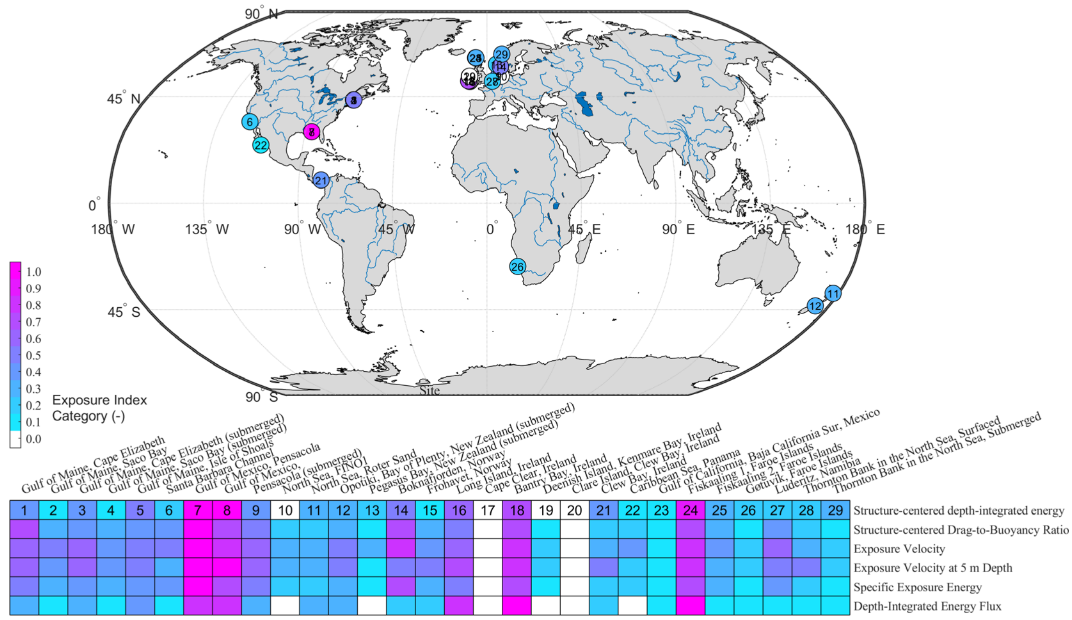

FIGURE 2
Mapping of selected aquaculture structure locations, associated with the six suggested exposure index definitions as per sub-section Hydrodynamic exposure indices Tabulated exposure indices, color-coded by normalized index values per index based on data compiled in Table 1. Map icons are color-coded according to the top-row of the index table (Table 1) representing the Structure-centered depth-integrated energy (SDE).

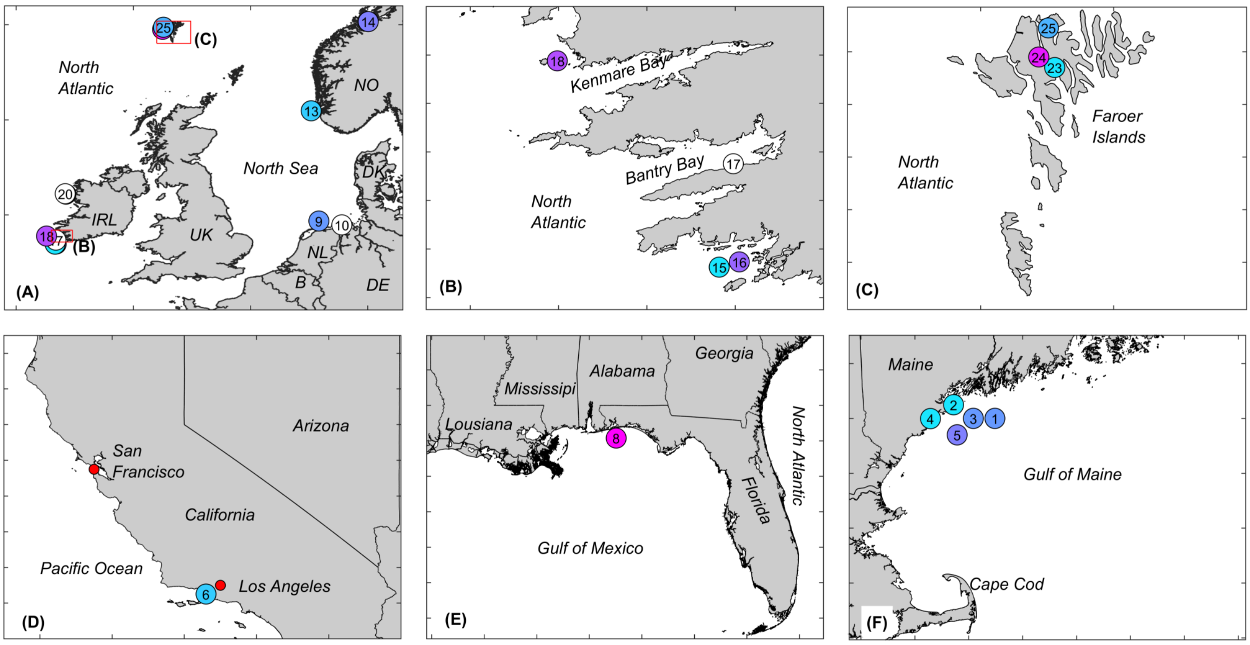

FIGURE 3
Select magnifications of exposure sites with **(A–C)** in northern Europe and **(D–F)** in North America. Color coded exposure index sites are based of the Structure-centered depth-integrated energy (SDE) index from the top row of the bottom panel in Figure 2 The SDE is mapped for **(A)** Northern Europe, with **(B)** Ireland harbouring multiple sites and three more situated on **(C)** the Faroe Islands. For the Pacific **(D)** a site is characterized near LA, with a site at the coast of the Gulf of Mexico **(E)** and multiple sites located within the Gulf of Maine **(F)**.

TABLE 2 Comparison of impacts of return periods (1versus 50 years) on the different exposure indices for a given location.

			Return Period	Water Depth	Sig. Wave Height	Peak Period	Oceanic Current Speed	Position in Water Column	EV	EV at 5 m depth	SEE	DEF	SDE	SDBR
ID	Location	Source	yr	m	m	s	m/s	m	m/s	m/s	J/kg	kW/m	kJ kg/m^3	–
11	Opotiki, Bay of Plenty, New Zealand (submerged)	0 Heasman	1	45	4.6	12.0	0.3	-5.0	1.5	1.5	1.2	125.5	7.5	0.16
11	Opotiki, Bay of Plenty, New Zealand (submerged)	0 Heasman	50.0	45.0	7.6	15.2	0.6	-5.0	2.48	2.48	3.07	392.64	19.06	0.25
Ratio of 50-year value to 1-year value					1.7		2.0		1.6	1.6	2.6	3.5	2.8	2.6

1) Colors matching to previously used scheme in Table 1 for ease of comparison.

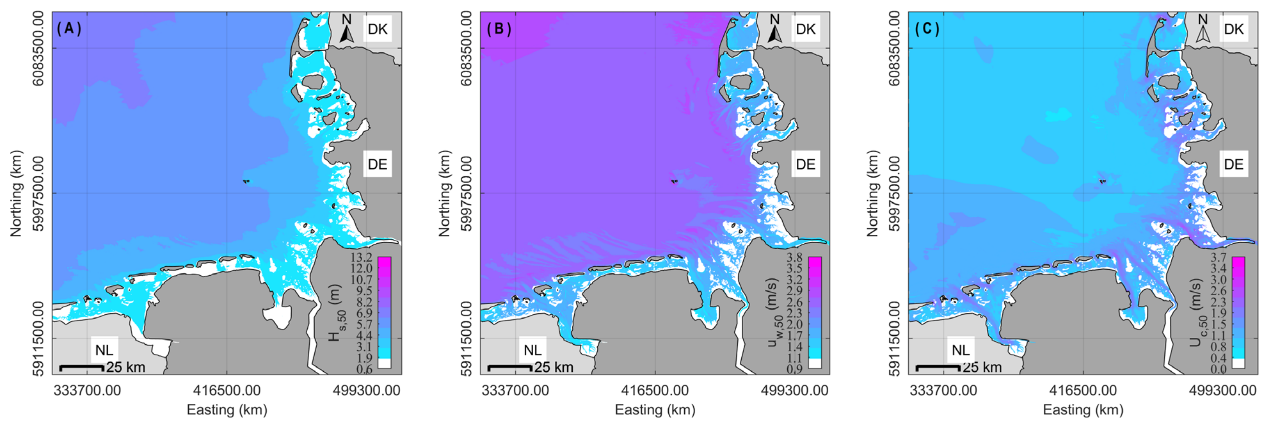

FIGURE 4
From left to right, the 50-year **(A)** H_s, **(B)** u_w at the surface, and **(C)** depth averaged U_c. Bathymetry (black contour) is shown for z = 20 m and z = 40 m, while the upper limit of the color bar in **(B)** and **(C)** is the 99th-percentile of u_w. These values are estimated from hindcast data and should not be used for design.

4 Discussion

4.1 Relation to other previously proposed indices

The study at hand concentrates on environmental conditions and structure-related characteristics to assess the exposure of various sites. In comparison, Calleja et al. (2022) included species related prerequisites for a successful cultivation covering waves and currents as well but also including sea surface temperature, salinity and optical water clarity in coastal waters. Furthermore, they matched potential sites with other coastal stakeholders and activities such as energy production, shipping or recreation and assessed potential for upkeep such as maintenance, feeding and accessibility. A similar approach was presented by Benetti et al. (2010) in a broad study on site selection procedure for open ocean aquaculture. Similar to Calleja et al. (2022), that proposed classification scheme omitted the need to assess ocean site specific exposure and concentrated on species related aspects. However, neglecting to assess environmentally based physical conditions such as ocean currents, wave climate and water depths and structure related properties and performance can easily end in uneconomic scenarios. In contrast, no biological characteristics have been included in the development of the indices presented in this work. Species connected cultivation optima have been considered to be secondary in this study and subject to a different work in the special issue (Heasman et al., 2024). These exposure indices primarily relate the to the cultivation structures that must be planned, constructed and maintained in challenging conditions. However, it is quite possible that the suitability of various aquaculture species for certain sites may be similarly quantified using the proposed exposure indices.

The indices presented are based on physical abiotic parameters alone. Consequently, they do not cover water temperature, nutrients, or turbidity. Such parameters are of interest to aquafarming in that they confine the range of species which can potentially be cultivated at a given site. Nevertheless, this can be overcome by adding additional index metrics for those aspects of mariculture and does not preclude the identification of beneficial cultivation sites. Another parameter not covered by the indices

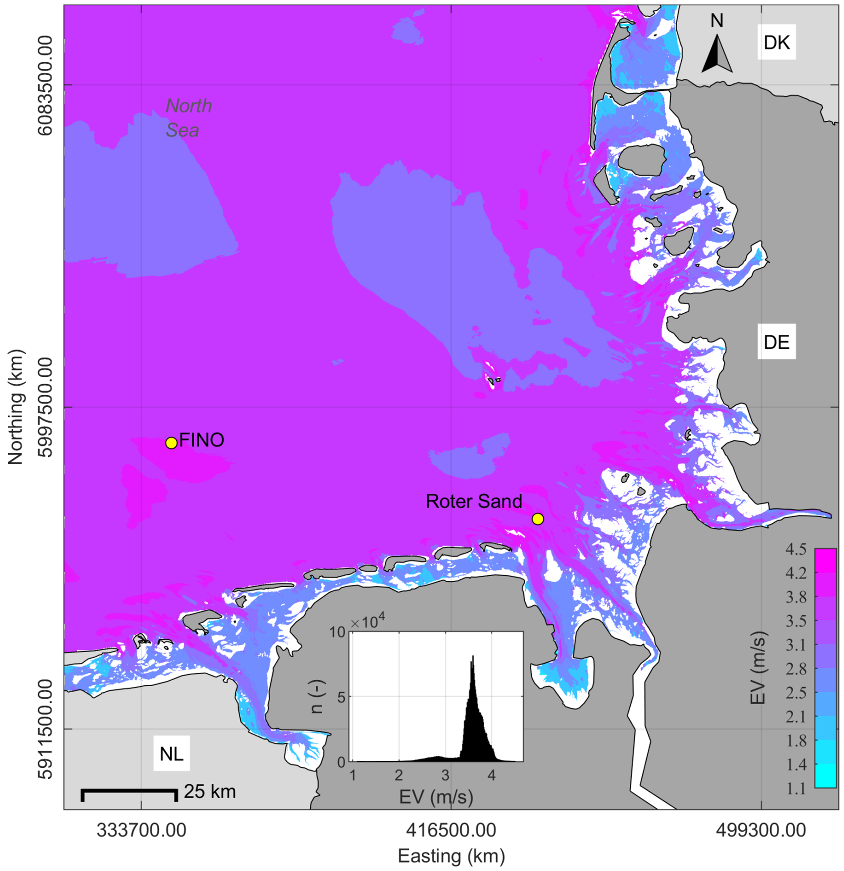

FIGURE 5
Exposure Velocity (EV) for 50-year surface currents.

presented constitutes wind speed, which might be an important aspect for certain types of open ocean structures depending on their profile above the water line. In addition, wind speed, like waves and currents, will certainly affect harvesting operations and could therefore be also included in a broader framework for mariculture site assessment in future works.

Future developments of further indices or the refinement of other approaches can therefore easily be integrated into the classification approach presented in Section 2.1 This will allow for future aquaculture sites to be easily assessed with multiple perspectives in mind. For example, an integration or addition of species-specific ocean condition requirements could be added. Another extension could entail an investment perspective, depending on the structure in question e.g., floating or anchored, near or far from land, and further enhance the classification.

4.2 Observations from mapping indices on the global and regional scales

Among 29 sites, high energy conditions resulted in high index values for sites fully exposed to the North Atlantic (cf. Figure 2E sites 16 & 22), the Gulf of Mexico (cf. Figure 2E sites 7 & 8), and the Arctic Ocean (cf. Figure 2C site 27) for the data provided for a return period of 50 years. In the Gulf of Mexico, the annual occurrence of Hurricanes within this region is expected to constitute a major driver for these values (Zuzak et al., 2021). Similarly, the Atlantic coast of Ireland is frequently impacted by extratropical cyclones following an eastward trajectory across the North Atlantic in the winter season (European Commission. Joint Research Centre, 2020). All other sites fall below these hotspots regarding exposure index values.

Figure 5 through Figure 16 show that certain *sites can simultaneously be close to land and highly exposed*. With the exception of the depth-integrated indices, the proposed indices show that in the German Bight, the regional focus we chose for this work, high exposure values are found on the seaward sides of the barrier islands, where large waves enter shallow water, producing very large oscillating fluid particle velocities and resulting drag forces, and near constrictions that amplify current velocities. In contrast, many of the indices show a markedly sheltered region East of the island Heligoland which is less exposed by larger waves.

4.3 Comparison of proposed indices

The EV and EVRD have the beneficial quality of being straightforward and easily comprehensible, with well-understood units (velocity). They, along with the SEE and SDBR, capture the large fluid velocities that can occur even in shallow, nearshore sites.

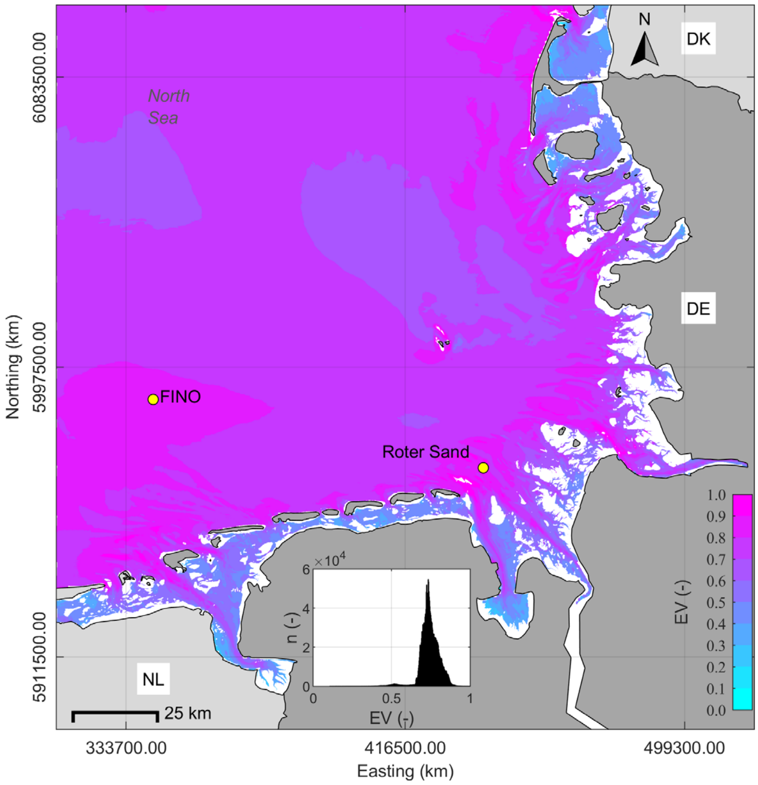

FIGURE 6
Normalized Exposure Velocity (EV) for 50-year surface currents.

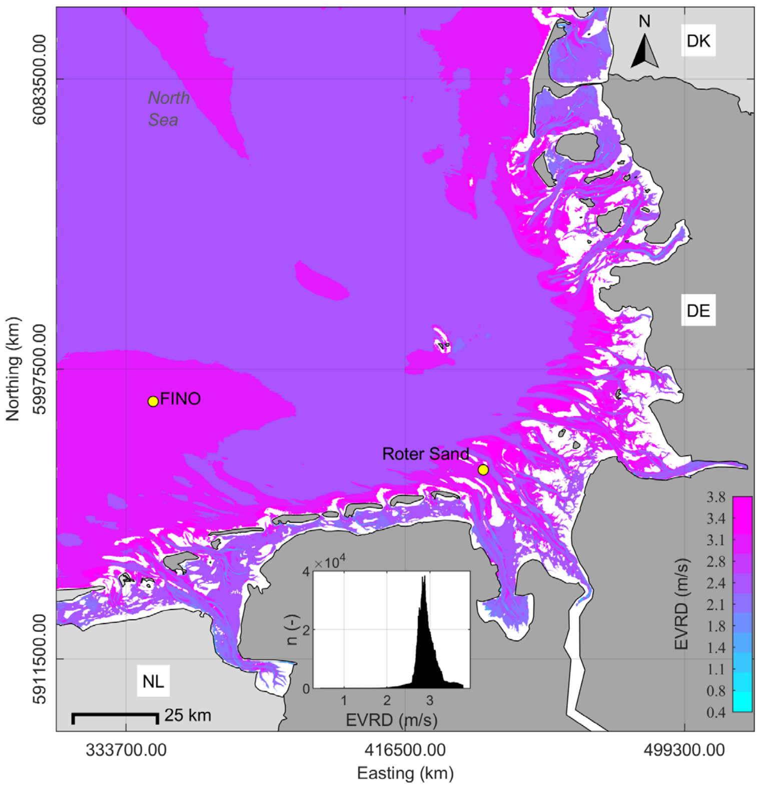

FIGURE 7
Exposure Velocity at Reference Depth (EVRD) at 5 m below the surface for 50-year surface currents.

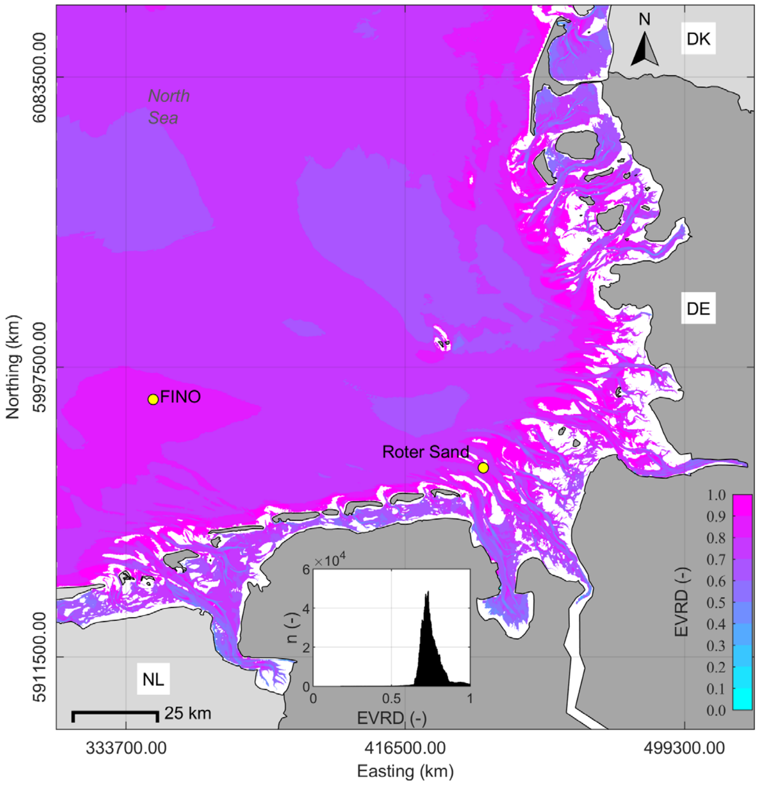

FIGURE 8
Normalized Exposure Velocity at Reference Depth (EVRD) at 5 m below the surface for 50-year surface currents.

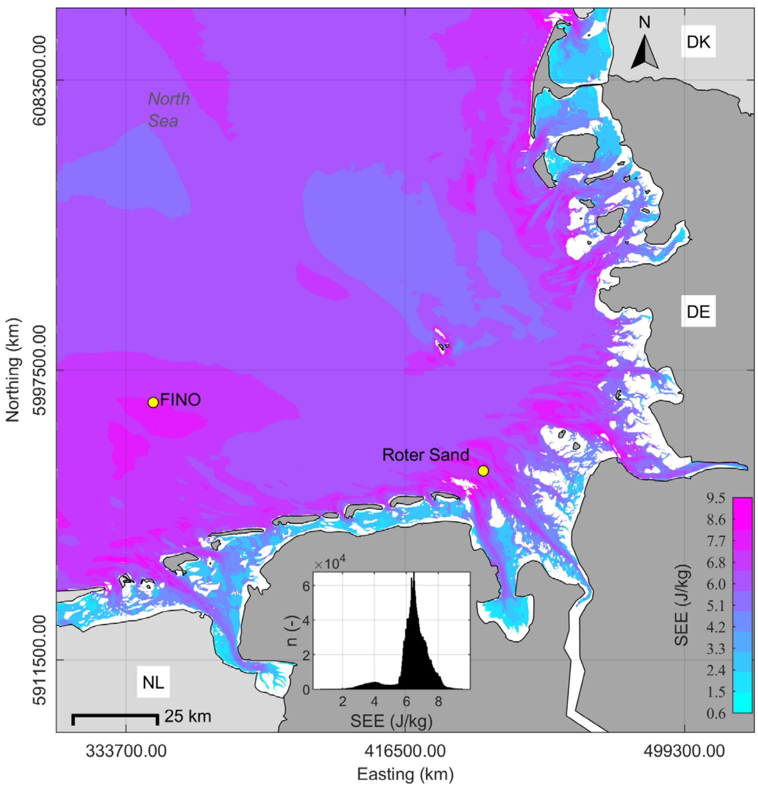

FIGURE 9
Specific Exposure Energy (SEE) for 50-year surface currents and wave induced velocities.

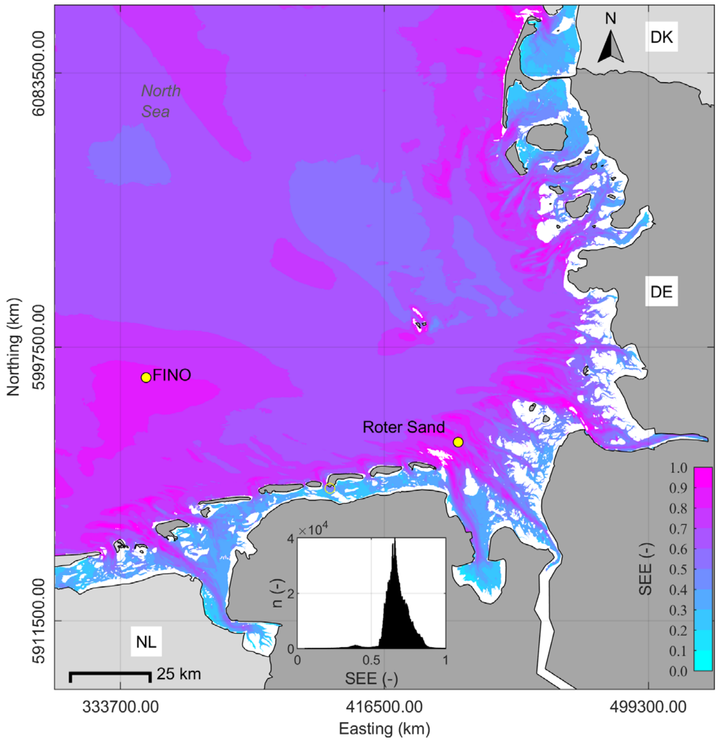

FIGURE 10
Normalized Specific Exposure Energy (SEE) for 50-year surface currents and wave induced velocities.

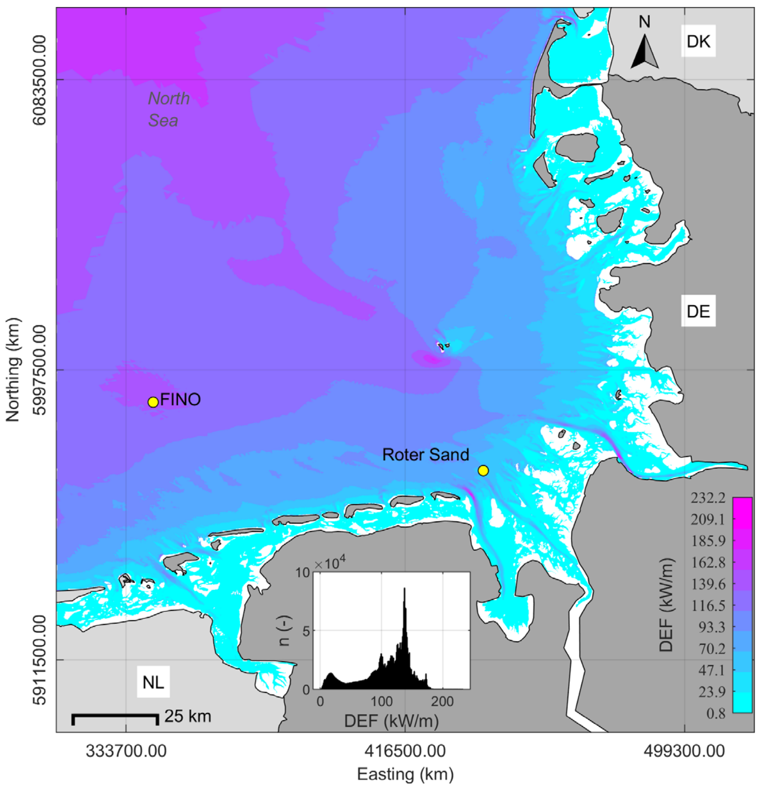

FIGURE 11
Depth-integrated Energy Flux (DEF) evaluated with 50-year depth averaged currents and with the deep water wave energy flux for 50-year sea states.

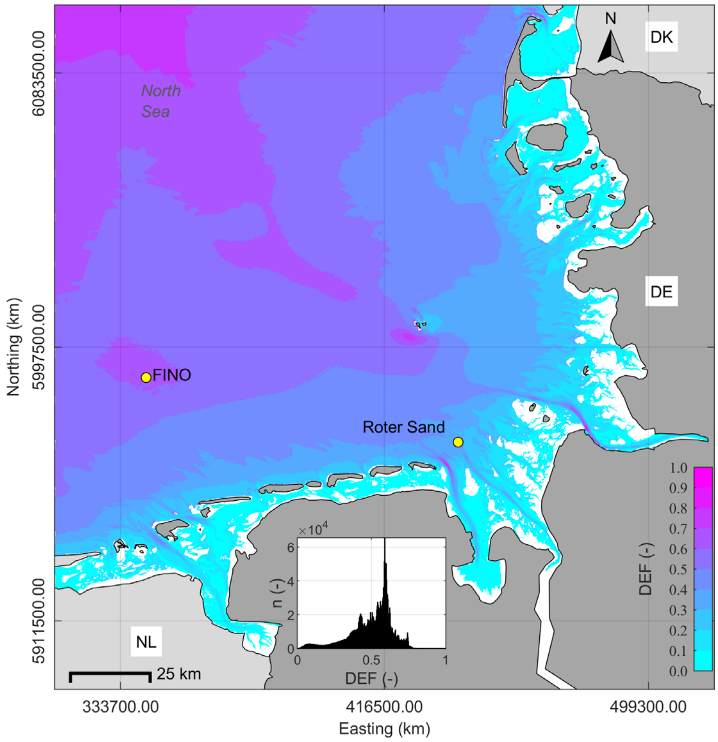

FIGURE 12
Normalized depth-integrated Energy Flux (DEF) evaluated with 50-year depth averaged currents and with the deep water wave energy flux for 50-year sea states.

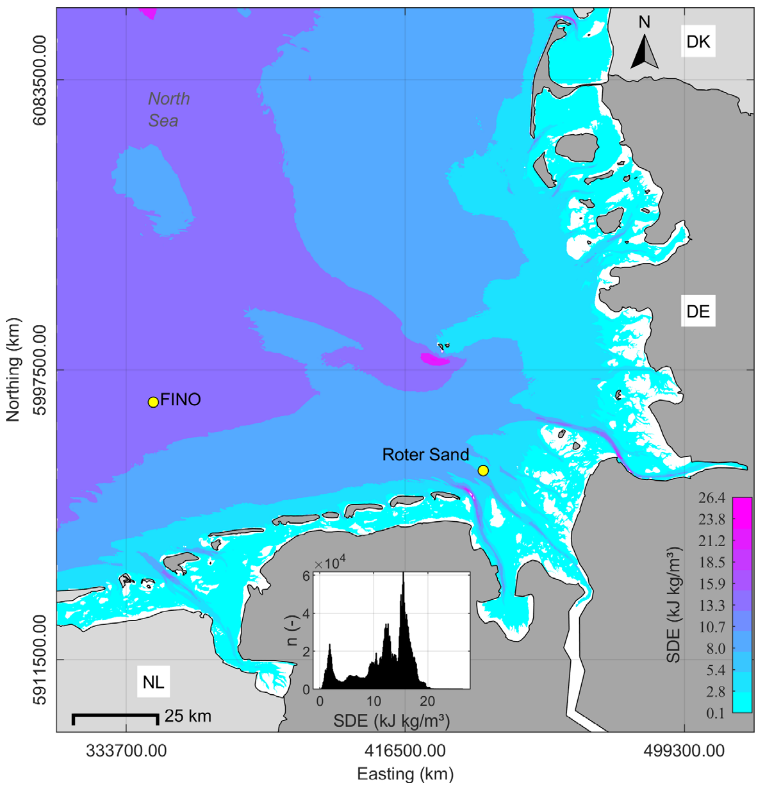

FIGURE 13
Structure-centered Depth-integrated Energy (SDE) associated with the 50-year significant wave heights and depth averaged currents, with constant density 1025 kg/m3, structure solidity of 0.3 and surface area $\pi/4$.

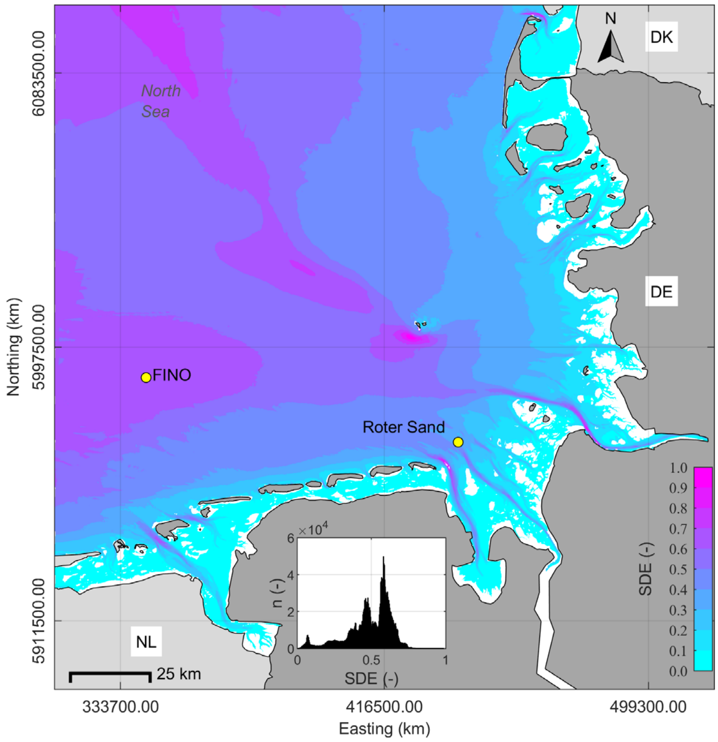

FIGURE 14
Normalized Structure-centered Depth-integrated Energy (SDE) associated with the 50-year significant wave heights and depth averaged currents, with constant density 1025 kg/m3, structure solidity of 0.3 and surface area $\pi/4$.

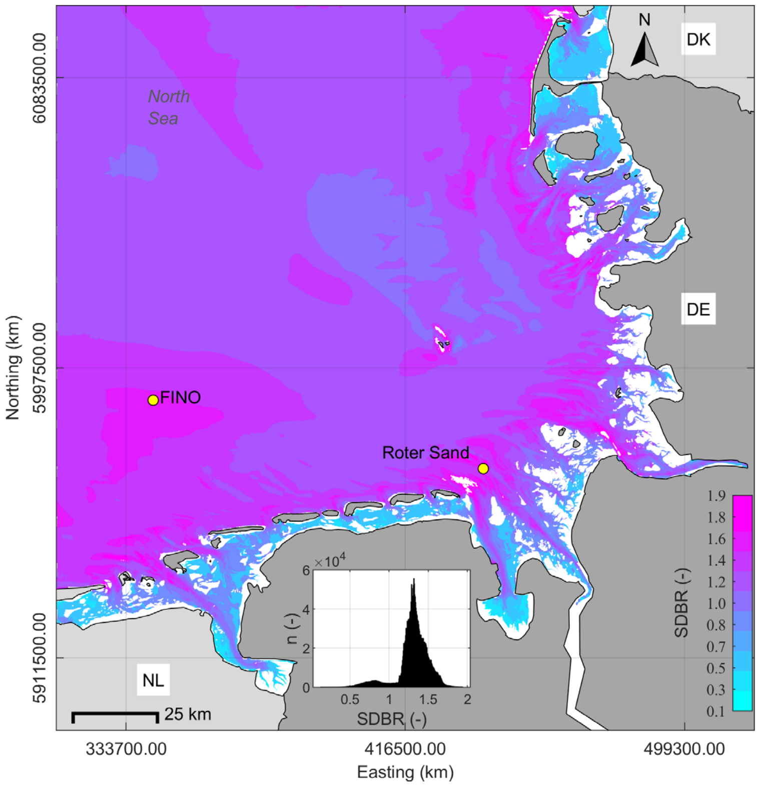

FIGURE 15
Structure-centered Drag-to-Buoyancy Ratio (SDBR) evaluated with 50-year surface u_w and Uc and D = 1 m is non-dimensional and proportional to the SEE.

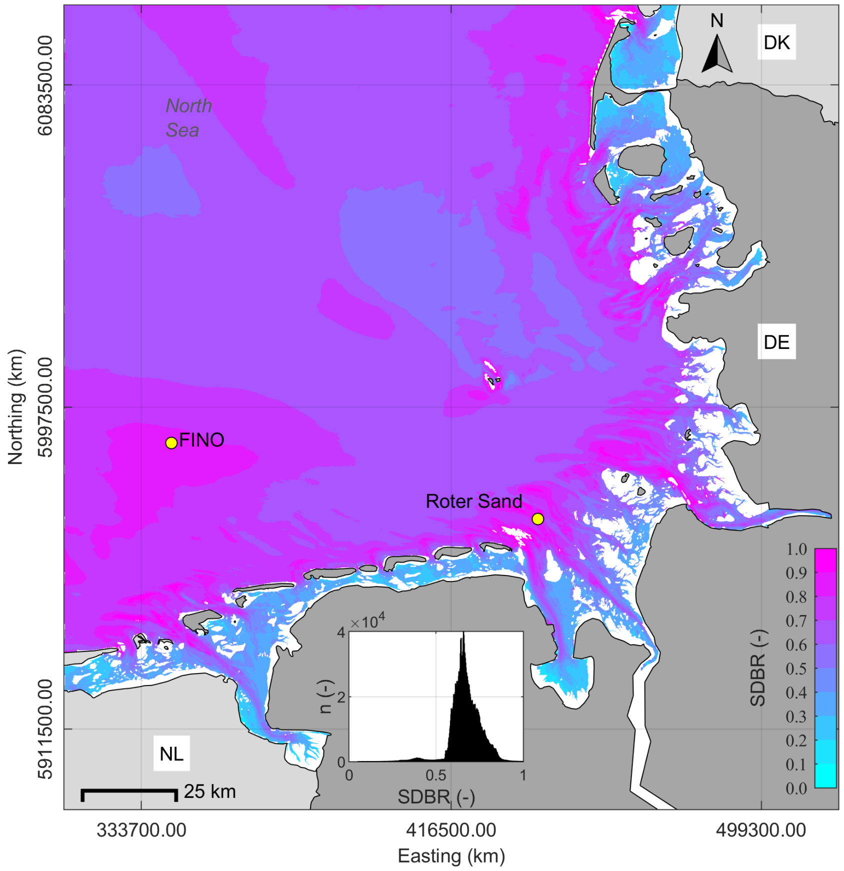

FIGURE 16
Structure-centered Drag-to-Buoyancy Ratio (SDBR) evaluated with 50-year surface uw and Uc and D = 1 m is non-dimensional and proportional to the SEE.

The SEE has the additional qualities of being proportional to both kinetic energy and fluid drag, while it has physically meaningful units (kinetic energy per mass of water, J/kg in SI). Figure 9 shows that this index (as with the SDBR) provides a large range of differentiation between index values for sheltered and exposed sites even in close proximity (e.g., on either side of a barrier island).

The depth-integrated, energy-based indices (DEF and SDE) are convenient in that they do not require the calculation of wave kinematics described in Section 2.1.1 and show that these indices increase significantly with deep water generally found far from shore, these values may not be closely tied to the magnitude of forces on floating structures.

Like the SEE, the SDBR has qualities of being proportional to both kinetic energy and fluid drag. It has the additional quality of being non-dimensional. Since this is accomplished by incorporating a characteristic length for the structure, this index depends on knowledge or assumptions about the selected gear type.

The six indices appear to provide quick and plausible site characterizations. However, no single index has been determined to outperform the others. They appear to be complementary, each with strengths and weaknesses. The authors herein present the indices to the aquaculture and ocean engineering communities for discussion, application, potential adoption of one or more of the proposed indices. Table 3 summarizes key aspects of the EI formulations, using criteria such as the applicability with respect to the dimensionless water depth, the complexity (for layperson), strength and weaknesses of the EI formulation.

This work has, through intense discussions within the author collective, decided to select two of the six indices to continue to work with; the selection has been made based on some of the arguments pondered on in the discussion section, summarized in Table 3. Heasman et al. (2024) will continue to work with the two selected indices EVRD and SEE.

5 Conclusion

Bearing in mind the basic goals laid out at the end of Section 1, a broad and objective formulation of hydrodynamic exposure has been accomplished and exposure indices been introduced. Through the application of the exposure indices to known aquaculture sites around the globe, their respective performance has been assessed across six indices. The sensitivity towards return periods of ocean conditions has been investigated and discussed in Section 3.2 Furthermore, the indices have been applied on a basin wide synoptic scale, showcasing their performance for the rough North Sea (cf. Section 3.3). The advantages and caveats of the indices introduced were laid out and discussed. In addition, the developed approach has been compared to other indices found in literature (cf.

TABLE 3 Overview over specific aspects of the six presented EI, using common criteria.

	EV	EVRD	SEE	DEF	SDE	SDBR
Applicability for d/L	all water depth	all water depth	all water depth	> 0.5, only deep water	all water depth	all water depth
Complexity	low	low	low	high	low	low
Strength of index formulation	easy application	easy application	Strength in physics-based formulation	Inclusion of potential energy	formulation gives units of energy	Normalization straight-forward
Selected limitations of index formulation	Dominant focus on velocity alone	See EV	-/-	-/-	considers entire water depth, while gear could be only close to surface	Composed of Dimensionless numbers, potentially difficult to grasp

Section 4). Rigorous calculation and mapping of 50-year extreme storm conditions for the German Bight, with results entered as inputs to the exposure indices, showed that sites can simultaneously be close to shore and highly exposed. This demonstrates the need to separate the term "offshore" into two separate metrics: exposure and distance from land. With the proposed indices, it is now possible to objectively quantify exposure on a continuum according to the severity of ocean conditions. The approach presented by this study is limited only by the availability of data for a respective site. Thus, the indices presented are globally applicable for characterizing potential mariculture sites. The novelty of this study compared to other classification studies for mariculture sites pertains to the assessment of physical ocean exposure characteristics, which are generally omitted by other assessment metrics. This may result in non-economic designs. The six EI proposed in this study solely focus on abiotic aspects for characterizing mariculture sites. However, species related biotic factors, such as water temperature can be easily added and are the focus future work. Another important aspect that has not been included in the EI proposed here constitutes wind speed, which drives wave mechanics and is also a focus for future work. Furthermore, the EI presented here clearly show, that unsheltered sites closer to major storm pathways like the Gulf of Mexico, the North Atlantic or Arctic Ocean exhibit higher values. Simultaneously, shallower and more sheltered areas behind barrier islands or within bays exhibit more favorable oceanic exposure conditions.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Non-public data will be made available upon reasonable request. Requests to access these datasets should be directed to Nils Goseberg, n.goseberg@tu-braunschweig.de.

Author contributions

OL: Data curation, Formal analysis, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. NG: Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. HF: Conceptualization, Data curation, Methodology, Writing – review & editing. TD: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Writing – review & editing. TB: Data curation, Software, Visualization, Writing – review & editing. KH: Conceptualization, Methodology, Validation, Writing – review & editing. BB: Conceptualization, Methodology, Writing – review & editing. DF: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. SR: Data curation, Formal analysis, Software, Visualization, Writing – review & editing.

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Conflict of interest

Authors TD and SR were employed by the company Kelson Marine Co.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Variations of aquaculture structures, operations, and maintenance with increasing ocean energy

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Aquaculture in exposed and/or distant ocean sites is an emerging industry and field of study that addresses the need to improve food security along with the challenges posed by expansion of urban and coastal stakeholders into nearshore and sheltered marine waters. This move necessitates innovative solutions for this industry to thrive in high-energy environments. Some innovative research has increased understanding of the physics, hydrodynamics, and structural requirements enabling the development of appropriate systems. The blue mussel (*Mytilus edulis*), the New Zealand green shell or green lipped mussel (*Perna canaliculus*), and the Pacific Oyster (Magallana gigas), are the primary targets for commercial exposed bivalve aquaculture. Researchers and industry members are actively advancing existing structures and developing new structures and methodologies for these and alternative high-value species suitable for such conditions. For macroalgae (seaweed) cultivation, such as sugar kelp (*Saccharina latissimi*), oar weed (*Laminaria digitata*), or kelp sp. (*Ecklonia* sp.), longline systems are commonly used, but further development is needed to withstand fully exposed environments and improve productivity and efficiency. In marine finfish aquaculture, three primary design categories for open ocean net pens are identified: flexible gravity pens, rigid megastructures, closed pens, and submersible pens. As aquaculture ventures into more demanding environments, a concerted focus on operational efficiency is imperative. This publication considers the commercial and research progress relating to the requirements of aquaculture's expansion into exposed seas, with a particular focus on the cultivation of bivalves, macroalgae, and marine finfish cultivation technologies and structural developments.

KEYWORDS
aquaculture structures, marine bivalves, macroalgae, seaweed, exposed ocean, marine finfish

1 Introduction

Urban expansion into agricultural land has begun to impact food supply (Güneralp et al., 2020) and portends a similar trend in aquaculture due to increased anthropogenic activity in coastal areas. Currently, aquaculture sites are concentrated in sheltered bays and regions with low exposure to wind, currents and waves (Milewski, 2001; Buck et al., 2024a). However, ocean space near population centres is increasingly occupied by other industries and stakeholders resulting in reduced potential aquaculture carrying capacity through physical, ecological, and social limitations (Inglis et al., 2000; Buck et al., 2004; Gibbs, 2009; Smaal and van Duren, 2019; Wijsman et al., 2019; Galparsoro et al., 2020; Mascorda Cabre et al., 2021). In addition, extractive aquaculture, such as production of bivalves and macroalgae, require larger production scales than fed aquaculture to be viable (Harvey et al., 2024) necessitating more water space in a diminishing area. Extending aquaculture from sheltered sites into more exposed and/or distant sites increases the energy, through larger waves and stronger water currents, impacting structural design, material choices, species selection, and commercial viability (Heasman et al., 2024; Lojek et al., 2024; Dewhurst et al., in review; Lien and Fredheim, 2001; Stevens et al., 2008; Morro et al., 2022). Advancement into exposed and/or offshore areas will require increasing robustness of equipment, improved installation protocols, reviewed health and safety protocols, and robust infrastructure maintenance protocols (Chambers et al., 2003, 2007).

Terms, such as "offshore aquaculture", "open ocean aquaculture" or "exposed aquaculture", are frequently used, although there is no differentiation between these terms or descriptive definitions currently. As a result, they are used entirely interchangeably and there is no clear categorisation. The definition of "exposed", "offshore", and "open ocean" aquaculture has been discussed in Buck et al., (2024a) as well as in Lojek et al., 2024, who discusses the various parameters, which impact farming at these sites (Figure 1). In the following, we will use the term "exposed", as this article is focused on the extension into exposed conditions and about the adaptation of aquaculture farms to harsh weather conditions, irrespective of distance from the shore.

This publication considers the current trends of bivalve, macroalgae and marine finfish commercial systems found in sheltered waters and investigates the requirements enabling the advancement of these aquaculture species group into the exposed waters. Marine shrimp cultivation is not discussed in this article despite being an important aquaculture species, as there has been limited successful activity in exposed environments.

2 Information sources

Peer-reviewed articles from relevant journals and publications from grey literature (reports, expert opinions, other articles, etc.) were used to research data. The authors also had access to a very broad, global network of scientists working in the field of exposed aquaculture. In addition, data collection was supported by collaboration between international research projects/working groups, (ICES[1] WGOOA[2], ICES WGSEDA[3], ARPA e[4], etc.).

3 Species and technology: a comparison of the requirements between sheltered and exposed sites

Certain traditional aquaculture production methods and technologies that have been used in sheltered water for decades may be mentioned here but not discussed in detail if they are not pertinent to the advancement into an exposed farming environment. Structures that have developed more recently and that have been considered and tested in exposed areas are the focus of this manuscript.

Many technologies that withstand the extreme conditions on the high seas, i.e. exposed and/or offshore, are at an early stage of development (Kimmel et al., 2020), and often have a research project background or are still in a conceptual and drafting stage. However, there are some systems that are semi-commercial, which provide insights into requirements for expanding into more exposed regions.

Advancing from sheltered into exposed ocean environments demands a number of adaptations due to the increased energy that the structures, vessels, and species will endure. The change required is to avoid the energy forces or increase the ability of the structures, and relevant supporting infrastructure, to withstand damaging energy. To avoid energy, the structures can be partially or fully submerged (Bourque and Myrand, 2014; Idhalla et al., 2017). However, infrastructure being submerged often results in complex or more demanding methods of operation, such as methods to bring the structure close enough to the surface to be operated. Submerging aquaculture farming systems usually involves changing the buoyancy, with robust mooring also being required. It is technically complex to keep the system in the water column such that (1) it is permanently held in the desired position below the water surface, (2) it does not descend too deep and, in the worst-case scenario, sinks to the seabed, where it could collapse and result in the loss of the crop and 3) the submergence process can be reversed, usually by controlling buoyancy again which is challenging and can require extensive maintenance. Measured control is required, for example, if the system is raised too quickly, swim bladders of physoclistous fish (i.e. Cod – *Gadus* sp.) will inflate with decreased depth pressure, resulting in mortality of fish. In

1 International Council for the Exploration of the sea

2 ICES Working Group Open Ocean Aquaculture

3 ICEA Working Group on Social and Economic Dimensions of Aquaculture

4 Advanced Research Projects Agency – Energy, U.S. Department of Energy

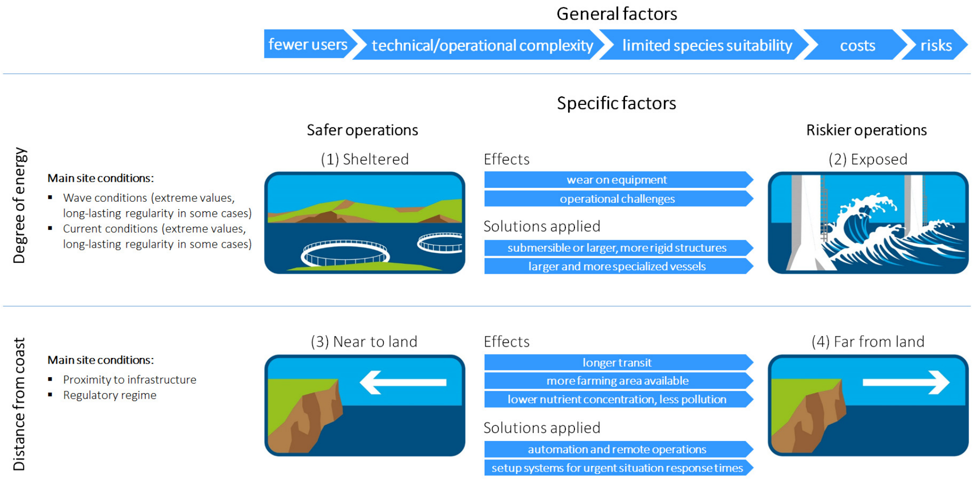

FIGURE 1
Comparison of "Safer operations" vs. "Riskier operations" (top) as well as "Degree of energy" vs. "Distance from coast" (left) environments along with a selected collection of general and specific descriptions of each. Modified after Buck et al. (2024b).

addition, the increased biomass of the species (particularly bivalves and macroalgae) and fouling will change the hydrodynamic and physical characteristics of the structure, making design challenging.

Taking a structure that has been successful in the inshore and sheltered regions, enlarging ropes and floats, and placing it into an exposed site (i.e. evolving the gear) can be a successful strategy in some instances but has its limitations. We refer to this type of modification of existing system design, which only undergoes a slight change in size and weight, as an evolutionary adaptation. The structure may survive but the organisms being cultured will not be able to endure the response of the structure to the extra energy found at the exposed site resulting in stressed, damaged, detached crop, or mortality. A revolutionary approach requires unique solutions and new strategies (such as efficient submerging equipment) or innovative, novel equipment, probably with materials not commonly used before under marine environmental conditions. Linear systems and marine finfish pens lend themselves well to modification or revolutionary (as opposed to evolutionary) adaptation to higher energy while maintaining their production efficiency.

3.1 Bivalves

Globally, there are a number of molluscan bivalve species including scallops, clams and oyster species cultivated in sheltered environments (Wijsman et al., 2019) and nine prominent cultivated species of mussels (Kamermans and Capelle, 2019). Although Asia produces the majority of the world's bivalves through aquaculture (Wijsman et al., 2019), there do not appear to be sites with published information in truly exposed areas in Asia. Currently, commercial exposed ocean bivalve aquaculture operations worldwide appear to primarily rely on three species. In the Northern Hemisphere, *Mytilus edulis*, commonly known as the blue mussel, as well as *Mytilus galloprovincialis*, known as Mediterranean mussel, are cultivated, with sites situated in the USA, England (Gagnon, 2024), and Germany (Heasman et al., 2024; Buck et al., 2024b). Conversely, in the Southern Hemisphere, culture of *Perna canaliculus*, or the New Zealand green shell mussel, is the primary focus (Newell et al., 2021) although Chile is an important producer of Chilian mussels (*Mytilus chilensis*) in semi exposed sites (Gonzalez-Poblete et al., 2018). Mussels are well suited to cultivation in exposed situations as their primary habitat is generally high energy, and they are capable of reattaching or reinforcing their attachment to artificial substrates. Mussels, however, yield a low profit margin and are therefore required to be produced in high volumes with high efficiency.

Mussels (e.g., *Perna* sp. *Mytilus* sp. etc), oysters (e.g., *Crassostrea* sp. *Magallana* sp.), clams (e.g., Quahog, *Mercenaria mercenaria*, Manila clam, *Venerupis* sp., little neck clam, *Protothaca* sp. etc.), and scallops (e.g. *Aequipecten* sp., *Argopecten* sp., *Chlamys* sp., *Pecten* sp., etc.) are good candidates for exposed ocean production, however, there is limited exposed ocean cultivation activity with all four of these shellfish. Therefore, discussion will be limited to inshore and experimental exposed ocean systems.

3.1.1 Trends of current commercial bivalve aquaculture in sheltered systems

The most productive systems for the cultivation of bivalves in sheltered areas range from bouchots, rafts, seabed cultivation and linear systems, such as the New Zealand long line (Kamermans and Capelle, 2019; Strand et al., 2022). Some of these systems (e.g. bouchots) are traditional, going back to the 13th century and continue today (primarily in France), with improving seeding and harvesting technology. On-bottom culture is also traditional but with variations, such as warehousing (grow-out and storing blue mussels on the seabed) until market size is reached, as is conducted in the Netherlands and Germany. Spat collection can be done in the water column via a single-backbone-longline or -longtube systems and the following conditioning (fattening) of adults through on-bottom cultivation, as is done in Germany. Bottom culture represents approximately 15% of overall production, with the remainder being produced on suspended structures (Mckindsey et al., 2011). Mussel rafts are primarily used for production in Spain (Wijsman et al., 2019). Bouchots, on-bottom cultivation (except for the German variant), and rafts have not varied much in recent years, with most of the modifications relating to carrying capacity, seed production/collection, and efficient use.

The use of linear systems, particularly in bivalves, appears to be directly related to the efficiencies these systems offer associated with space utilisation, and ease of use for seeding and harvesting (Goseberg et al., 2017; Newell et al., 2021) as can be seen with linear systems such as the longline, Smart Farm[5] (Lien and Fredheim, 2001), and Flipfarm[6].

3.1.1.1 The New Zealand longline system – green-lipped mussels

In comparison to the European longline version, the sheltered New Zealand mussel longline systems have a double backbone (header rope) with floats (approximately 300 litres in size) spaced evenly along the length of the backbone (Figure 2A) (Newell et al., 2021). The typical backbone may be synthetic rope (polyethylene/polypropylene), 29mm to 32mm in diameter and 100m in length (range 70 to 180m). Currently there are 3,000 to 4,000m of continuous dropper lines (cultivation rope) and produce up to 32,000kg of mussels per cycle (between 4 and 9 kg/m). Water depth ranges from 15 to 35m and mooring normally has a 1:3 depth to mooring length ratio. Floatation is added as required during the growth cycle to accommodate increased crop and biofouling biomass. The structures are generally run parallel with the shoreline to maximise space usage (which is not always conducive to the cultivated species) and are normally spaced from 10 to 15 m apart (Goseberg et al., 2017; Newell et al., 2021). Most New Zealand longline systems utilise both wild caught spat and hatchery spat. A single company has a large hatchery which subsidises their wild caught spat. Other companies are following this trend with new hatcheries in construction.

3.1.1.2 The Smart Farm™ - blue mussels

The Smart Farm (Figure 3A) has made two primary advancements from a standard mussel cultivation system with many individual surface floats: the utilisation of a continuous inflatable float in the form of a High Density Polyethylene (HDPE)-tube, about 310mm in diameter and usually 100m long, from which a culture net is suspended with weights at its lowest edge. The structure parameters and floatation vary according to the energy environment. The second is the husbandry and harvesting is carried out in the water with bespoke brushing equipment which is mounted on the vessel. All activity is machine driven improving staff safety. Vessel size can vary according to the volume of the operation and the environment. At this time, Smart Farm utilises only wild caught spat.

3.1.1.3 Flipfarm™ (New Zealand - Pacific Oysters - *Magallana gigas*)

The Flipfarm (Figure 3B) is a semi-autonomous linear system for growing oysters in sheltered waters. It is a floating linear system with oyster baskets at the surface. The baskets are spaced evenly and perpendicular to the central spar around which the basket can rotate. Each basket provides its own flotation. Periodically a small vessel (8 to 15m) with bespoke equipment runs alongside, and parallel, to the baskets flipping them over and exposing fouling to the air and redistributing the oysters within the basket. After a short period of exposure, the baskets can be flipped back to submerge the oysters. Baskets can also be brought into a servicing zone on the vessel in a semi-autonomous, continuous basis at which time each basket can be stocked or harvested. Staff effort is reduced, and safety increased in handling the oysters with this system. The Flipfarm is reliant on hatchery produced oyster spat as it requires unattached individuals.

3.1.1.4 Vessels

Current vessels utilised for inshore green shell and blue mussel longlines are 15 to 45m long, up to 6m in width and generally flat bottomed. The flat bottom reduces the influence of water currents on the hull, but it makes handling more difficult. It is more likely to turn to the wind due to the windage of the surface structure and no or limited keel. The smaller vessels are used for sampling crop for harvestability and minor maintenance. A minimum of two individuals operate the vessel for efficiency and safety reasons. The larger vessels can accommodate 6 staff and undertake any maintenance, seeding or harvesting required by the operation. The deck is configured to optimise processing space and storage space for spat/seed/product. Vessels used for on-bottom culture are between 34 and 46m long and can be up to 10m wide. Smartfarm support vessels, compared to the other vessels, have a very large loading capacity to be able to transport mussels between cultivation areas or from the nets of the Smartfarms. A self-stabilising system with movable steel piles is used in the case of the Smartfarm when installation work is carried out on the tube, or support piles are driven into the ground on both sides to attach the tube. If the mussels are returned to the cultivation areas for further grow-out to market-size, an internal flushing system is used. It flushes the mussels out of the vessel storage holds, allowing them to fall to the seabed and anchor themselves.

3.1.2 Trends enabling advancement of molluscan bivalves into exposed sites of current commercial aquaculture systems

Bivalve linear systems lend themselves well to modification or revolutionary (as opposed to evolutionary) adaptations, and they can be adapted to higher energy environments while maintaining their production efficiency. To successfully extend a linear system into exposed conditions it has to avoid the higher wave energy

5 www.Smartfarm.no

6 www.flipfarm.com

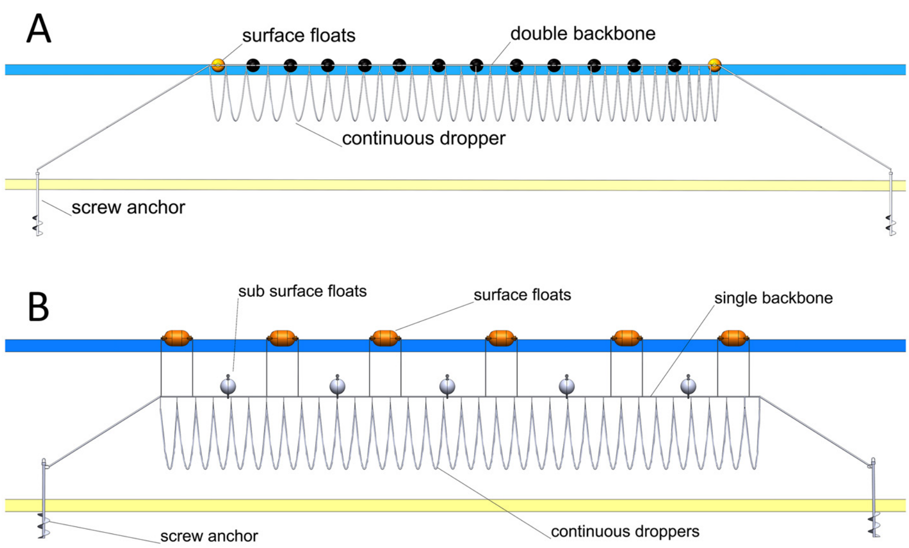

FIGURE 2
(A) Schematic of a general design of a mussel longline system in sheltered areas. The backbone has dropper lines hanging down perpendicularly being held at the water surface by buoys. This is normally configured as a "double backbone" which equates to two header ropes running parallel with floats in between. **(B)** Schematic of a general design of a mussel longline system for exposed sites. The backbone with the dropper lines is submerged and flotation at the surface is reduced. This is normally configured in a single backbone which is a single header rope from which floats are attached.

found at the exposed site by either reducing its surface buoyancy or be fully submerged while still supporting the crop. This is achieved through reducing buoyancy (e.g. float size and shape), transferring energy to the main cultivation structure i.e. reducing the number of floats on the surface, reducing the number of header ropes, or completely submerging the structure (Figure 2B). The most effective transition of a linear system that is in commercial use in exposed regions can be found in New Zealand, Europe, and the USA (Newell et al., 2021). The most successful exposed aquaculture sites are in deeper water reducing the influence of the interaction of large waves with the seabed, where energy increases inversely-proportionately to depth (Heasman et al., 2024).

Moorings are varied and generally have to offer greater purchase or mass to maintain their position in higher energy situations. Drag embedment anchors (e.g. Danforth anchors) can be used, however there are generally more than one per mooring line. Concrete blocks (both flat bottomed or shaped bottomed for suction) are used, however they are generally required to be very large and heavy which becomes very cumbersome and expensive to handle and deploy. In sandy or muddy sea beds, heavy but flat shaped anchor stones make it much safer as a mooring as the increased surface area at the seabed "sucks" itself into the sediment. Screw anchors (also known as helix anchors) are becoming more prominent (Newell et al., 2021) as they do not drag, can be positioned accurately, and many can be held on an installation vessel deck at one time and installed in one day. Their use and reliability are dependent on the substrate into which they are being drilled. They can be shaftless or have a shaft with attachment points at the top or on the side of the shaft. Attachment from the screw anchor to the structure may have a large link chain and then a rope or just a rope. Though, in comparison to the use of small anchor blocks, the deployment of screw anchors can be costly and depending on the mooring depth.

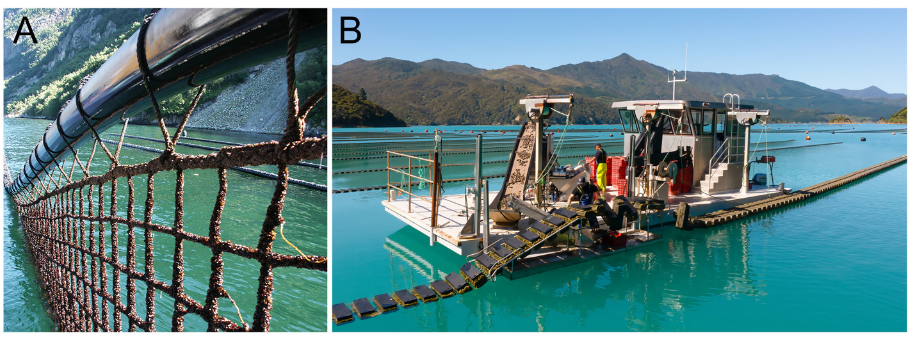

FIGURE 3
(A) The Smart Farm long tube with suspended culture net (copyright, Smartfarm). **(B)** The Flipfarm (copyright Flipfarm) oyster system showing the linear configuration of the baskets being rotated (flipped) on the barge.

However, as the anchor block increases in size the cost of the block and deployment may exceed that of screw anchors. Should the sites require decommissioning and complete recovery of moorings, then drag anchors and smaller concrete blocks will be the least problematic. Larger concrete blocks, or shaped blocks (which increase suction to the seabed) will be difficult to dislodge. Some blocks have eyes mounted at the edge of the mooring which can be utilised to break the suction with the seabed, but these can be difficult to access in deep water with limited diver access. Screw anchors, particularly the shaftless variety which are driven several meters deep into the substrate, will be difficult if not impossible to recover as they are metal they will erode over time.

3.1.3 Examples of exposed bivalve aquaculture farms

In New Zealand, the most exposed farms are in 30 to 70 m of water with a 50-year significant wave height anticipated to be 7.6m and a water current speed maxima of 0.6 m/sec. The main species grown is *Perna canaliculus*. The structures consists of up to 200m of growing header rope and the mooring legs (from header rope to mooring) are 3 times the depth. The moorings consist of screw anchors. In these systems the header rope has been reduced from 2 lines to 1 and most of the floatation is submerged to 9m (Figure 2B). More flotation is added as the crop grows. The header rope has enough slack in it to allow it to be brought to the surface, in an apex, by vessels. The equipment has been upgraded for strength with the header ropes being increased to 44mm with diameter and different floats being tested (shape, volume, attachment methods) to assist with the durability and maintenance of the structure. Each header rope has approximately 4000m of continuous longline on which the mussels are grown.

Service vessels are up to 40m long and can operate in swells of up to 1.5m which in normal years is approximately 72% of the year.

3.1.3.1 Submersible Long Tubes

Longtube systems, such as the Smart Farm, are usually installed at the water surface, but due to the HDPE-tube floats they can also be modified to be submerged (Figure 3A). It has a net on which to culture mussels (*Mytilus edulis*) as opposed to the continuous longline system. The nets have an advantage over dropper lines in that the mesh transfers wave energy across its surface and the nets act as a single unit. Dropper lines respond independently to energy transfer and will interact with each other resulting in the loss of crop and greater maintenance. A further development of the long tube is that the hollow buoyancy tube can be fitted internally with additional inflatable smaller tubes (Tayler et al., 2022). These smaller tubes can then be filled with air, depending on the position of the overall structure in the water column or on the water surface. In this further development, one end cap of the long tube is open so that water can flow into the spaces between the tubule bundles. The cap on the other tube-end is equipped with valves which supply the inner smaller tubes with inflating air when buoyancy is needed. This means that only the volume of the inflatable smaller tubes needs to be calculated when assessing the sinking or floating, which makes operation much easier. One smaller tube within the main tube is always filled with air (3 bar). This guarantees a minimum buoyancy so that the system will not sink to the seabed if it is lowered without appropriate inflation.

3.1.3.2 Shellfish tower

The shellfish tower (Heasman et al., 2021) (Figure 4) is a unique structure designed for complete submergence and the production of single seed bivalves (such as pacific oysters, *Magallana gigas*, and scallops, *Pecten novaezelandiae*). This structure shows all the attributes required for the extension of a structure into exposed waters. The shellfish tower consists of a stainless-steel hexagonal frame equipped with six hexagonal subunits which rotate freely (Figure 4). In the centre of the main frame, a mooring rope runs through a steel tube which is enclosed by the buoyancy device providing the shellfish tower with positive lift. It is fully submerged, avoiding surface wave energy. It has a single mooring which can be referred to as a tension leg, which allows the structure to be drawn off the vertical in strong currents where it can shed energy (Landmann et al., 2019). It is fully floated during initial deployment to allow for crop growth and fouling during the grow-out stage, reducing operational maintenance requirements. Further developments of this structure for the EEZ in the German North Sea can lead to the expansion of cultured species. This refers not only to similar candidates, such as the European oyster (*Ostrea edulis*), but also macroalgae, such as sea lettuce (*Ulva* sp.) and sugar kelp (*Saccharina latissima*). The modified shellfish/seaweed tower, which is deployed in 6-7m depth in the southern North Sea is a bit smaller in width (Figures 5A–E) compared to the New Zealand type to be handled easier by the available operation vessels. Additionally, some technical modifications are included concerning the cultivated species and the release system being fixed at the mooring rope below the shellfish tower (see 4.3.1).

3.2 Macroalgae (seaweed)

A number of macroalgae species are cultivated worldwide, which come from the three groups of green (Chlorophyta), red (Rhodophyta) and brown algae (Phaeophyta) (FAO, 2022). As is the case with other aquaculture species, the majority of macroalgae are cultivated in Asia, with the species such as *Laminaria japonica*, *Kappaphycus* spp., *Porphyra* spp., *Undaria pinnatifida* and *Eucheuma* spp. being particularly well represented. In the following, we will only focus on Sugar kelp (*Saccharina latissimi)* and Wakame (*Undaria pinnatifida*), as these macroalgae have been tested for cultivation in high-energy environments. The cultivation of macroalgae in the sea has a number of overlaps with mussel farming (see 3.1), as they are also cultivated on substrates, such as horizontal ropes. Production locations have historically been limited to sheltered bays and/or low-energy waters. One of the reasons for this is that most seaweed species cannot be submerged into deeper waters due to the light prerequisites required for photosynthesis. Submerging seaweed deeper in the water column affects the colours of light, the light intensity, and can reduce growth through shading (e.g. sediment load, strong attenuation) (Maltsev

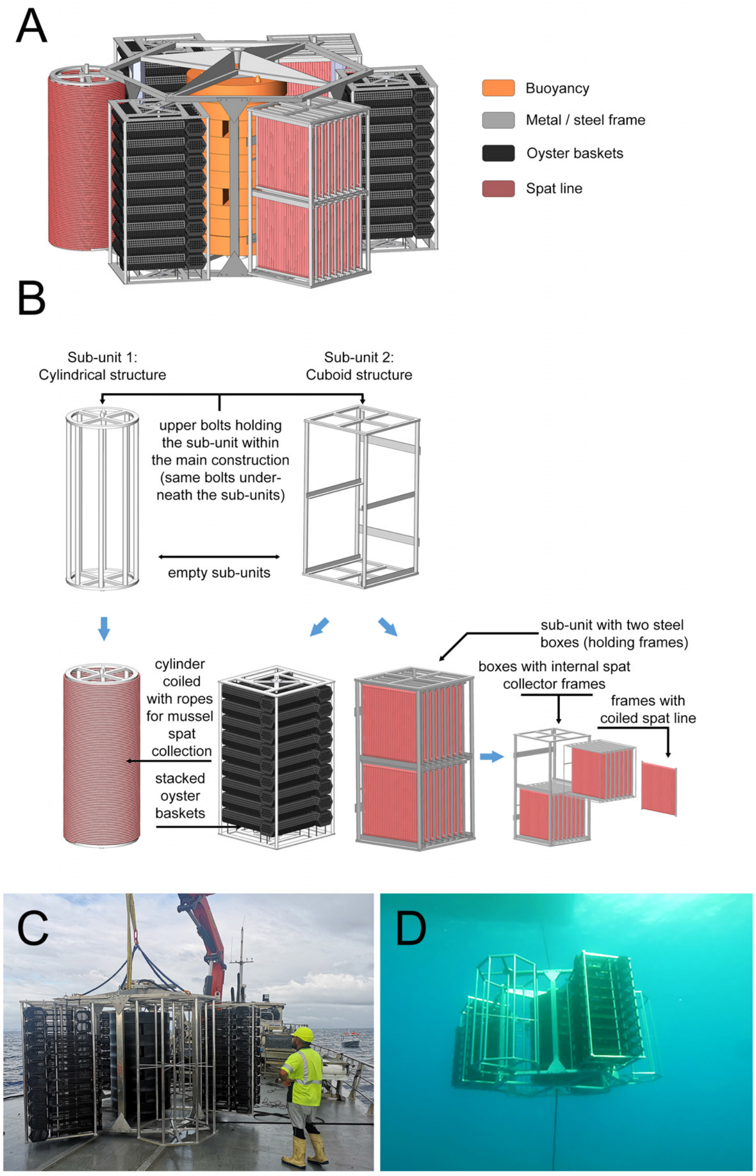

FIGURE 4
Illustrations of the shellfish tower design for the southern North Sea (modified after Heasman et al., 2021). **(A)** The tower showing variations of the subunits attached to it. **(B)** Variations of the subunit frames and their culture baskets/media. **(C)** The shellfish tower being deployed. **(D)** The shellfish tower in position 10m below the surface.

et al., 2021). There are exceptions for some macroalgae species, such as Macrocystis spp. that can be submerged down to 80 m below the surface (Tullberg et al., 2022). Nutrients can not only decrease with distance from the coast to the open sea, they can also be variable in the water column. There are regions that are nutrient-rich due to natural upwelling, such as the Humboldt Current (Peru), the Benguela Current (Namibia), the Canary Current off the coast of Galicia (Spain), etc (Kämpf and Chapman, 2016), but there are also areas, where the upper layers are nutrient-poor through limitation of a particular nutrient/element (Moore et al., 2013) or due to the blocked transport by a temperature-induced density gradient, with warm light waters residing on top of heavier cold waters (Ortiz Cortes, 2022). In contrast, nutrient availability in the lower layers of this water column may be higher than at the surface. In such areas, the idea of artificial upwelling as nature-based solution is often mentioned in order to bring nutrients to the water surface and thus bridge the shortage of nutrients and enable seaweed cultivation (Fan et al., 2019), e.g. via mounted or floating pumps (Fan et al., 2020) and/or offshore wind farms (Viúdez et al., 2016). A considerable amount of upwelled water is required (World Ocean Review, 2024[7]) to be of any use. Water also has to be upwelled efficiently in terms of energy usage and maintenance, e.g. solar and airlift systems (Zhang et al., 2024). On reaching the surface however, the colder upwelled water can also sink down from the surface as it is denser (Kemper et al., 2022), and therefore be effectively out of reach of the seaweed.

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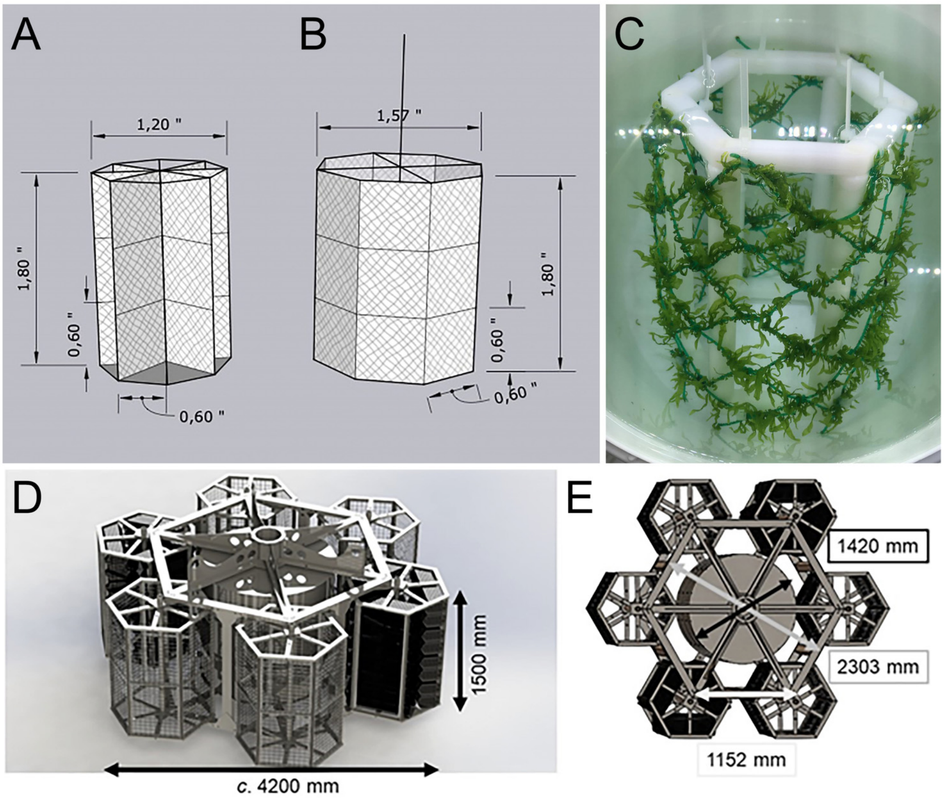

FIGURE 5
Modified "Seaweed-Tower". **(A)** The star design which increases the surface area for growing seaweed. **(B)** The cylinder system providing a plain surface area for growing seaweed. **(C)** The chequered design for growing seaweed as a Polyoxymethylene (POM) lab model. **(D, E)** Dimensions of the Seaweed-Tower from side and top view.

Alternatively, nutrients may be accessed through depth cycling, i.e. dropping seaweed into deeper nutrient rich waters periodically which results in morphological and biochemical variations to seaweed grown in the comparatively nutrient poorer surface waters (Navarrete et al., 2021). It is suggested that these variations may be targeted to improve the economic viability of seaweed culture in the future.

In contrast, there is concern that upwelled water may reduce surface temperatures and effect the carbon balance (Jürchott et al., 2023) which will influence the surface ecology, particularly with regard to carbon uptake, phytoplankton and zooplankton and the associated food pyramid. Therefore, uncertainty regarding the feasibility, effectiveness and potential risks and side effects associated with artificial upwelling still exists (Kemper et al., 2022). There are a number of research projects with Atlantic salmon (*Salmo salar*) (Rivas et al., 2021), Pacific oysters (Mizuta et al., 2014), blue mussels (Handå et al., 2014), to name a few, that have successfully utilised the principle of artificial upwelling. Although there have been studies conducted on seaweed farming and artificial upwelling (Fan et al., 2020), further research is required to clarify and quantify the issues and benefits to seaweed producers.

Although bio-stimulants, high value foods, and fermented feeds are increasing the value of macroalgae, generally macroalgae only yield a small profit margin and must therefore be cultivated in large-scale farms and with carefully considered efficiency. In Asia, beta components from macroalgae are part of people's daily diet creating demand and value for the unprocessed products. Elsewhere, it is more often about the components, such as phycocolloids (agar, alginates, carrageenan) as well as bioactive substances and other ingredients (Holdt and Kraan, 2011) which hold greater value than biomass.

3.2.1 Trends of current macroalgae commercial systems

For both sugar kelp and Wakame, cultivation begins in the laboratory, where young sporophytes are grown on ropes according to the reproductive cycle via zoospores. Once the macroalgae is planted at sea, kelp thalli can grow up to 2-5 m long or even longer and will be harvested between 6-8 months after deployment (Pereira and Yarish, 2008; Redmond et al., 2014). Following Buck and Buchholz (2004) and Buck and Langan (2017), macroalgae cultivation techniques in sheltered water bodies usually have a linear structure and can be deployed in the form of longlines, ladders, and horizontal grid systems (Figures 6A, B, D). These systems are the classic forms of cultivation used worldwide and lead to a global production of up to 140 million tonnes per year (90% in Asia) (FAO, 2022). Finer details of the construction and configuration are shown in Figures 6C, E–G.

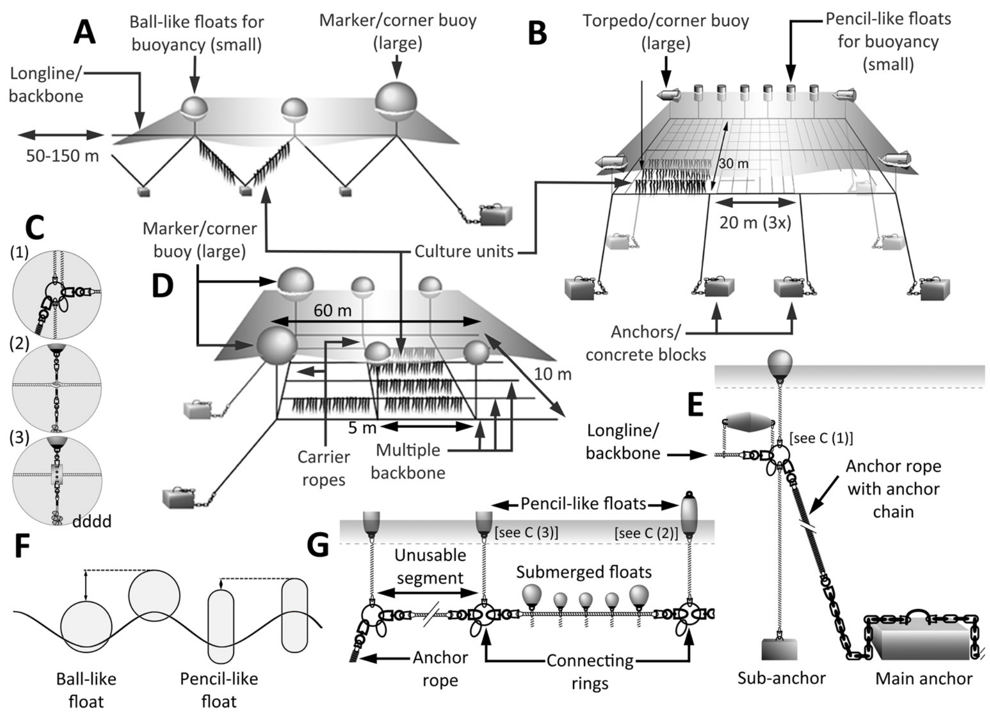

FIGURE 6
System design and concept of macroalgae cultivation devices. **(A)** Longline (backbone) system with floating buoyancy and seaweed culture unit hanging perpendicular in the water column. **(B)** large grid design with floating buoyancy and rectangular culture units. **(C)** Connection devices with (C1) rings as coupling centre piece; (C2) connection of floats to the backbone within the strands of the rope or (C3) by using metal tiles. **(D)** Ladder construction with culture units attached to the multiple backbone of the system. **(E)** Unit at one end of a backbone with different anchors, holding devices (chains, ropes), and floatation. **(F)** Different buoy shapes and dipping depths when riding the swell. **(G)** Backbone with floating and submerged flotation as well as the "unusable segment". Modified after Buck and Langan (2017) and Buck (2007).

3.2.2 Trends enabling advancement of macroalgae into exposed sites

Most cultivation systems for seaweed deployed in exposed areas between 1985-2015 were comprised of ropes (horizontal, vertical) and in some cases cages or rope nets were installed (Fernand et al., 2017). In their comprehensive review, Tullberg et al. (2022) indicated that in order to preserve the basic spatial layout in exposed regions, cultivation systems have to be fixed by multi-point moorings and buoys or the design has to include high internal resistance to cope with compressive loads, resulting in heavier and more expensive structures. The authors recognised that trials of testing cultivation systems revealed the most promising systems for offshore seaweed cultivation seem to be linear systems with macroalgae growing on the sea bottom or in the water column. Though, the authors emphasis that circular systems could catch up with the linear systems when the automation of cultivation processes (i.e. harvesting) are further developed.

Research into macroalgae aquaculture at offshore sites in Germany began in 1992 with an initial prototype of a circular farm design (Lüning and Buchholz, 1996). This system design was improved over the years and ended in the so-called "offshore ring system" for the cultivation of macroalgae (Figures 7A–D) (Buck and Buchholz, 2004). Here, the best results were achieved with the brown macroalgae *S. latissima*, as it quickly adapts to the harsh weather conditions in exposed marine commercial fishing and aquaculture areas and thus there was no loss due to breakage of the stipes or detachment of the holdfasts (Buck and Buchholz, 2005). A key aspect of why this ring system withstood the harsh conditions in exposed waters well was the anchoring, which consisted of a single-point mooring (anchor stone or screw anchor) with the ring attached to the tether upwards and downwards via a crow's foot lashing, a knot used to spread the force of the ring over a wider area, preventing damage to the culture unit. This allowed the ring to turn with the current in all directions and be less affected by the waves due to the submerged mode of about 3 metres.

Whale entanglements in marine gear are a major concern along the North Atlantic US coast. Although there are no documented whale entanglements with aquaculture equipment in this area, incidences involving fishing gear such as gillnet or pot lines resulted in rope wrapping and knotting around whale fins, flukes, or jaws. To help resolve this issue, a submerged, stiff, composite kelp farm structure was developed and deployed at an exposed site near Saco Bay, Maine (Figures 8–10) (Moscicki et al., 2024; Chambers et al., 2023). This project, called "A Validated Finite Element Modeling Tool for Hydrodynamic Loading and Structural Analysis of Ocean Deployed Macroalgae Farms" was funded by the US Department of Energy ARPA-E's MARINER program to develop technologies that enable large scale macroalgae cultivation

8 https://aquavitaeproject.eu/

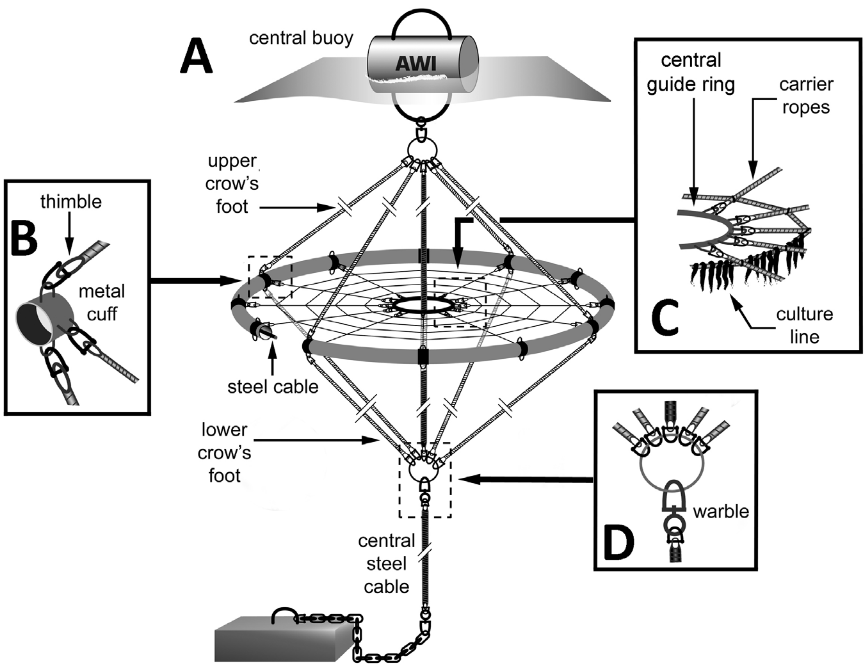

FIGURE 7
Offshore-ring device for the cultivation of extractive species. **(A)** Ring construction for the culture of sugar kelp (*Saccharina latissima*) at exposed locations. **(B)** Metal cuffs, to which the upper and lower crow's feet, the ring tube, and the carrier ropes are attached to provide better attachment and strength during rough conditions. **(C)** Central guide ring with attached carrier ropes and culture lines to avoid entanglement. **(D)** Transition between the central steel cable of the mooring and that of the lower crow's foot. (Modified after Buck and Grote, 2018).

for the purpose of generating material for sustainable human food, animal feed, and biofuel. The *Aqua vitae program*[8] has designed a system that is an air pressure controlled longline system (Strand et al., 2022), however there are controlling intellectual property considerations that limit the transfer of specifics.

3.2.3 Examples of exposed macroalgae aquaculture farms

Worldwide macroalgae aquaculture farms, which are located in highly exposed waters, are rare. Most of the farm structures that have been and are being built in such high-energy environments are more for research purposes and are still at an early stage of development. Therefore, in the present paper we decided to include examples of farms that can at least partially experience strong currents and higher waves.

A good example of a farm that is exposed to medium to large waves and currents, cultivating sugar kelp is Ocean Rainforest Sp/F based off the coast of the Faroe Islands. The technology of the farm is called 'Macroalgal Cultivation Rig' (MACR). The 500m long horizontal backbone is tensioned 5-10m below the water surface, held in position by up to four steel anchoring systems at the beginning and end, and buoyed into position in the water column. The line is connected between buoyancy devices and the cross lines, which makes operations and maintenance (O&M) easier. With this system, about 30 tonnes of sugar kelp per hectare per year can be achieved (Bak et al., 2020).

Engineering tools have been adopted by the University of New Hampshire in the Gulf of Maine. This has allowed kelp farming systems based on parallel, tensioned longlines to move to sites that may be exposed at certain times of the year. Finite element modelling (AquaFE) and physical scale testing in a wave basin provides preliminary data for their survival offshore (Moscicki et al., 2022). In addition, environmental monitoring buoys are placed close to the farm and measure temperature, dissolved oxygen, salinity, chlorophyll, dissolved organic matter, turbidity, pH, and nitrate as well as currents and waves. Storm events are recorded and loads on the mooring lines are measured to validate and update the AquaFE modelling software that aids in these efforts (Fredriksson et al., 2023).

The above-mentioned project funded by the ARPA-E-program was based on a farm that was exposed to stronger currents and higher waves at certain times of the year (Costa-Pierce and Fredriksson, 2022). It was moored by thirty-six 6.5m long helical anchors and utilised 12mm diameter fiberglass rebar for kelp culture and mooring lines. Special terminations were developed to attach the fiberglass rods to other lines in the farm via shackles. The farm was tensioned by surface buoys that maintained the grid structure 2.5m below surface during storm and tidal events. Fiberglass rod was chosen as it was similar in cost to traditional kelp culture lines and has a high tensile strength (10,000 kg). It can be rolled in a coil for shipment and deployment. Most notable is when it is bent to a certain radius, it will snap similar to uncooked spaghetti, avoiding wrapping marine mammals as rope does. This aspect makes this material attractive in reducing whale entanglement (Figures 9, 10). The farm was seeded in the fall of 2021 with juvenile kelp from Atlantic Sea Farms in Biddeford, Maine. It was harvested in the spring of 2022 at a yield of 8 kg/m

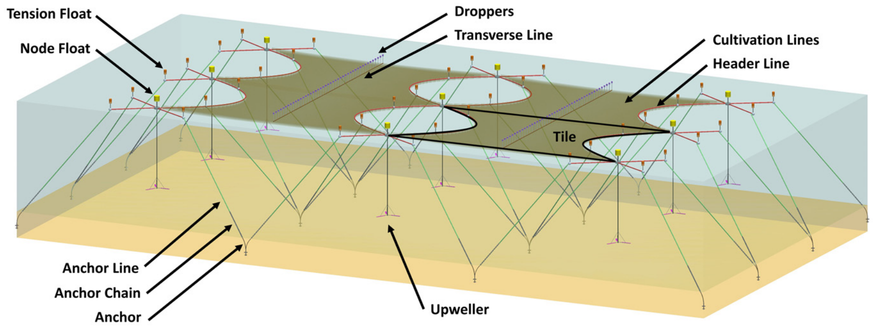

FIGURE 8
Kelp cultivation structure with four modular "tiles". Each tile represents a semi-independent array of kelp cultivation lines, deemed "tiles", each with four associated moorings extending outwards from the corners. Kelp cultivation lines extended parallel along the long side of the "tile", between header lines on either end.

(Chambers, personal experience). All the structures were removed from the site for further analysis onshore. No interactions with marine mammals were observed during the deployment. Analysis of the composite rod after deployment is ongoing. The composite kelp farm survived winter storms with waves up to 6 m in height (Chambers, personal experience). The positive results warrant further investigation.

For the farming of *Ulva* sp. In the EEZ of the German Bight, a design adapted from the Shellfish Tower was deployed (Heasman et al., 2021; Landmann et al., 2019) (Figures 5A–E). This design is referred to as the 'Seaweed Tower'. The outer subunits were modified in such a way that cross bars were attached to create the largest possible surface area, either in a 'star design' from the inside to the outside (Figure 5A) or completely to the outside referred to as the cylinder system (Figure 5B). Both designs were built to measure the shading and therefore favour the design with the largest surface area. Laboratory tests were carried out in advance with many different rope arrangements, with the greatest yield being achieved with a chequered design (Figure 5C). Two of the six subunits will be used to hold gear (baskets) for the culture of eastern Oysters (*Crassostrea virginica*) in a test trial (Figures 5D, E).

3.3 Marine Finfish

Marine finfish are the most diverse group of marine species that are farmed although only a few species have been produced or trialled in exposed environments. Salmonids, primarily Atlantic salmon (*Salmo salar*) and steelhead trout (*Oncorhynchus mykiss*) have received the most attention as they are the predominant species produced in several major aquaculture nations, particularly those with advanced net pen industries (e.g. Norway, Chile, Scotland, Canada; FAO, 2022). Salmonids are well suited to production in high-energy environments, being athletic fish with a

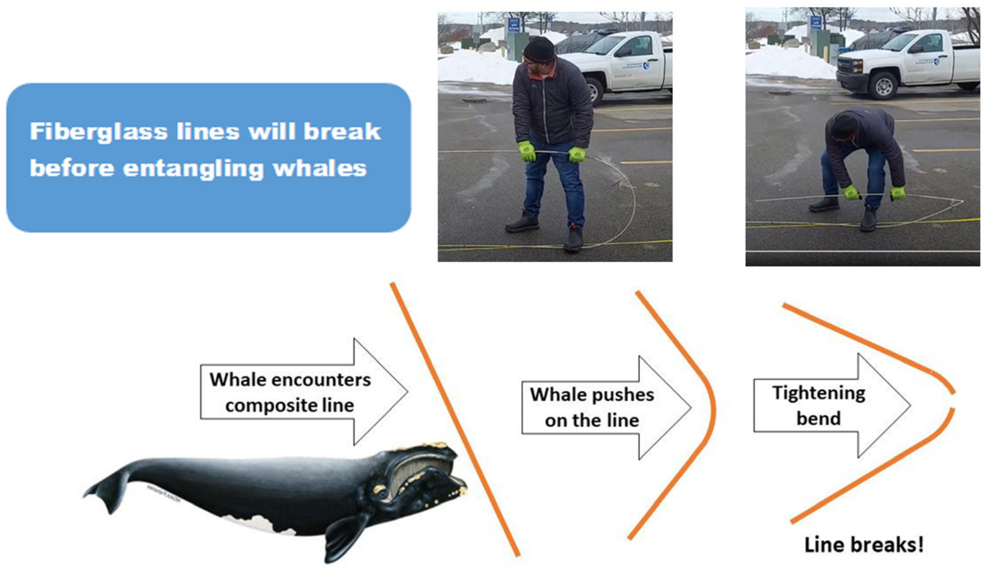

FIGURE 9
An illustration of a 12 mm diameter fiberglass rod bending and breaking, by a human. The same would happen, in theory, if a whale hit the rod, bending, breaking and swimming on, resulting in loose lines to entangle marine mammals.

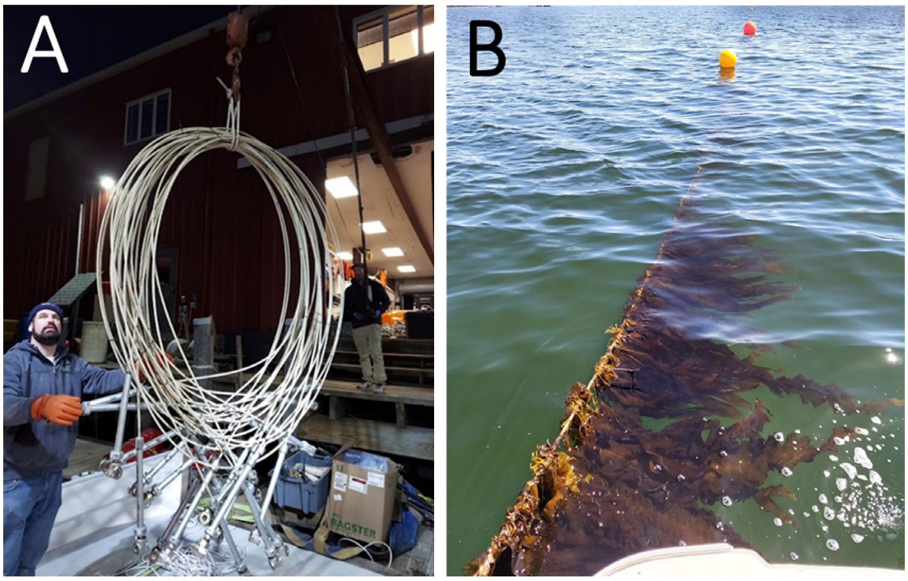

FIGURE 10
(A) Fiberglass rebar with terminations being loaded onto a vessel for deployment. **(B)** Photo of sugar kelp (*Saccharina latissima*) growing on the fiberglass rod.

high optimal swim speed (Quinn et al., 2011; Hvas and Oppedal, 2017) and seeing benefits from forced exercise that strong currents can create (Waldrop et al., 2017; Prescott et al., 2023). Salmon, however, are less well suited for production in submerged net pens since they have physostomal swim bladders and require regular exposure to an air-water interface to maintain neutral buoyancy. Research on this topic indicates that culturing salmonids in submerged pens may be feasible by using submerged air pockets or raising the pen to the surface at set intervals (Sievers et al., 2021). Lindfors (2022) explored the underlying causes of different industry development paths between the offshore salmon industries in Norway and Tasmania, although the focus was on regional differences at the industry and regulatory levels.

Other species are receiving attention, particularly those suitable for tropical climes where the occurrence of hurricanes, typhoons, and other extreme weather events make almost any location at risk of encountering high energy conditions. Cobia (*Rachycentron canadum*) and several species of *Seriola* have been produced in commercial farms at exposed locations. Most species being farmed or considered for production at exposed sites are higher value fish as the high unit price is needed to overcome higher equipment depreciation and operating expenses. That price pressure may lessen as more high energy farms are started, enabling equipment to be produced in larger quantities, more vendor options to become available, and operating procedures to streamline.

3.3.1 Trends of current marine finfish commercial aquaculture systems

Marine finfish in sheltered locations are overwhelmingly produced using floating gravity pens (Lien et al., 2007). Most utilise a rim made of HDPE plastic pipe although some use steel frames. These styles of pens are cost effective and have seen some innovation over the past decade, mostly through increases in size and changes in the netting materials.

The pens are typically moored to a grid system composed of surface floats connected to anchors such that tension is maintained on all components (Huang et al., 2008). The consistent tension minimises movement and wear on the connection points and reduces anchor movement from the shock loads generated when a slack line comes quickly tensioned which often occurs when the tidal direction changes.

The fish are fed using one of two methods. Air-driven feed lines connected to a barge are the predominant method for delivering feed at salmon farms while farms in other locations often use “feed cannons” or are hand fed. In both cases, feed is delivered at the surface. Other farm operations such as harvesting are also dependent on surface access to the pen.

3.3.2 Trends enabling advancement of marine finfish farming into exposed sites

There are three broad categories with respect to net pen design employed in marine fish aquauclture; flexible gravity pens designed to conform to wave motion, rigid megastructures designed to resist wave energy, and submersible pens designed to evade the strongest surface energy (Wang et al. (2024) although Chu et al. (2020) describe 5 classifications of net pens using similar categories). Each of these strategies offers different advantages and disadvantages that make them each more or less preferable for a given project. The energy tolerance ranges that are appropriate for the net pen types are subject to the energy characteristics which affect equipment choice (i.e. a flexible gravity pen may be suitable for a site with 3m waves and a 15 second period, but not at a site with 3m waves and an 8 second period). Further, other project considerations such as business strategy, risk tolerance, available capital, distance from shore, technological sophistication, and personnel experience will influence the optimal equipment type.

Flexible gravity pens designed for open ocean environments differ from their nearshore counterparts being larger and utilising more highly engineered designs and materials. These pens are generally less robust than submersible pens or megastructures but are a cost-effective option for sites with less extreme conditions or longer period waves.

Rigid megastructures such as SalMar Aker Ocean's Ocean Farm 2 or Pan Ocean Aquaculture and De Maas' Semisubmersible Spar Fish Farm resemble offshore oil platforms more than aquaculture net pens. Nordlak's HavFarm is another model that uses different design concepts. The HavFarm is 430m long and 54m wide (Wang et al., 2019; Chu et al., 2020) giving it an appearance similar to a large ship, and it has the ability to be propelled or rotate around a mooring point off its bow. The steel frame of these structures is strong enough to resist waves of up to 15m in height[9]. In addition to resisting surface energy, the megastructures allow for sensors and farm systems to be installed and powered. Chu et al. (2020) mentions feed silos and distribution systems, as well as water desalination units and oxygen generator on board the platforms. These systems are expected to reduce operating costs and help mitigate the high capital expenditure which, along with their large scale, could make the final cost of products sold similar to traditional systems.

Submersible pens can have different designs with some being fully enclosed at all times and designed to be operated in a submerged position, while others resemble surface pens and are intended to be operated at the surface most of the time to enable operations similar to traditional pens (Chu et al., 2020). The main driver to submerge pens is to escape the highest energy encountered near the surface (Lopez et al., 2024) but submerged pens may also be selected to reduce visual impacts, access cooler or more stable water temperatures, discourage theft or vandalism, or mitigate surface-based risks such as sea lice or some harmful algal species. Submersible pens that are operated at the surface such as Innovasea's SeaProtean[10], Badinotti's Oceanis[11], [12]Akva's Atlantis, or the SeaFisher being developed by the Blue Economy Cooperative Research Centre (Wang et al., 2023), are more compatible with existing equipment (e.g. harvest systems) and farming protocols. Submersible pens (Figures 11, 12) require deep water to accommodate free clearance above the pen to dissipate energy, the pen's height, and free clearance below the pen to disperse effluence. This can limit the available locations suitable for submersible pens and often leads to farms being sited further from shore than traditional farms, imposing a logistical hurdle on the farmer. Waters deeper than 50m are usually sufficient for submersible pens although the minimum water depth varies based on the pen model. Large megastructure style pens also require deeper waters with the Ocean Farm 1 designed to be deployed in 100 – 300m of water (Chu et al., 2020). The top few meters of the water column often have other characteristics that farmers prefer to avoid. Sea lice and other parasites are more abundant near the surface (Nelson et al., 2017). In fact, several novel pen designs have been tested that exclude the top few meters of the water column from the pen and have shown reduced sea lice infections (Oppedal et al., 2017).

Norwegian development licenses have been effective in encouraging the development of novel farming systems design for exposed environments (Føre et al., 2022). This includes both net pens as well as de-lousing, collection of waste, improved fish welfare, and surveillance systems which are important for the success of exposed farms although these innovations are not focused on exposed farms per se. Føre et al. (2022) report that 37% of the applications for development licenses and 39% of awarded licences were focused on open ocean environments (which they define as sites with an expected significant wave height above 4m). Of the 9 awarded open ocean development licenses, four were submersible and five were rigid structures. Chu et al. (2020) describes prototype marine finfish aquaculture pen designs that are not yet in commercial or semi-commercial use.

3.3.3 Examples of exposed marine finfish aquaculture farms

Open Blue Sea Farms[13], located in Panamá, grows cobia (*Rachycentron canadum*) in 64 m of water. The site is exposed to the full fetch of the Caribbean Sea causing rough but manageable conditions during normal operations but conditions during a 50-year storm can be quite extreme (Heasman et al., 2024). To manage these forces, they use submersible SeaStation™ net pens to reduce the energy experienced by their equipment. They also use several operational strategies to streamline farm work. The submerged pens require a feed system that delivers feed underwater, so the farm uses a system called the FlowFeeder from Innovasea which transports feed to the pens in water and delivers it to pens while submerged. They also use a wireless sensor array to provide live data on temperature, oxygen, waves, and currents so farm managers can react faster to changing conditions. The farm has been operating at a commercial scale for over a decade.

Blue Ocean Mariculture, located in Hawai'i, experiences both rough normal conditions and episodic extreme events from hurricanes. During normal operating conditions, the farm is in the lee of the Big Island of Hawaii creating moderate energy conditions. However, the 50-year return conditions show extreme high energy conditions (Heasman et al., 2024). Blue Ocean Mariculture also uses SeaStation pens which have helped them withstand storms such as Hurricane Douglas (2020), Hurricane Erick (2019), and Hurricane Olivia (2018).

Santomar, located in Baja California Sur, Mexico, is a more protected site with calm conditions most of the time, but experiences hurricanes which can cause potentially damaging conditions (Heasman et al., 2024). Santomar uses Evolution Pens

9 David & Lucil Packard Foundation 2019

10 www.innovasea.com/open-ocean-aquaculture/submersible-aquaculture-systems/seaprotean-pen/

11 https://www.badinotti.com/marine/submergible-cages/

12 https://www.akvagroup.com/sea-based/deep-farming-lice-control/

13 https://openblue.com

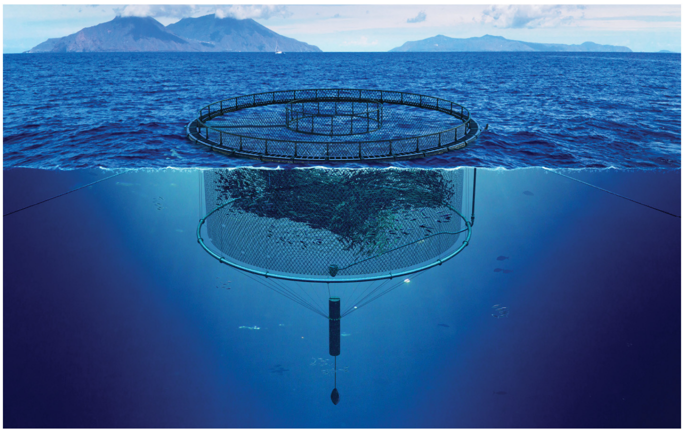

FIGURE 11
Innovasea's SeaProtean pen is designed to look and operate like a surface pen, but with the ability to submerge during inclement weather.

and SeaProtean (Figures 11 and 12A, B) pens supplied by Innovasea which look and operate like surface pens most of the time but can be submerged as needed when inclement weather is anticipated. This solution has worked well for Santomar as the frequency and severity of hurricanes requires a technical solution to make the farm feasible, but does not warrant adjustments to operating protocols that fully submerged pens would require. They are affected by hurricanes every few years, most recently Olaf in 2021, Bud in 2018, and Newton in 2016.

SalMar Aker Ocean operates two Atlantic salmon farms in exposed conditions. The Ocean Farm 1 is located near Hábranden, Norway, has a significant wave height of 5.5m and their Arctic Offshore Farming site near Fellesholmen, Norway, which has a significant wave height of 6.6m (Romuld, 2024). Both farm sites use rigid megastructure type pens. The Ocean Farm 1 is 64m tall and 110m in diameter, while the two systems at the Arctic Offshore Farming site are 78.5m tall and 78m in diameter (Romuld, 2024). The Arctic Ocean Farming site uses a double net with the top net 10m below the surface, limiting the salmon's access to surface waters.

3.3.4 Other important developments "Attachment and Release systems"

If a structure is submerged to the point where there is only a marker float on the surface, a release mechanism is required to allow the structure to the surface for operations and maintenance. There are limited options at this time although there are some functional systems in pre commercial development. The most functional at this time is the patented set and forget system (Figure 13) found in conjunction with the Shellfish tower Heasman et al. (2021). It is a mechanism consisting of a cylindrical housing which is shaped with tapered sides. A cone of two halves is placed in this taper.

Each half that sits in the taper has a toothed groove of the appropriate rope diameter (when under tension the rope diameter will reduce). The mooring rope goes through this mechanism. A hydraulically driven unit is attached to the top of the mooring rope which moves down the rope pushing the shellfish tower before it. At the desired depth the unit will stop and start coming up the mooring rope. The rising shellfish tower results in the mooring rope interacting with the two halves of the cones (green and tan in Figure 13) and the

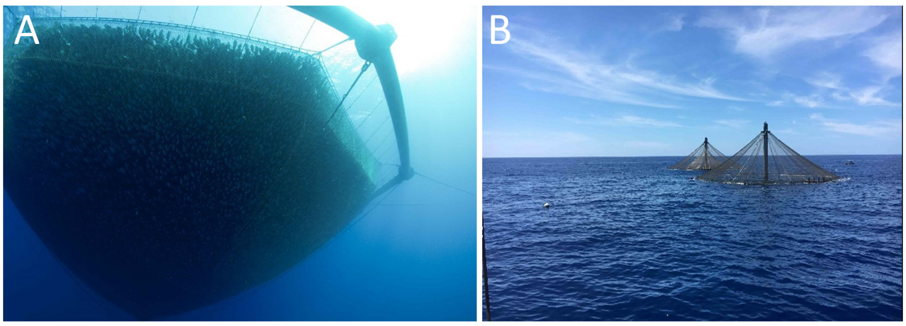

FIGURE 12
Innovasea's Seastation pen in the submerged **(A)** and surfaced **(B)** position.

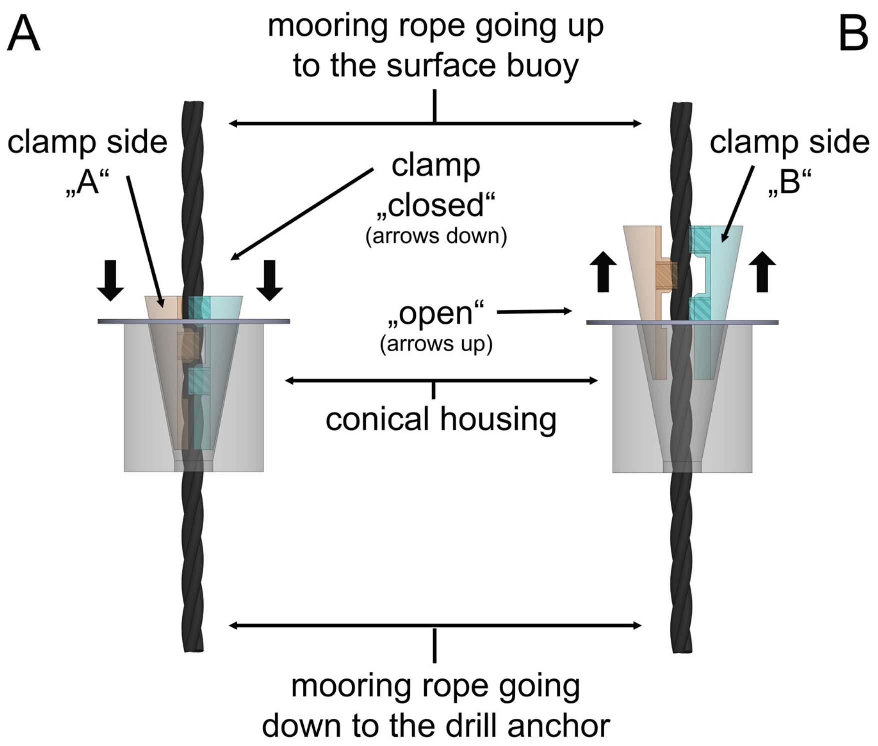

FIGURE 13
The set and forget clamp showing the housing in which there is a cone shaped taper into which the two half shells (green and tan) encompassing the rope are situated. **(A)** the clamps (green) and its opposing clamp (tan) are shown seated and the rope clamped between them. Pushing the housing down releases the two clamps **(B)** (green) and its opposing clamp (tan) which liberates the rope and allowing free movement.

halves are pulled into the taper and tighten onto the rope holding the structure in place. When the structure is required to be released, the hydraulically driven unit or decoupler is sent down the mooring rope to disengage the two halves in the taper, releasing the rope and the buoyancy brings the shellfish to the surface.

A second system is being tested in New Zealand with the research project Nga Punga o te Moana[14], which is used to attach ropes under tension. It relies on a coupler which consists of a male and female assembly, each attached to the ends of a rope that one needs to join. This system is being used on submerged longline systems to pull the structure under water and affix it such that it remains submerged. A simple release line is on the surface which can be used to trigger a release mechanism which allows the structure to surface.

4 Modern system design

4.1 Modelling

Several precursors were required to advance exposed aquaculture including computing tools such as finite element methods [FEM] and computer assisted design [CAD] (Fredriksson et al., 2007). These methods started in 1959 (Clough and Wilson, 1999) and only became available after breakthroughs in the late 1990’s regarding mathematics and rapid advances of the computer science (Liu et al., 2022).

Modelling is an effective means of testing new aquaculture structures in their early phases of development. It allows for rapid exploration of different prototypes under a variety of ocean scenarios.

Static modelling (the state of a structure at a specific point in time) is useful to determine whether there is sufficient buoyancy and ballast in the optimal places of an aquaculture structure for it to sit in the desirable part of the water column. Dynamic modelling (focusing on the system behaviour and interactions between components) is necessary to capture the influences of waves and currents.

For simpler line-based structures, programs such as Orcaflex™ are relatively straightforward and fast-solving model. Some limitations of programs such as Orcaflex are that they cannot easily replicate objects with complex geometries and they only account for the effect of the structure on flow – which may be important where parts of the structure are blocking flow or cause flow to accelerate downstream. However, Orcaflex also does not model internal flow structures such as where some parts of the flow go around the object while other parts go through (e.g. an intake and pipe).

For structures with unusual geometries, structures where turbulent processes are important, or where drag and lift dynamics are important, a more complex CFD (computational fluid dynamics) model (e.g. fluent, openFOAM, reef3d) will likely need to be adopted. The more complex the model, the more

14 Nga Punga o te Moana, Ministry of Business, Innovation and Employment funded project, New Zealand.

computational power is required to solve it, and the longer it will take to solve. This can slow down the modelling process.

After initial sandbox design, modelling can also be undertaken to further refine aspects of design. Reducing drag, optimising lift, or reducing turbulence generation will require more complex CFD modelling. Modelling does however provide the means to study, test and de-risk innovative ideas quickly and relatively cheaply prior to committing to the development and deployment of prototype structures.

Wave tanks, flow tanks, and various other test tanks that can simulate ocean conditions are more readily available than they have been in the past, usually through academic institutions. These facilities allow for the testing of scaled-down models which can generate representative empirical data on drag coefficients or relevant factors (Swift et al., 2006).

4.2 Materials

Materials are advancing and there are an increasing number of materials available for structures and crops. Different materials offer durability, corrosion resistance, abrasion resistance, longevity, flexibility, cost effectiveness, and recyclability, however there are few, if any, that will offer all these parameters. Selection of materials is incredibly important as they will have a significant influence on the success of any enterprise.

HDPE is used across aquaculture as it has excellent strength, toughness, erosion and UV resistance, and inertness (Wesley, 2020). In shellfish, macroalgae, and marine finfish aquaculture it is used primarily for floatation. Floats range in size from marker floats and 300l backbone (header rope) support floats (Goseberg et al., 2017; Newell et al., 2021) to large diameter circular pipes which provide floatation for fish pens (Fredriksson et al., 2007). Baskets and trays used in shellfish aquaculture are made from HDPE (Newell et al., 2021). HDPE can however be fouled with some variation depending on the colour of the substrate and the positioning (geographically and in the water column) of the substrate (Freitas et al., 2023).

Fish pen floatation rings have been made with HDPE or other polymers. There is increasing research into the behaviour of pen nets in various conditions (Chen et al., 2019, Liu et al., 2020; Fan et al., 2023) and use of alternatives to the polymers such as alloys (Chen et al., 2019; Sclodnick et al., 2020; Gümpel et al., 2021) for the nets of fish pens.

Polyethylene and polypropylene are also used extensively for ropes to secure the structures (moorings etc.) but also for the growing media (e.g. mussel cultivation ropes) (Newell et al., 2021) and are well suited to the demands required of them (Maddah, 2016; Arantzamendi et al., 2023). Synthetic fibre ropes are a good replacement for steel cables both in terms of weight and corrosion and they can be combined in terms of mixing the fibres or by constructing the ropes in different ways (e.g. eight strand or double braded etc.) (Foster, 2002). Cost is, however, a serious consideration with some fibres (e.g. Kevlar and Dynema®) as while they have improved properties in terms of strength and stretch, but they are more expensive (Foster, 2002).

As useful as these plastics are, they are contributing to the microplastic load in the marine habitat (Gomiero et al., 2020; Iheanacho et al., 2023). While alternatives ropes of other materials are being considered (Arantzamendi et al., 2024), the true benefits, durability, and cost of these new ropes do not appear to have been assessed.

Exposed environments lend themselves to different materials for marine finfish containment nets. Low energy sites often use a woven net of nylon or Dyneema (an ultra-high-molecular-weight polyethylene), which are also used at exposed sites, but the stronger forces make other options that can reduce drag more attractive. Some farms are using an extruded monofilament of PET plastic called Kikko net which creates less drag and fouls slower than fibrous nets (Bannister et al., 2019). Other farms are using copper alloys which are also smoother than fibrous nets and the copper provides a natural fouling retardant (Yigit et al., 2018; Bannister et al., 2019). Foster (2008) provides information and outlines a number of materials that are used increasingly in the development of exposed aquaculture while Ashby (2016) highlights the complexities and properties of materials in general, some of which could be used in aquaculture.

4.3 Future developments

The ongoing development of genetic tools will have significant implications in advancing the production of efficient and environmentally tolerant aquatic organisms. This is a necessity when taking organisms into different environments and in view of the influences of climate change. More rapid growth rates through selective breeding reduce the time organisms are in production, which in turn reduces the exposure period, husbandry requirements, and costs. Value added characteristics (e.g. uniform sizes and shapes), will contribute to the viability of operations. The production of triploid bivalves has the benefits of maintaining condition of the animal for longer periods than diploid organisms, alleviating the necessity to lose condition and harvest prospects during inclement weather at inshore but mainly at exposed sites. New materials such as composite growing rods are being tested which address some issues (e.g. marine mammal entanglement) as they will not wrap or fold over appendages and entangle the organism (Moscicki et al., 2024).

Environmental and structure sensors will become more important with increasing exposure. Knowledge of the conditions at the site, under the water and on the structure, will significantly improve management, efficiencies, survivability, and reduce costs. Fortunately, sensors are becoming cheaper and more robust, however the ability to overlay data sets to develop predictability and assessment tools is still in its infancy.

5 Discussion

In terms of knowledge, development, and advancement of commercial production in exposed sites, marine finfish aquaculture are far in advance of bivalve aquaculture, which in turn are more advanced than macroalgae production. Some of the advancement can be related to the value and demand for fish but every fish is cultivated for a single purpose - food (with a few cultivated species to assist with husbandry such as lumpfish, *Cyclopterus lumpus*) i.e. a protein source. There is generally sufficient value in the fish for expansion to exposed sites to be viable. Bivalves are also cultivated for food but are of lower value and therefore expansion is more tentative and requires far larger space. Although macroalgae have been cultivated for millennia for food (Buschmann et al., 2017), their true value in terms of uses is widespread (Farghali et al., 2023) and still being discovered. Macroalgae are also known to change their characteristics when subjected to higher energy and different light regimes (Maltsev et al., 2021). Macroalgae species occupy a large spectrum of habitats, and each has their particular biochemistry and physical attributes (Buschmann et al., 2017). Therefore, each macroalgae species will need to be analysed for these attributes and also for how the energy and light variations influence them. The opportunities in macroalgae are extensive, however, the cultivation/husbandry/processing methods, O&M, equipment, etc. still need to be developed for a large proportion of the macroalgae species. The few species that have been developed (e.g. *Saccharina* sp., *Laminaria* sp., *Undaria* sp.) provide the foundation of future development and the basic knowledge required to progress.

Although there are specific requirements for the farming of bivalves, macroalgae and marine finfish, there are some common characteristics which are found across all exposed ocean structures: all are subjected to greater forces; all will require more robust design; modified and more robust mooring systems are required; and suitable and cost-efficient materials must be identified.

To endure the greater energy in exposed situations, increased structural integrity and maintenance requirements are needed which result in escalating costs (Chu et al., 2020; Dewhurst et al., in review). Operators can therefore design structures which can tolerate sea surface conditions (Wang et al., 2022) and improve efficiencies in other ways (e.g. sensors, food efficiencies, automation) (Solvang et al., 2021; Wu et al., 2022; Scholtens et al., 2023), or they can avoid the main surface energy by semi or fully submerging structures (Wang et al., 2023). If the structures are linear, they can be orientated such that they respond less aggressively to the main energy sources (waves and water currents) reducing wear, maintenance, and crop loss[15].

Macroalgae aquaculture is a challenge in that, with the exception of a few deep-water kelps, species must remain close to the surface in the sunlight. Novel approaches are being developed to address the ability of structures to tolerate the surface energy (St-Gelais et al., 2022), be marine mammal friendly, and be commercially viable (Moscicki et al., 2024). In some respects, however, the (in)ability of the specific species of macroalgae tolerance of energy being propagated may override the energy tolerance of the cultivation structure as the macroalgae may be damaged before the structure is stressed.

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6 Conclusions

6.1 Limitations

This manuscript mentions social license, however as it is a topic deserving of its own manuscript it is covered elsewhere in this special issue by Krause et al. (2024). This is not intended to disrespect or diminish the importance and implications of social licence aspects in any way. It has been assumed that due diligence in this regard has, and will continue to be, considered should any party wish to expand into exposed ocean aquaculture.

There are many parameters that should be considered when selecting a site for aquaculture. One of these is the provision of power for vessels and operation of equipment (as found on some marine finfish farms). Consideration should be given to the efficiency and carbon footprint of the derived power. This has not been discussed in this manuscript due to the diverse and now expanding (e.g. battery and hydrogen fuel cells) opportunities provided by alternative power sources.

6.2 Current obstacles

- De-risking the expansion into exposed oceans is key. Only in recent years have the risks (cost and environment) become known as exposed ocean endeavours are successful, which is providing greater enthusiasm to innovate and succeed in this environment. However, there is still some way to go.
- The exposed ocean aquaculture environment is relatively unknown from an oceanographic perspective simply due to the fact that many of the sites have not been assessed for aquaculture parameters. Assessments are required to determine the species and equipment required for the site. Certain assessments take time, e.g. growth rates, fouling assemblages, hydrodynamics over a season, etc. These assessments can be costly and require permits which are time consuming.
- Social licence is very important and not limited to exposed ocean usage. However, a lack of knowledge of a site (and aquaculture in general) can lead to misconceptions and inadvertent conclusions leading to complications with permits, etc.
- Materials to be used on the exposed sites are available, however there are requirements that will facilitate increased reliability, durability, and efficiencies. In addition, they would preferably be recyclable and relatively inexpensive. They should also lead to future semi or full automation. There are very few, if any, materials which currently can meet all these requirements.
- It is unknown how some species will respond to the environment and new structures. Therefore, new methods (husbandry, harvesting, and operations) need to be developed. This will be followed by health and safety requirements for the crews.

- In some instances (e.g. macroalgae) products and markets need to be further developed. There is an issue of balance between the demands of the markets and the expansion of aquaculture sites. The ability to expand both simultaneously in sync with each other is a desirable but difficult task.
- The value of products grown in exposed ocean sites have to cover the extra cost of equipment and operations that the exposed environment imposes on a business.

The advancements that have enabled farmers and researchers to utilise higher energy environments have come primarily from: engineers identifying issues and advancing technical feasibility of materials and structures; researchers studying species suitability and requirements and the environment and net benefits. These advancements have been successful as the examples described indicate. However, the expansion of the aquaculture industry into exposed waters and the contribution to sustainable development goals (Troell et al., 2023) has not been as fast or extensive as the market demand for seafood or spatial opportunities in exposed waters warrants. The perceived risk, increased capital costs, and more difficult operations remain as major deterrents for new entrants into this sub-sector.

One of the motivations of this manuscript is to broaden awareness for the advancements that make exposed farming feasible, and to highlight the success that some groups are having. Yet, further work is required to get the cost of goods sold from exposed farms consistently in line with products from wild fisheries or sheltered farms as they are effectively perfect substitutes, or new to the market.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

KH: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. NS: Investigation, Methodology, Writing – original draft, Writing – review & editing. TS: Conceptualization, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. MC: Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. BC: Methodology, Validation, Writing – original draft, Writing – review & editing. TD: Methodology, Validation, Writing – original draft, Writing – review & editing. WI: Methodology, Validation, Writing – original draft, Writing – review & editing. BB: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

Author BC-P was employed by the company Ecological Aquaculture International, LLC. Author TD was employed by the company Kelson Marine Co. TS works is employed by Innovasea.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s note

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From "open ocean" to "exposed aquaculture": why and how we are changing the standard terminology describing "offshore aquaculture"

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The term "offshore" with regards to aquaculture has hitherto encompassed various perspectives, including technology, geographic location, legal jurisdiction, and more. To resolve the ambiguity in this term and understand its implications for current and future aquaculture development, "offshore" should be resolved into two separate metrics: distance from shore and energy exposure. The United Nations Convention on the Law of the Sea (UNCLOS) distinguishes between internal waters, territorial sea, contiguous zone, exclusive economic zone (EEZ), and the high seas, but currently has no precise definition for "offshore" in its provisions, and therefore no applicable laws pertaining to "offshore" aquaculture. Regulating a multi-technology aquaculture sector may require integrating new spatial concepts into the law rather than merely adapting and extending current regulatory designs to include new production concepts. The metrics of distance from shore and exposure are seen as a range rather than a specific threshold, allowing for a continuum. Distance from shore is readily quantified as a distance from a baseline. To rigorously quantify the exposure, the influence and interactions of oceanic parameters (water depth, water current, and wave height and period) we utilized to generate six indices. These oceanic parameters are seen as the main contributions which influence the physical and some biological parameters required for site, species, and technology selection. Four shellfish, three seaweed, and three finfish sites along with 20 potential aquaculture sites were examined using the indices in association with the energy index to determine tolerances of the structures and their ability to cultivate their relevant species. Two indices, Specific Exposure Energy (SEE) and Exposure Velocity (EV), were selected for utilization in the analysis of sites based on their ease of use and applicability. The interaction between the energy indices and various aspects of farm operations and performance were explored. The indices developed and used in the case studies presented have been shown to be useful tools in the general assessment of the energy that will influence the species and equipment selection at potential aquaculture sites. The indices do not provide a definitive answer as to the potential financial success of a site as this requires other inputs relating to infrastructure costs, annual production, distance from port, sales strategy, etc. However, the Specific Exposure Energy index creates a useful tool to describe site energy and be comprehensible to a wide range of stakeholders. We recommend the SEE index be adopted as the predominant tool to communicate the exposure level of aquaculture sites.

KEYWORDS

open ocean aquaculture, offshore aquaculture, exposed aquaculture, net pen, ocean energy, finfish, bivalve, seaweed

1 Introduction

1.1 Current status

Urban expansion and population growth (set to reach 9.7 billion by 2050) has led to a reduction in arable land particularly seen throughout Asia and Europe with 60% of land expansion previously being used as an agricultural source of food (Güneralp et al., 2020). Changing climates due to excess CO_2 emission has begun to impact the productivity of the remaining agricultural crops (Malhi et al., 2021). Global food and nutritional security are a growing concern when those impacts are combined with inequitable food distribution, food waste, soil-degrading farming practices, and high-input crop production (such as beef) (FAO, 2022). To meet the demands for the future, many are looking toward all forms of aquaculture to provide a sustainable protein source for the global population.

The United Nations sustainable development goals (SDGs) has highlighted food security as their major focal point for the future. Aquaculture, in that context, is the fastest growing food production sector with many products providing critical proteins, micronutrients, and fatty acids necessary for human basic nutrition (Azra et al., 2021). The development of aquaculture contributes positively to many of the UN Sustainable Development Goals (Troell et al., 2023) and has become a focal point in recent years to provide food security for the global population.

1.1.1 The motivation to expand marine aquaculture into offshore and exposed sites

Urban expansion into agricultural land foreshadows similar changes expected in aquaculture as populations grow and push the sough-after coastal area outwards, putting them under pressure from other stakeholders. This is typically from sectors such as marine energy production or storage, fisheries, shipping and navigation, environment conservation, or tourism, to name a few (Gourvenec et al., 2022; Ansorena Ruiz et al., 2022; Papageorgiou, 2016). This is particularly prominent throughout Europe with multiple countries having aquaculture production areas within limited water spaces. Aquaculture tends to be concentrated toward sheltered bays and regions with low exposure to wind and waves (Milewski, 2001). These areas are attractive to many stakeholders and, as we have seen with agriculture, will be impacted by growing stakeholder pressure and could eventually be displaced (Mascorda Cabre et al., 2021).

The need for aquaculture in distant and/or exposed ocean regions arises from several factors, including increasing demand for sustainable protein sources, limited space in coastal areas, nowadays exacerbated by ambitious renewable energy policies to minimize CO_2 emissions (Ostend Declaration, 2023), and the impact of climate change and pollution on nearshore aquaculture sites. Aquaculture further away from the coast or in areas that seem more exposed due to their conditions and may be unsuitable for many users, provides an opportunity to expand production. However, careful and scientifically educated choices in site selection are essential. Greater exposure and increased ocean energy regimes present challenges in terms of robustness of material and structures, operations, and maintenance. By venturing into energetic sites, aquaculture can mitigate the strain on limited coastal areas, utilize low-demand ocean sites to produce protein, and develop innovative techniques to ensure sustainable and efficient production of seafood to meet the growing global demand.

In addition to alleviating concerns around spatial conflict, when moving from sheltered nearshore sites to exposed sites further offshore, there is a trend toward stronger currents leading to higher dispersion capacities, lower background nutrient levels, and deeper water leading to less light reaching the seafloor. This should lead to reduced near-field impacts on water and sediment chemistry and changes to ecology (Riera et al., 2017) or, conversely, higher stocking densities, leading to higher returns on capital expenditures while meeting the same environmental impact thresholds. The ecosystems found in these environments typically exhibit lower biodiversity compared to shallower areas receiving more light on the seafloor (i.e. coral reefs, seagrass meadows, etc.) and are less sensitive to stressors. These types of environments should be prioritized for food production over most terrestrial environments or shallower coastal areas.

Despite the promising future aquaculture development in more exposed or distant locations might hold, there is also the question as to the effects sudden, disruptive, large-scale events could have when the world is more frequently relying on farmed protein resources. The disruption on global food supply chains by the Covid-19 pandemic has been a vivid example for such profound effects (Laborde et al., 2020). There is only scarce discussion as to the effects that natural hazards, i.e., tsunami, cyclones, mass algal blooms, etc. could have on aquaculture installation. This is particularly relevant in regions such as the Pacific or Indian Ocean nations where tsunami-genic sources are prevalent (Daly et al., 2017; Taubenböck et al., 2009). Deeper waters are advantageous in assessing the hazard of aquaculture installations against tsunamis, as it decreases the long-wave amplitude, thus increasing the chances that the gear survives hazardous events. Oppositely, cyclone- or hurricane-induced waves in more exposed conditions would likely result in large waves and result in more energetic conditions that eventually may lead to failure of aquaculture farms (Karim et al., 2014). Using submersible net pens, grids, or longlines can reduce this risk (Benetti, 2004). The effects of natural hazards on individual sites will potentially also have implications for insurance conditions (Mia et al., 2015). Natural hazards have shown to temporarily or permanently alter environmental conditions for aquaculture operations, for example in Japan, where mud content and chemical oxygen demand changed before and after the 2011 tsunami (Naiki et al., 2015).

Changing climate conditions and pollution are also putting aquaculture at risk in areas close to urbanization. Marine heat waves during the summer cause hypoxia and thermal stress which hampers fish performance and can lead to mortality in aquaculture species (Mugwanya et al., 2022). Excessive nutrient loading from land-based sources have been known to cause eutrophication resulting in harmful algae blooms (Davidson et al., 2014) and changing water chemistry impacting certain aquaculture species such as those that deposit calcareous shells or exoskeletons. Deeper waters further from sources of stress should provide a more stable farming environment.

Aquaculture is a commercial activity, and any change will be driven by the belief that profits can be improved or risks mitigated. Expanding farming operations into exposed or offshore locations can improve financial outlooks in many (but not all) instances. This is mostly due to the availability of space and the alleviation of user conflicts which may allow farms to utilize better economies of scale, access lower licensing fees, or avoid resource taxes in some areas. There is potential for biological or operational advantages which are discussed in detail in Heasman et al. (2024a) and include reduced parasite loads, stable temperatures, and fewer interactions with anthropogenic impacts that are concentrated near shore. The slow adoption of open ocean sites and technologies is due to risk aversion of aquaculture operators and uncertainty on whether these production systems can meet the cost of goods sold that traditional farms see, however as protected sites become less and less available, or more and more expensive, alternative production methods including exposed farm sites become more attractive.

1.1.2 Moving away from shore to adapt to environmental change and mitigate land-based impacts

In some areas, these factors push aquaculture into sites further away from the coast and/or into more exposed sites but this creates a different set of constraints. Extending aquaculture sites out of sheltered bays or fjords results in greater exposure to larger waves and ocean energy. Stronger currents necessitate larger mooring structures to hold farms in position, raising capital costs. The sea state and frequency of waves also impacts operational processes with vessels having a maximum sea state and affecting the number of days where workers cannot access the site. These effects will impact the selection of cultured species due to species requirements since large waves can result in crop loss and additional stress on cultured bivalve or seaweed species (Morro et al., 2022; Lien and Fredheim, 2001; Harvey et al., 2021) and strong currents create excessive energetic demands for some fish species (although this can enhance growth in other species; MacKenzie et al., 2021). Water depth has implications as wave interaction with the seabed, up to a maximum of half the wavelength of the largest wave, can add additional lateral water currents. This can increase wear on equipment and create challenges during installation, increasing costs to the business with repercussions for maintenance and diving crew (servicing). Nutrient availability (for bivalve and seaweed culture) can be less than what is observed close to the shoreline (Xu et al., 2020), however there can be regions of upwelling which can enrich the waters (Mascorda Cabre et al., 2021) even though with potential constraints for cultured species (Ramajo et al., 2020). There can also be nutrients deeper in the water, which may become available if suitable cultivation equipment such as cost-effective upwelling devices are developed. Temperatures show less variance as one moves away from the influence of land or into deeper waters, which is preferable for farm operations.

The suite of publications in this Research Topic with the theme "Differentiating and defining 'exposed' and 'offshore' aquaculture and implications for aquaculture operation, management, costs, and policy" highlights some opportunities for industry development and future research that would benefit the nascent offshore/exposed sub-sector of the aquaculture industry. The need for advancements in farm structures has been mentioned, however it is important to note that the protocols for operations and maintenance must be advanced with them. In addition, due to the limitations in opportunities to access the farm site (as a result of harsh environmental condition or lengthy commute times) and the need to control costs, automation must also be considered. Automation will include the ability for surveillance, and to harvest, seed and maintain the crop and structures with as great efficacy as possible. This will also improve the health and safety of staff. Increased automation in the form of feedback from sensors to land based management will increase efficiency, production and adaptive management capability while reducing cost, unnecessary trips and the carbon footprint of any operation (Antonucci and Costa, 2020).

The ICES Open Ocean Aquaculture Group is undertaking an effort to redefine and clarify the terminology used in aquaculture, specifically transitioning from vague uses of "offshore aquaculture" to terms that describe the environment more quantitatively such as "exposed aquaculture". They propose the creation of an index that appropriately describes the level of exposure at a given site. This index will be the primary tool for communicating the energetic conditions at a site and can be used by regulators, equipment designers and retailers, insurance underwriters, farm mangers, and other industry participants in understanding, evaluating, and comparing farm locations. Conversely, they encourage the use of the term "offshore" to refer specifically to the distance from shore, which can be further described by simply stating the distance.

2 Results

The suggested definition of terms such as "offshore" versus "nearshore" and "exposed" versus "sheltered" is based on two distinct factors: the distance from shore and the oceanic conditions. By categorizing sites into discrete categories based on these factors, a more precise characterization of aquaculture locations can be achieved. Other parameters, such as temperature, salinity, and nutrient levels, may vary across these categories but are not essential for site categorization. Instead, these additional parameters can be discussed separately during evaluations of specific sites.

This approach allows for a more accurate description of exposure by linking physical attributes with various aspects such as engineering, logistics, biology, health and safety, operations and management, social and environmental factors, economics, and policy and regulation. It enables stakeholders to better understand and assess the conditions and challenges associated with specific aquaculture sites.

The establishment of precise definitions for these terms is crucial for the development of the aquaculture industry. With open ocean farms operating in various regions globally, there is a need for standardized terminology that supports growth, research and development efforts, regulatory environments, and stakeholder interactions. The publications in this Research Topic have delved into the term "exposed" and its implications for aquaculture and society, providing a comprehensive analysis of the changes and their potential challenges and opportunities.

The following is a review of the content of the publications written by the ICES Working Group for Open Ocean Aquaculture (WGOOA) in this Research Topic. The essential knowledge gained from working on the various topics on "exposed" and "offshore" aquaculture is presented. Other authors have contributed to the Research Topic based on work outside of the WGOOA but those are not summarized here.

Publication 1: "Resolving the term 'offshore aquaculture': The importance of decoupling it from 'exposed' and 'distance from the coast'" by Buck et al. (2024).

The terms "offshore", "open ocean" and "exposed" have been used to describe aquaculture operations either further from shore or in higher energetic environments. None of the terms are clearly defined in the scientific literature or in a legal context, so the terms are often used arbitrarily and thus often incorrectly.

To this end, Buck et al. (2024) researched the etymological and semantic derivation of the word "offshore" and find that the term "offshore" was often used as an additional description (often in the form of an adjective) to describe a business activity or location, such as offshore oil & gas, offshore banking, or offshoring. This was used exclusively to explain a vast distance from the location of the observer, either out of sight or, more likely, a situation that is symbolically unreachable and takes place somewhere beyond the horizon or on another continent on the other side of an ocean.

The suggested definition of terms such as "offshore" and "nearshore" and "exposed" and "sheltered" is based on two main factors: the distance from shore and the wave and current conditions. By categorizing sites into discrete categories based on these factors, a more precise description of aquaculture locations can be achieved. Other parameters, such as temperature, salinity, and nutrient levels, may vary across these categories but are not essential for site categorization in this case. When positioning a farm in either offshore or exposed regions, these parameters are secondary (not unimportant), as the initial planning for the system design and its technical realization with reference to the selected species, in terms of distance or exposure, so they should not be included in an overarching definition. However, these parameters are then worked through as the next step in terms of the site selection criteria catalogue (Benetti et al., 1998, 2023; Buck and Grote, 2018).

To define this term and understand its implications for current and future aquaculture, two axioms have been proposed. First, "offshore" should be seen as a range rather than a specific distance, allowing for a continuum of offshore aquaculture definitions. Second, the distance from the shore to the farm should be a key parameter in the definition. Other terms describing the location of aquaculture in marine areas are also covered.

Publication 2: "Finding the Right Spot: Laws Promoting Sustainable Siting of Open Ocean Aquaculture Activities" by Markus (2024).

Markus (2024) argues that existing aquaculture laws do not capture the range and variation in locations and conditions in which aquaculture facilities operate, which is specifically important for areas far from shore and/or exposed to higher hydrodynamic energy levels. The United Nations Convention on the Law of the Sea (UNCLOS) (United Nations, 1994) is the starting point for all semantic or legal analyses for international waters but does not use the term "offshore" in its provisions, and its precise meaning is therefore not defined. The term has been used in some international legal practices, for example, in the International Court of Justice's decision in the Continental Shelf Cases in which the court noted that the term "offshore" was used by some states to refer to the seabed beyond their territorial sea but within the continental shelf. However, the court observed that the term was not precise and, therefore, had no legal significance in determining a specific spatial extent.

Accordingly, future regulations should be developed to allow governments and stakeholders to identify existing conditions and objectives for aquaculture and to strategically integrate them in marine spatial planning and site selection processes. It is also argued that objective physical criteria indicating marine spaces' characteristics and their suitability for aquaculture should complement geographical concepts such as "nearshore", "foreshore", "offshore", or "open ocean". This is based on the assumption that increased conceptual clarity allows for a more rational use of ocean space. These steps will hopefully contribute to guiding spatial planning and site selection processes in order to secure suitable spaces for aquaculture production in the exposed ocean and help all actors involved in siting farms to optimize aquaculture's economic performance, reduce its environmental impacts, and prevent or mitigate social conflicts.

Publication 3: "Variations of aquaculture structures, operations, and maintenance with increasing ocean energy: trying to avoid evolution and aim for revolution" by Heasman et al. (2024a).

The transition from sheltered farming locations to exposed locations is an ongoing process driven by competition for near shore and protected sites, as well as the opportunity to expand farming operations into regions without protected coastlines. The status quo and progress to date on the changes and innovations in farming equipment is reviewed and discussed for each of bivalves, seaweeds, and finfish.

For each species group, the trends in commercial systems currently used are described along with advancements enabling the expansion into exposed waters. For bivalves and seaweeds, most of these advances involve submerging systems and using more robust materials, however, both of these changes need to be weighted against the financial performance of the farm and the need for the culture organisms to be provided a suitable growing environment (e.g. in the case of seaweed, intense sunlight that is only available at the surface). For finfish, submerging grids and pens is also a common strategy although other systems are using rigid megastructures or compliant surface pens to accommodate the ocean energy.

Advancements outside of the main culture systems are also necessary. Vessels, sensors, modeling software, and other ancillary technologies are developing, making farming in exposed ocean conditions more feasible.

Publication 4: "Hydrodynamic exposure – On the quest to deriving quantitative metrics for mariculture sites" by Lojek et al. (2024).

From a mechanistic point of view, any aquaculture installation in the ocean or in shelf seas will be subjected to environmental loading because of meteorologic or oceanographic action. With respect to structural components of aquaculture installations or the entire installation, these environmental loadings constitute the relevant forces to design for. This article develops a series of indices, explained below that aim to express metrics that allow a sound assessment of potential aquaculture sites. The indices were developed with the idea to consider the ocean as a continuum in which the relevant indices could vary seamlessly between very sheltered to extremely exposed conditions, irrespective of their locations with respect to other considerations that affect the overall question posed in this Research Topic.

Indices were developed relative to their sensitivity to wave height, water depth, and water currents, which are considered the most influential parameters of water energy at a marine site. The six indices proposed in the study are Exposure Velocity (EV), Exposure Velocity at Reference Depth (EVRD), Specific Exposure Energy (SEE), Depth-integrated Energy Flux (DEF), and Structure-centered Depth-integrated Energy (SDE), and the Structure-centered Drag-to-Buoyancy Ratio (SDBR). Four of the proposed indices consider only environmental conditions, while the other two also consider the dimensions of the gear that is exposed to the external loads. Of these six metrics, the Exposure Velocity (EV) and the Specific Exposure Energy (SEE) were recommended for examination based on their sensitivity and expression of site suitability as seen in the case studies they were tested against in Heasman et al. (2024b).

Publication 5: "Utilization of the site assessment index for aquaculture in exposed waters: Biology, technology, and operations and maintenance" by Heasman et al. (2024b).

When moving from a very sheltered aquaculture site to a very exposed oceanic aquaculture site, the energy increases proportionally in a continuum. Lojek et al. (2024) considered the primary influential parameters (water current, waves length and period, water depth) which dictate the species, structure, technology, methods, and operational aspects of any aquaculture endeavor and investigated six possible indices which cover these variables. Added to advanced computer modeling, assisted by detailed and constant environmental monitoring, it may be possible to refine site selection, structure selection and design, species selection, equipment and logistic requirements and health and safety requirements. This manuscript has selected two indicative indices from the potential equations provided by Lojek et al. (2024) and compared them with known operational aquaculture sites highlighting present structural capability and limitations. The two indices are also utilized to reflect on their suitability for assessing sample sites with respect to biological, technological, operational, or maintenance aspects of aquaculture activities.

Publication 6: "The effect of site exposure index on the required capacities and material costs of aquaculture structures" by Dewhurst et al. (2024).

Dewhurst et al. (2024) investigated the relationship between the site Exposure Index (EI) and the required capacities and material costs of aquaculture structures for a range of sites in the German Bight of the North Sea. Their research built upon the exposure indices proposed by Lojek et al. (2024) and employed Hydro-/Structural Dynamic Finite Element Analysis (HS-DFEA) to quantify the required structural capacities as a proxy for structural capital expenditures for cultivation structures as a function of exposure index. They selected representative sites across the German Bight based on extreme hydrodynamic and mean bathymetric conditions, utilizing a k-means clustering approach to analyze the data in a five-dimensional parameter space. For each site, the required capacities were quantified for three representative farm types: finfish net pens, mussel longlines, and tensioned macroalgae arrays. Through a detailed analysis of the dynamic simulations under 50-year storm conditions, the research calculated the minimum required breaking strength of structural lines for each farm type for each site. This study aimed to offer insights into the efficacy of reducing the design significant wave height, peak periods, horizontal wave orbital velocity amplitudes, horizontal current speeds, and water depth into a single index to represent the effects of exposure level. The results showed that 1) significant wave height and water depth are poorly or even negatively correlated with the required structural capacity of the cultivation structure, making them poor indicators of the severity of ocean sites. Of the six proposed indices, the Specific Exposure Energy (SEE) and the Drag-to-buoyancy Ratio (SDBR) had the highest correlations across structure types. (It should be noted that for any given structure, the SEE and SDBR are exactly proportional, but with different units. Since the SEE is independent of structural parameters, the authors prefer it over the SDBR for most applications.) The Exposure Velocity at Reference Depth (EVRD) yielded marginally higher correlation coefficients for the finfish system while the Specific Exposure Energy showed the highest correlations for the shellfish and seaweed structures. Therefore, this investigation indicates that this exposure index can be used to better quantify exposed ocean sites and aid in communication between stakeholders.

Publication 7: "The Social Science of Offshore Aquaculture: Uncertainties, challenges and solution-oriented governance needs" by Krause et al. (2024).

As technology allows for aquaculture development in exposed locations further from shore, social and governance challenges associated with aquaculture are amplified and new challenges are emerging. Therefore, it is important to bring a social science perspective to offshore aquaculture that bridges science and society. A critical social science evaluation of offshore aquaculture focusing on the existing state of knowledge and governance brings forward important challenges and uncertainties for aquaculture that require a social science epistemological understanding to inform solutions-oriented governance of offshore systems.

Although some jurisdictions are beginning to explore offshore aquaculture policies, a lack of regulatory frameworks that support permitting is an obstacle for the industry. Frameworks remain fragmented and issues of jurisdictional authority must be resolved. Improved understanding of societal perceptions of offshore aquaculture including conflicts arising from expansion into the offshore space and acceptance of new technologies is required. While moving aquaculture offshore has the potential to mitigate environmental impacts, uncertainty regarding the costs of new technology, benefits to society, and new supply chain logistics requires investigation.

Governance of offshore aquaculture requires a fundamental shift in regulatory frameworks and epistemological approach. New regulatory frameworks should be purpose-built to avoid the mistakes of the past, including highly fragmented and continually adapted frameworks. Solutions-oriented governance frameworks must recognize the complexity of emerging offshore production systems and integrate social dimensions to ensure the legitimacy, effectiveness, and long-term sustainability of the industry. This will require evolving transdisciplinary approaches that engage citizens and contribute to new transformative approaches to governance.

3 Discussion

3.1 "Offshore" versus "exposed"

The term "offshore" generally refers to activities or objects located far from the coast, typically in the open sea or oceanic environments, and is the antonym of the terms "onshore", "nearshore", and "coastal", which refer to activities or structures located on or near coastal land (see Buck et al., 2024 in this compilation). As the term "offshore" can have different meanings in different contexts, we refer only to the use of this term in the specific setting of aquaculture. This is the geographical region that is in the sea or ocean, away from the coastline. Often these waters are deep (but not necessarily so). We have defined the distance from the coastline as 3 nautical miles to consider an aquaculture farm as "offshore". This is approximately the distance from which an observer (average human height: 1.7 m tall) can no longer see an object (1 m height above the water surface) from the beach, i.e., it is out of sight. The term offshore can be qualified easily by specifying the distance from shore that a farm is.

Compared to "offshore", the term "exposed" refers to a condition in which an aquaculture farm is unprotected, vulnerable, and exposed (at least temporarily) to the direct impact of external factors.

As with the "offshore" definition, the word "exposed" can be used in different ways depending on the audience (exposed upland groups, exposed data and/or information, etc.). Again, we discuss this term with specific reference to aquaculture. In this context, aquaculture systems are "exposed" to levels of hydrodynamic energy or forces on the structures that vary as a function of their environment. Simply, an exposed site has a harsh climate. Not only are the organisms that are to be cultivated there subjected to stress, but the infrastructure, which is not shielded or protected from potential extreme oceanic conditions or external influences, is as well and thus must have a certain robustness. In the context of a site selection criteria analysis, the index defined by Lojek et al. (2024) can help to classify the sites made available for aquaculture and, according to Heasman et al. (2024b), to identify the right candidates for this site, including the O&M required for it. The index provided by Lojek et al. (2024) provides a means to describe a site's exposure with more granularity than the binary terms exposed vs sheltered allow. Finally, Dewhurst et al. (2024) showed how the capital expenditure of an aquaculture farm vary as a function of site exposure level.

Operational costs are also likely to vary as a function of exposure level, however, this is more difficult to model or comment on. There are no publicly traded companies that focus on exposed farm sites, making financial information difficult to access. Further, operational costs and the long-term financial success of farms are subject to many factors unrelated to the farm environment including management type, sales strategy, species, and farm size. Unlike with capital costs, it is difficult to make robust comparisons for operational costs and farm profitability between protected and exposed farm sites. Analysis on this topic will be increasingly feasible as exposed farms, commercial and research-scale, publish and share data. A better understanding of the impact of site energy on costs and profitability will be critical to investment and advancement in this sector.

As with almost all definitions that attempt to distinguish one term from the other, there are also smooth transitions. For example, an offshore site may also be subjected to harsh weather conditions. In this case, one could speak of an exposed offshore site. However, we do not want to set up small-scale definitions that could reignite the confusion in the terminology. Finally, the final take-home message from the entire Research Topic is: **"Offshore" is a question of distance, while "exposed" is a question of environment**.

3.2 Future research needs for "offshore" and "exposed" aquaculture

The future of marine aquaculture in offshore and/or exposed areas holds significant potential to meet the increasing global demand for seafood while reducing pressure on wild stocks. Below are some key research avenues that will facilitate the expansion of offshore and exposed marine aquaculture. Note that this list is specific to offshore and exposed sites and is not intended to capture all major research needs for aquaculture as a whole.

1. **Technological advances in system design:** The development of innovative and robust technologies for both floating and submergible service modes, as well as new materials for offshore and exposed environments is of prime importance to improve the reliability and reduce operational requirements and maintenance. Extreme conditions from tsunamis, cyclones, or hurricanes have not received sufficient attention to allow robust load estimations and render design recommendations feasible. The already unfavorable conditions that prevail in exposed areas have been considered - after all, such high-energy environments have so far been undesirable for many stakeholders and aquaculture is one of the few users to take this step. New technologies must be cost-effective enough to fit within farm capital structures while still allowing for competitive returns on investment (see Heasman et al., 2024a).
2. **Technological advances in operations and O&M:** Improved sensors and monitoring systems, automatic feeding systems, increased automation of operations, underwater drones, remote sensing, and artificial intelligence driven solutions increase the efficiency and sustainability of marine aquaculture in areas that cannot be reached easily or daily. These technologies help optimize feed conversion, water quality management, disease detection, automatic submerging and resurfacing of the farm depending on weather conditions, risks and hazards, and overall productivity (Føre et al., 2018; Parra et al., 2018).
3. **Environmental stewardship:** The future of offshore and/or exposed aquaculture will emphasize environmental sustainability. Considered and relevant regulations, best management practices and improved environmental impact assessments will be critical to minimizing the industry's environmental footprint. This includes minimizing effluents, capturing, retaining and transforming wastes from fed aquaculture, preventing fish escapes, and managing/avoiding interactions with wild fish populations. A greater understanding and utilization of the benefits of non-fed aquaculture species (e.g., bivalves and seaweeds) to environment restoration is needed. In that context, a better hydrodynamic understanding of closed systems, for example, for aquaculture fish farming is deemed necessary. Interactions with threatened species including cetaceans is critical as well although that is true for all forms of marine aquaculture.
4. **Confidence in financial model**: Offshore and exposed aquaculture farms are businesses which, like any business, require financial investment for operations to get started. This in turn requires confidence from lenders and investors. It can be difficult to build this confidence in a nascent industry, especially one that requires high initial capital costs and large economies of scale to succeed. Two areas that are particularly lacking are examples of success, and second-hand markets for equipment. Although there are several commercial scale farms that operate in offshore or exposed environments, and additional research scale facilities, there are no publicly traded companies that make their financial track record available. Further, given that a perspective farmer will be looking at a particular species and geography, there may be very few or zero comparable examples for that project. Financial models that are based on empirical examples can fill this need to some degree but more efforts to understand and communicate the financial opportunities and risk are needed. Second-hand markets for fish farming equipment are poor as there are limited buyers and the cost of relocating equipment is high. Still, systems or organizations that can connect sellers to buyers or create a better understanding of the value of capital assets will make it easier for farmers to borrow money, since lenders would have more confidence in the assets that are being borrowed against.
5. **Multi-use with other offshore ocean users:** There is potential for synergy between marine aquaculture and renewable energy production. Co-locating aquaculture facilities with offshore wind farms (OWF), for example, can help optimize resource use, create a more sustainable and integrated marine ecosystem, and increase the benefits of a locality while sparing other ecosystems that are consequently not used by such symbioses. New business structures, insurance models, and bold regulatory changes are needed to support development in this area. The

synergies between the aquaculture and the OWF operators or other multi-use stakeholders can be exploited to varying degrees. In addition to the simple sharing of the area for both users, the economic benefit can be significantly increased through the joint use of vessels, training, carrying out surveys (e.g. EIA) and many other aspects.

6. **Innovation and research in general production efficiency:** Ongoing research and innovation in areas that improve all sectors of aquaculture such as selective breeding, disease management, habitat design, and improved monitoring of candidate species health will continue to drive progress in offshore and/or exposed aquaculture. Many of these research areas will have different outcomes when looking at exposed environments, so research should consider variance in different farm environment when designing experiments. A new level of applied, transdisciplinary, international research efforts are required. Establishment of international research platforms at a meaningful commercial scale is recommended (e.g. the Bremerhaven Declaration). As stated by Stickney et al. (2006), due to the "the absence of large-scale facilities in the EEZ and associated research in conjunction with such facilities, the potential risks of open ocean aquaculture cannot be adequately evaluated".
7. **Cooperation among different stakeholders:** It is particularly important in offshore and exposed aquaculture to get improved cooperation among all stakeholders since the operations are more difficult, potentially more expensive, and with greater environmental risks, but also with a much higher potential to produce healthy food for the world. An understanding across all parties that aquaculture includes seaweeds and invertebrates (e.g. mussels) will lead to more efficient and integrated production systems. Collaboration between scientists, policy makers, industry stakeholders and conservation groups is essential for sustainable growth and addressing new challenges. This can only be made possible through the participation of all and through consistent and constructive exchange.

It is important to emphasize that the future of both offshore and exposed aquaculture depends on responsible and well-regulated practices that prioritize environmental sustainability, animal welfare, and social aspects. By adopting innovative approaches and incorporating best practices, offshore and exposed aquaculture has the potential to make a significant contribution to global food security while minimizing environmental impacts.

4 Conclusion

In conclusion, the need to expand ocean aquaculture has emerged due to various factors, including the growing demand for sustainable protein sources, and increased competition for sheltered marine locations and areas near urban centers. Expanding aquaculture operations into offshore and exposed waters presents opportunities to alleviate strain on coastal areas with limited space, address challenges posed by climate change and pollution on nearshore aquaculture sites, and access new resources. To ensure sustainable and efficient marine production, this will require:

1. a solid definition of the terms related to the site description where aquaculture takes place (not just "offshore", "exposed", or others) (see Buck et al., 2024 in this compilation);
2. a thorough understanding of the legal framework for all regions of our seas, marginal seas, bays, fjords, etc., especially for "offshore" and "exposed" areas (see Markus, 2024 in this compilation);
3. provision of trustworthy metrics (indices) for quantifying the exposure of aquaculture sites (see Lojek et al., 2024 in this compilation);
4. an understanding of the applications of the exposure indices (see Heasman et al., 2024a, 2024b in this compilation);
5. an understanding of the financial impacts of the transition to farming systems suitable for exposed environments (see Dewhurst et al., 2024); and
6. an understanding of the social science implications of "offshore", "exposed" as well as other regions for marine aquaculture (see Krause et al., 2024 in this compilation).

Defining the terminology associated with offshore aquaculture is essential for effective communication and standardization within research and industry. The ICES WGOOA has worked to redefine and clarify terms such as "offshore" and "exposed" based on distance from shore and hydrodynamic conditions. This effort aims to establish a comprehensive index that accurately describes the level of exposure at a given aquaculture site. Standardized terminology and site categorization provide a more precise understanding of the conditions and challenges associated with specific aquaculture locations. It enables stakeholders to evaluate physical attributes, engineering considerations, logistics, biology, health and safety, operations and management, social and environmental factors, economics, and policy and regulation.

The development of offshore aquaculture requires technological advancements that can operate effectively in more exposed ocean environments. Revolutionary breakthroughs and adaptations in technology, cultivation methodologies, as well as improvements in operations and maintenance procedures are necessary to ensure safe and sustainable operations. The utilization of indices, such as the exposure indices proposed by the ICES WGOOA, allows for the assessment of aquaculture sites in terms of potential and risk. These indices consider key parameters defining potential aquaculture sites such as wave height, water depth, and water currents, providing a standardized method for evaluating hydrodynamic exposure. The use of these indexes is free/open access for every interested individual and can be found under https://www.kelsonmarine.com/resources.

By addressing the need for offshore and exposed aquaculture through the establishment of precise definitions, technological advancements, and the utilization of standardized assessment methods, the industry can navigate the challenges and opportunities associated with expanding aquaculture into these environments. With a concerted effort from researchers, policymakers, and stakeholders, aquaculture in distant and exposed environments has the potential to meet the increasing global demand for seafood while ensuring sustainability and environmental stewardship.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

TS: Conceptualization, Formal analysis, Investigation, Supervision, Writing – original draft, Writing – review & editing. MC: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. BC-P: Conceptualization, Investigation, Writing – review & editing. TD: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. NG: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. KH: Conceptualization, Formal analysis, Investigation, Supervision, Writing – original draft, Writing – review & editing. WI: Conceptualization, Investigation, Writing – review & editing. GK: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. TM: Writing – original draft. DW: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. BB: Conceptualization, Formal analysis, Investigation, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

Author BC-P was employed by Ecological Aquaculture LLC. Author TD was employed by Kelson Marine Co. TS was employed by Innovasea Marine Systems Canada.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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The effect of site exposure index on the required capacities of aquaculture structures

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This study investigates the relationship between an ocean site's Exposure Index and the required capacity of finfish, shellfish, and seaweed aquaculture structures. This study provides insights into the efficacy of combining the design significant wave height, peak periods, horizontal wave orbital velocity amplitudes, horizontal current speeds, and water depth into a single index representing exposure. The research builds upon exposure indices proposed previously, and uses Hydro-/Structural Dynamic Finite Element Analysis (HS-DFEA) to quantify the required structural capacities for cultivation structures as a function of exposure index based on representative sites in the German Bight of the North Sea. The selection of 36 sites in this region was based on extreme hydrodynamic and mean bathymetric conditions, utilizing a k-means clustering approach to identify a collection of sites within a broad range of environmental conditions. Through a detailed analysis of the dynamic simulations of each farm type under 50-year storm conditions, we calculated the required capacities of each system for each site. We then evaluated the performance of significant wave height, depth, distance to shore, and the proposed exposure indices as linear predictors of the normalized required capacities. No meaningful linear relationship existed between structural loads and water depth or distance to the nearest coastline. While there is still uncertainty about the utility of exposure indices as a linear predictor of structural loads, this research found that Exposure Velocity was the best linear predictor across structure types by a slim margin, followed closely by the Specific Exposure Energy, Exposure Velocity at a Reference Depth of 5 m, and the Structure-centered Drag-to-Buoyancy Ratio (R^2 = 0.69, 0.61, 0.60, 0.60 respectively). This investigation indicates that these exposure indices can be used to communicate what physical ocean conditions mean for an aquaculture structure's required capacity.

KEYWORDS

exposure index, aquaculture, ocean engineering, shellfish, macroalgae, finfish, site selection

1 Introduction

Aquaculture is the fastest growing animal food production sector in the world (FAO et al., 2020). It has the potential to be sustainable and environmentally friendly compared to land-based agriculture (Nijdam et al., 2012; Gephart et al., 2014; Troell et al., 2014) and even has major ecological benefits (Theuerkauf et al., 2022). Aquaculture is a proven alternative to conventional capture fisheries and can become a stable economic engine for coastal communities that have had to deal with overfishing (Hilborn and Hilborn, 2012), ocean warming (Oremus, 2019), acidification (Byrne, 2011), more restrictive catch quotas (NOAA, 2017), and declines in migrating species (Limburg and Waldman, 2009).

Technologies and production methods for nearshore aquaculture exist, but suitable sites in protected waters are limited (Marra, 2005; Duarte et al., 2009; Sanchez-Jerez et al., 2016). There is a significant opportunity and necessity to expand aquaculture in the open ocean. According to National Institute of Standards and Technology, if industrial scale offshore production could be achieved, the farm gate value would be approximately $1.5–2B USD (Browdy and Hargreaves, 2009). In response to the the potential benefits, NOAA Fisheries developed a permitting process for developing open-ocean aquaculture in the Gulf of Mexico (NOAA, 2016).

However, the costs of venturing into large-scale offshore operations will be substantial, involving considerable upfront capital expenditure typically driven by the required structural capacities of mariculture structures. To support new ventures in aquaculture and ensure sound site selection, the levelized cost of production must be considered. Earlier insights into the challenges of "offshore aquaculture" or site exposure point to the importance of water depth, significant wave height, and distance from the coast (Ryan, 2004; Lovatelli et al., 2013; Froehlich et al., 2017). Site suitability studies, which often are based on a Geographic Information System, account for socio-economic and marine use constraints, distance from a port or harbor, environmental impact, applicable biological and physical ocean conditions for growth, species and structure survival, and farm operations (Falconer et al., 2013; Puniwai et al., 2014; Porporato et al., 2020). The mariculture structure technology for exposed offshore environments is still in development (Goseberg et al., 2017; Moscicki et al., 2024) and a generalized relationship between the required structural capacities of mariculture structures and the physical characteristics that define a site (e.g. depth, current velocity, wave environments) is not defined. Defining this relationship in a digestible manner supports site suitability studies as well as estimates of capital expenditures associated with aquaculture structures.

Lojek et al. (2024) developed and presented six different indices ("exposure indices") to quantify the hydrodynamic exposure of various ocean sites, combining the effects of current velocity, significant wave height, peak wave period, depth, and structure characteristics into single characteristic values. Therein, extreme exposure indices with a 50-year return period were spatially evaluated within the German Bight of the North Sea using data products obtained from the EasyGSH-DB portal (Hagen et al., 2021; Sievers et al., 2021; www.easygsh-db.org). However, no relationship between 50-year exposure indices and the resultant structural loads on aquaculture structures was investigated. Defining how the proposed exposure indices relate to required structural capacities is necessary to understand their utility. To address this gap in knowledge, this study investigates the relationship between the required structural capacities and exposure indices across a range of exposed sites and a series of aquaculture structures.

This study places emphasis on understanding if an exposure index is approximately proportional to maximum loads on an aquaculture structure; the existence of this quality supports both (a) the utility of the exposure index and (b) its interpretability by subject matter experts and non-experts alike. This research demonstrates that select exposure indices can effectively quantify ocean site exposure and its implication for the required capacity of aquaculture structures through a linear relationship. While this approach provides a general and accessible framework, there remains uncertainty in the relationship.

This manuscript is one of a suite of papers compiling a Research Topic, "Differentiating and defining 'exposed' and 'offshore' aquaculture and implications for aquaculture operation, management, costs, and policy". The Research Topic includes manuscripts focused on aquaculture policy and regulation in marine environments, the definitions of terms regarding aquaculture in marine systems, the derivation of the energy index, trends required to advance aquaculture into high energy marine zones, costs and implications in aquaculture of using the index and social science aspects relating to marine aquaculture (Buck et al., 2024).

2 Materials and methods

The proposed exposure indices in Lojek et al. (2024) each provide an indication of any ocean site's exposure to hydrodynamic energy or forcing. In the present study, we aim to evaluate the relationship between extreme 50-year exposure indices and design mooring line loads (proportional to the required capacity) of select mussel, macroalgae, and finfish aquaculture structures. Here, we evaluate relationships between exposure indices and mooring line capacities at representative sites in the German Bight of the North Sea by:

1. Selection of representative physical ocean conditions at aquaculture sites (n=36) through a k-means clustering approach,
2. Engineering design of aquaculture cultivation structures at each site with common geometries across structure types characterized by a 200-meter-long mussel backbone growline, a 38 m by 187m tensioned macroalgae array, and a 12 m diameter and 6 m deep finfish net pen,
3. Hydro-/Structural-Dynamic Finite Element Analysis (HS-DFEA) numerical modeling of the aquaculture structures under static calm-water and dynamic extreme load cases,
4. Calculation of the normalized required capacity of each aquaculture structure,
5. Calculation of the extreme values of exposure indices, and
6. Linear regression of (i) normalized required capacity on each of the parameters that previously designated sites as "offshore" and (ii) normalized required capacity on each of the extreme exposure indices.

2.1 Definition of hydrodynamic variables and exposure indices

Lojek et al. (2024) developed and proposed six exposure indices: Exposure Velocity (EV), Exposure Velocity at a Reference Depth (EVRD), Specific Exposure Energy (SEE), Depth-integrated Energy Flux (DEF), Structure-centered Depth-integrated Energy (SDE), Structure-centered Drag-to-Buoyancy Ratio (SDBR). Definitions of exposure indices consider (i) hydrodynamic variables describing design waves, currents, and depths and (ii) structural properties such as characteristic diameter or solidity. For the derivation and further description of each exposure index, readers are directed to Lojek et al (2024), Section 2.

Hydrodynamic variables considered in the definition of exposure indices include: vertical position z (positive up), depth d ($d = -z$ at seabed), horizontal current velocity $\vec{U_c}\,(z)$ and speed $U_c(z) = \| \vec{U_c}\,(z)_2 \|$, significant wave height H_s, peak wave period T_p, wave energy period T_E, horizontal wave orbital velocity amplitude $u_w(z) = \frac{\pi H}{T}\frac{\cosh k(z+d)}{\sinh kd}$ (in application, $H_s = H$ and $T = T_p$). Structure based variables include: non-dimensional structural component solidity S, structural component surface area surface area $A_{structure}$, structural component characteristic length D. Assumed constants in application include seawater density, ρ, and gravitational acceleration, g.

Of these metrics, EV, EVRD, SEE, and DEF are independent of structural properties, whereas SDE and SDBR incorporate the structural components characteristics. The EV and EVRD (or EV at a depth of 5 m),

$$EV = \;\; U_c(z) + u_w(z) \tag{1}$$

$$EVRD = U_{c5} + u_{w5} \tag{2}$$

have units of distance per unit time and were proposed to take into account the loads on aquaculture structures depend on the combined current and wave-induced fluid speeds. The SEE,

$$SEE = 1/2 \;\; (U_c(z) \; + \; u_w(z))^2 \tag{3}$$

which has units of energy per unit mass, was constructed to be proportional to the square of the sum of current and wave-induced fluid velocity, which is proportional to the drag force in the classical drag equation. The DEF,

$$DEF = \frac{\rho g^2 (H_s^2) T_E}{64\pi} + \frac{1}{2}\rho d (U_c)^3 \tag{4}$$

has units of power per unit distance and was adapted from measures of wave- and current-energy flux used in marine renewable energy applications. The structure-dependent SDE,

$$SDE = (1/8 \cdot g \cdot H_s^2 + 1/2 \cdot d \cdot U^2\,) \cdot \rho \cdot S \cdot A_{structure} \tag{5}$$

has units of energy times mass per volume and integrates wave and current energy from the seafloor to the water surface. The SDBR,

$$SDBR = \frac{U^2}{2gD} \tag{6}$$

is a non-dimensional number to represent the ratio of drag forces to buoyancy forces on a structure, using classical equations for a slender cylinder.

2.2 Study area characterization: German Bight of the North Sea

2.2.1 Study area description

The nearshore and coastal ocean of the German Bight of the North Sea (Figure 1) is characterized by tidal and atmospheric forcing from the North Sea and North Atlantic Ocean connection, which interact over a shallow, gently sloping seabed and within the estuaries, tidal

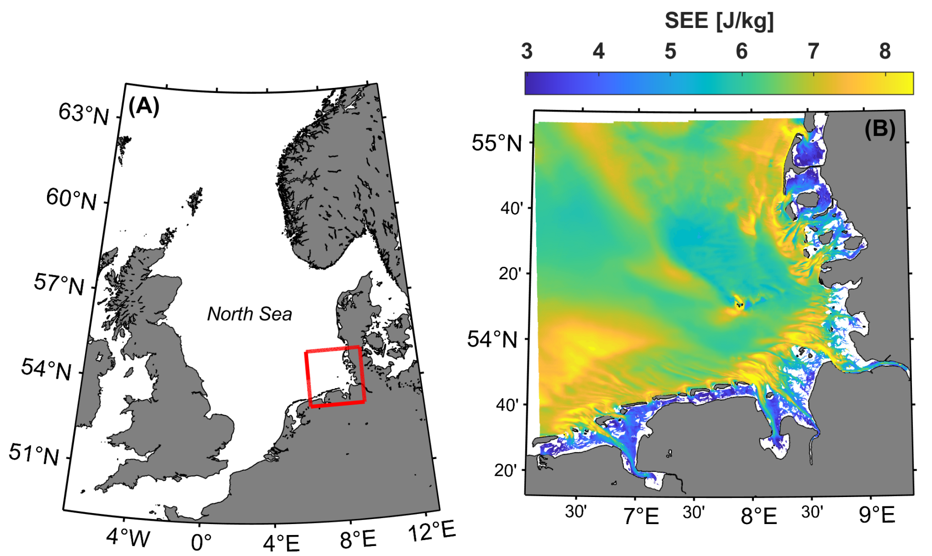

FIGURE 1
The **(A)** North Sea and German Bight study area (red box) in relation to **(B)** the computed 50-year Specific Exposure Energy (SEE). Adapted from Lojek et al. (2024). Graphic made with M_Map (Pawlowicz, 2020) with data products from Hagen et al. (2020), Sievers et al. (2020) and Wessel and Smith (1996).

inlets, and ~10 km wide intertidal mudflats of the Wadden Sea along the coast. Low pressure systems of winter storms in the North Sea produce storm surges and energetic wind waves in the German Bight. Oscillations in tidal currents and water levels, which enter through the Strait of Dover in the southwest and through an open-ocean connection in the northwest, are non-linear and reflect a co-oscillating response (Hagen et al., 2020). Semidiurnal tides dominate, with currents that propagate counter-clockwise about the German Bight and are deflected towards the coast, reaching maximum amplitudes in the center of estuarine channels (Hagen et al., 2020). Residual tidal circulation forms a counter-clockwise pattern along the German Bight coastline (Klein and Frohse, 2008). Variations in sea surface temperatures and salinity in the German Bight generally follow a positive and negative land-to-sea cross shore gradient respectively, driven from continental river run-off and the atmospheric warming of the shallow waters of the Wadden Sea. On shorter time scales of 1 to 10 days, fronts with a length scale of 5 to 20 km are observed and are known to concentrate the density of marine life.

Aquaculture within the German Bight is primarily focused on shellfish cultivation of mussels and oysters (Clawson et al., 2022). Scientific case studies have demonstrated that the German Bight is a suitable region for the cultivation of macroalgae (Buck, 2007). Historically, finfish aquaculture is not a common practice due to the regions extreme hydrodynamic conditions and shallow nearshore depths (Rosenthal and Hilge, 2000). However, future expansion into open ocean regions further from shore may be facilitated through the development of new technologies and co-location with offshore wind farms (Buck et al., 2018). Constructed, commissioned, and planned offshore wind park areas within the German Bight are available in Hannemann (2024) to provide further context to the body of literature that discusses multi-use concepts involving offshore wind and aquaculture production (Buck et al., 2008; Gimpel et al., 2015; Buck and Langan, 2017; Przedrzymirska et al., 2021).

2.2.2 High-resolution regional datasets

The characterization of surface currents, significant wave heights and associated peak periods, and mean depths follows that of Lojek et al. (2024). Analysis of hydrodynamic parameters was facilitated through EasyGSH-DB. EasyGSH-DB maintains open access to a 20-year 100 m gridded dataset of bathymetry, 100 m gridded wave parameters, and 1 km depth averaged current velocities in the German Bight—the latter two are derived from a spectral wave model hindcast and a 3D regional ocean model hindcast, respectively (Hagen et al., 2021). The EasyGSH-DB products (Hagen et al., 2020; Sievers et al., 2020) and metadata were obtained from the EasyGSH-DB portal (www.easygsh-db.org).

2.2.3 Extreme values of hydrodynamic parameters

Univariate extreme value analysis of significant wave heights and depth averaged current speeds follows that of Lojek et al. (2024), who fit series of annual maxima to the Gumbel distribution to derive extreme values at the 2% exceedance probability (50-year return period) for each parameter. The 50-year depth averaged current speeds were interpolated to the same 100 m grid as H_s and bathymetry, using linear interpolation throughout most of the domain and nearest neighbor interpolation along the coastline. 50-year surface current speeds were estimated from 50-year depth average current speeds by assuming current profiles followed a power law in the vertical with an exponent of 1/7 and no-slip at the bottom boundary.

2.3 Aquaculture site selection

To ensure that the breadth of possible site characteristics was considered, a subset of important hydrodynamic variables were sampled and used as criteria for representative site selection. The objective of aquaculture site selection was to define a representative subset of hydrodynamic variables that exist within the German Bight. The authors acknowledge the site selection methodology does not represent the full breadth of hydrodynamic variables that coexist in the coastal ocean.

A set of 36 representative sites across the German Bight were selected from the 100 m regular gridded values of extreme hydrodynamic variables and mean depth. Variables considered include (1) significant wave height H_S, (2) peak wave period T_p, (3) horizontal wave orbital velocity amplitude u_w, (4) horizontal current speed u_c, and (5) water depth d at mean sea level. Selected hydrodynamic variables were used both in the evaluation of exposure indices (e.g. Specific Exposure Energy, Figure 1) and in load cases for numerical simulation of aquaculture cultivation structures.

The selection of 36 representative sites in the 5D parameter space C with dimensions corresponding to variables (1)–(5) was achieved through k-means clustering in two discrete phases. The k-means algorithm seeks to identify clusters in an n-dimensional variable space by grouping (or clustering) data such that the sum of within-cluster variances is minimized (Hartigan and Wong, 1979). Each variable $x \in C$ was normalized by its mean μ and standard deviation σ , to define $x_n = \frac{x-\mu}{\sigma}$ such that equal scales of variables are considered against one another when computing the sum of variances in the k-means algorithm. The centroid of each identified cluster in the normalized variable space was then transformed back into the original variable space by multiplying centroids by σ and then adding μ. This implementation of the k-means algorithm does not explicitly account for spatial autocorrelation, since it does not directly consider the spatial arrangement of data points. In the first phase, the selection process considered all points with depths greater than 10 m. In the second phase, sites reflecting lower energy regions that were at least 1.5 km away from the coast were selected through k-means clustering of a subset of C defined by all locations where the horizontal wave orbital velocity amplitude and the horizontal current speed were below their respective 5th quantiles and a relaxed minimum depth of 7 m.

The cluster centroids, or the mean value of each cluster, are shown in Figure 2 with respect to C . The representative locations of each cluster defining the 36 sites are overlaid on maps of each key metocean variable in Figure 3. Lastly, the distance to the nearest coastline was calculated for each site.

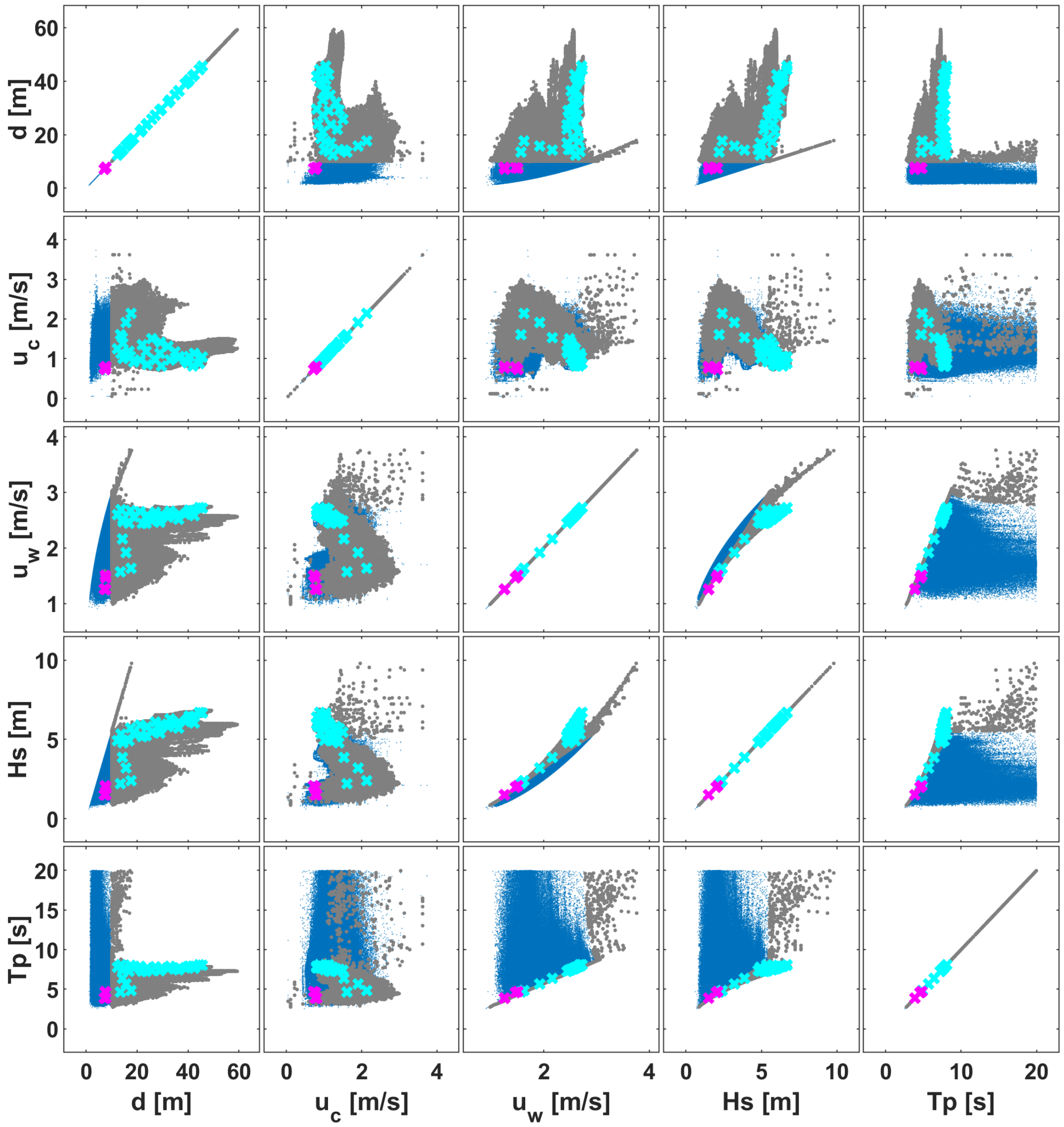

FIGURE 2
Cluster centroids of the 36 sites (cyan and magenta crosses denote phase one and two of site selection described in Section 2.3) that represent a wide range of water depths and metocean parameters in the German Bight. Blue and grey points denote the full German Bight dataset and the subset from which samples were selected.

2.4 Aquaculture structure design and engineering

The design and engineering of finfish, macroalgae, and shellfish cultivation structures incorporated existing industry and government engineering standards. Several industry and government engineering standards exist, some specific to aquaculture, including: Floating aquaculture farms–Site survey, design, execution and use (NS9415) (Standards Norway, 2022), "A Technical Standard for Scottish Finfish Aquaculture" (Ministerial Group for Sustainable Aquacultures Scottish Technical Standard Steering Group, 2015), "Guidance Notes on the Application of Fiber Rope for Offshore Mooring" (ABS, 2011), "Design and analysis of station keeping systems for floating structures" (API, 2005), and Basis-of-design technical guidance for offshore aquaculture installations in the gulf of Mexico (Fredriksson and Beck-Stimpert, 2019).

NS9415 and the Scottish standard mandate that structures be designed to withstand 50-year storms. No agreed-upon standard exists for non-finfish aquaculture. For uniformity, the 50-year storm condition was used as the design standard for the present study.

For each site selected in Section 2.3, the following procedure was followed: (1) design of cultivation structure with a site-specific mooring design, (2) simulation of cultivation structure under dynamic 50-year conditions (the 50-year storm) based on

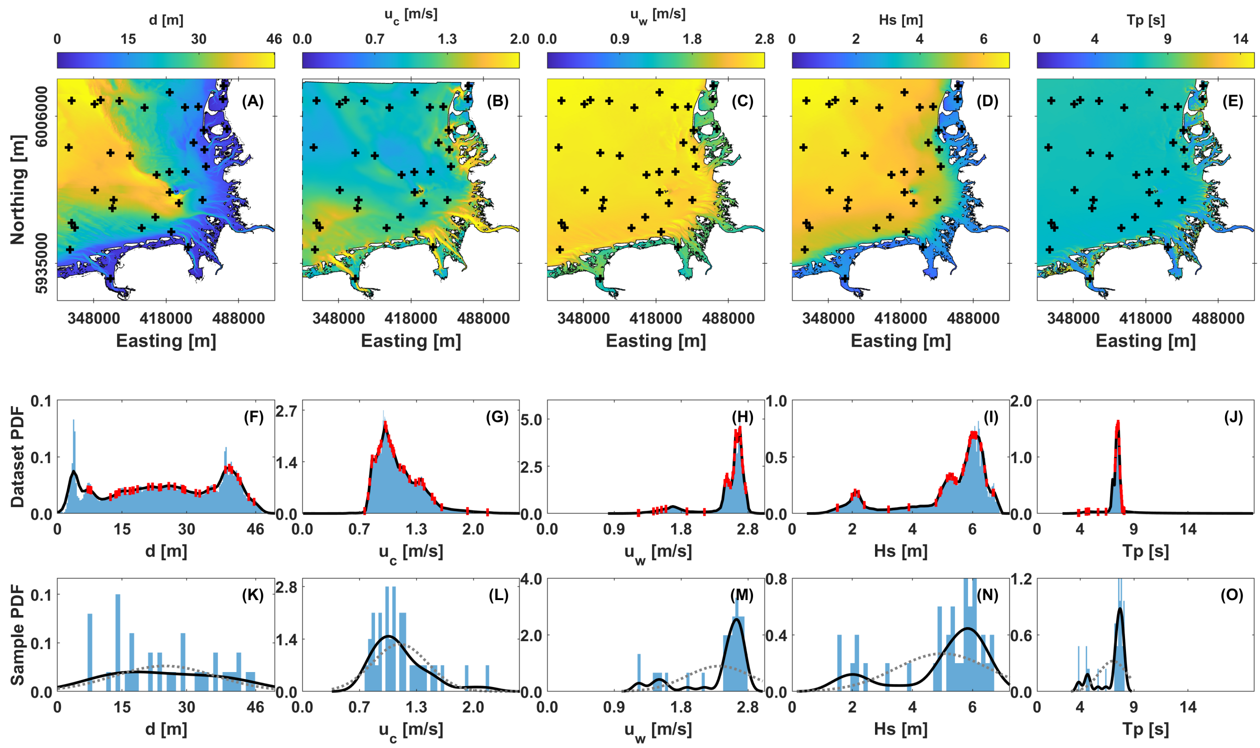

FIGURE 3
The German Bight in relation to the nearest $x \in C$ to each of the 36 selected sites black crosses in **(A–E)**. From left to right, columns represent the variables: mean depth, 50-year horizontal surface current speed, 50-year horizontal wave orbital velocity amplitude at surface, 50-year significant wave height, and peak wave period associated with 50-year significant wave heights. In **(F–J)**, the selected sites are represented in relation to the histogram and kerel density estimate (KDE) of the PDF by the red vertical points. In **(K–O)**, the histogram and KDE of the sample of 36 selected sites is visualized similarly in comparison to the best fit-fit normal distribution.

extreme values of hydrodynamic parameters found in Section 2.2.2, and (3) quantification of the required loading capacities of mooring lines and anchors under 50-year conditions.

2.4.1 Numerical modeling approach

The hypothetical farms are located in exposed ocean sites subject to waves and currents. Each cultivation system is comprised of flexible components subject to nonlinear wave and current forces. Therefore, static analysis of the structure was not sufficient for determining the required structural capacity. Instead, numerical models of the proposed backbone systems were developed using a Hydro-/Structural Dynamic Finite Element Analysis (HS-DFEA) approach. This HS-DFEA approach solves the equations of motion at each time step using a nonlinear Lagrangian method to accommodate the large displacements of structural elements, as described in Fredriksson and Beck-Stimpert (2019) and as applied previously in Coleman et al. (2022) and Moscicki et al. (2024a). Wave and current loading on buoy and line elements (including mussel rope elements) is incorporated into the model using a Morison equation formulation (Morison et al., 1950) modified to include relative motion between the structural element and the surrounding fluid. For elements intersecting the free surface, buoyancy, drag, and added mass forces are multiplied by the fraction of the elements volume that is submerged.

2.4.2 Mussel farm design

The mussel farm consists of a single 200-meter-long backbone line with anchor lines on either end (Figures 4, 5). Mussels are grown

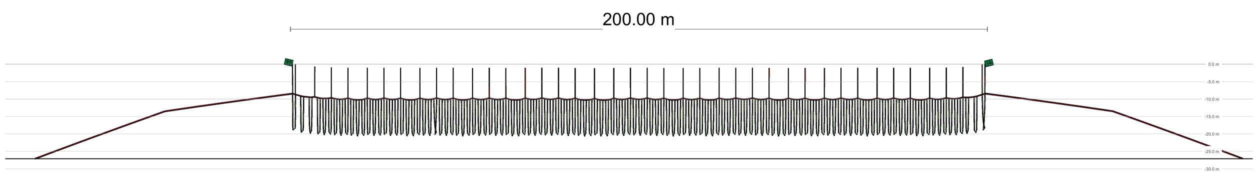

FIGURE 4
Dimensioned profile view of evaluated backbone system in still water.

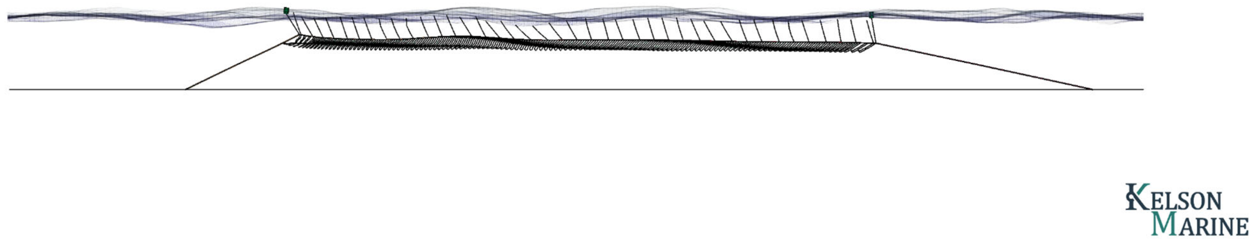

FIGURE 5
Dynamic HS-DFEA simulation of the mussel backbone system in 50-year storm conditions at Site 27.

on hanging growlines attached to the backbone line, with large floats at anchor line connection points and dropper floats spaced along the backbone line. The structural and hydrodynamic parameters of the mussel lines were taken from Dewhurst (2016) and Dewhurst et al. (2019). The diameter of the mussel ropes was set so that the dry weight of mussels was 12 kg per m of mussel rope. This was based on observations of typical maximum growth on mussel farms in the Gulf of Maine. The net in-water weight of the mature mussel ropes was taken to be ¼ of the dry weight (Bonardelli et al., 2019). Since each backbone in the array has its own anchors and is independent of the other backbones, an individual backbone system was examined with components as defined in Table 1.

2.4.3 Macroalgae farm design

For macroalgae, a tensioned array with 18 growlines (i.e. substrate for macroalgae growth) and four mooring lines was evaluated (Figures 6, 7) The structural layout was similar to that described in (Coleman et al., 2022) but designed to have approximately the same amount of biomass as on the mussel backbone system. The farm is anchored with lines at each corner. A pair of header lines connect the anchor lines and serve as end attachments for the growlines. As with the mussel farm, large buoys are located at each header-anchor line junction and dropper floats are spaced along growlines to maintain buoyancy. Loads on the structure were evaluated using a methodology as described in Moscicki et al. (2024) and validated against the dataset in Fredriksson et al. (2023).

2.4.4 Finfish farm design

The finfish structure considered was a single net pen whose properties were based off a prototype built and tested by Gansel et al. (2018). The structure properties as evaluated are given in Table 2. The net hydrodynamics were simulated using a method developed and validated by Kelson Marine that accounts for net solidity, instantaneous relative fluid speed, and incident flow angle on the net panels. This model was validated to within 25% RMS error of the full-scale field measurements reported by Gansel et al. (2018). In the present study, this cage system was embedded in a single-bay, four-mooring line mooring grid as shown in Figures 8, 9.

2.4.5 Load cases considered

NS 9415 and the Scottish finfish standard mandate that structures be designed to withstand 50-year storms. They stipulate that two 50-year events should be examined in each of the eight compass directional sectors: (1) 50-year wave conditions combined with 10-year current conditions (the wave-dominated case) and (2) 50-year current conditions combined with 10-year wave conditions (the current-dominated case). For simplicity, the present study considered coincident in time and co-directional 50-year wave and 50-year current conditions with no wind loading. Since the seabed is planar and the aquaculture structures are symmetric about at least one axis, three 50-year load cases are evaluated for each farm design, with waves and currents directed at 0, 45, and 90 degree angles relative to their axis of symmetry.

TABLE 1 Mussel backbone components as analyzed in HS-DFEA simulations.

Component	Material	Qty	Length each m	Net Buoyancy total for material kgf	Volume each m^3
Mooring Line	PPE*	2	84	14.4	5.77E-02
Backbone	PPE* (weighted)	1	200	5	2.04E-01
Surface Floats	220L Float	26	1.20	5102	2.20E-01
Surface Float Tether	PPE*	26	8.00*	10	3.16E-03
Mooring Midline Float	800L Float	2	0.55	125	8.00E-02
Mooring Midline Float Tether	PPE*	2	2.00	1	7.89E-04

*Polypropylene, polyethelene blend. Surface float tether length and resulting backbone depth, z, were dependent on water depth, such that $z = max(-\frac{1}{2}(d - 10\text{ m}), -8\text{ m})$.

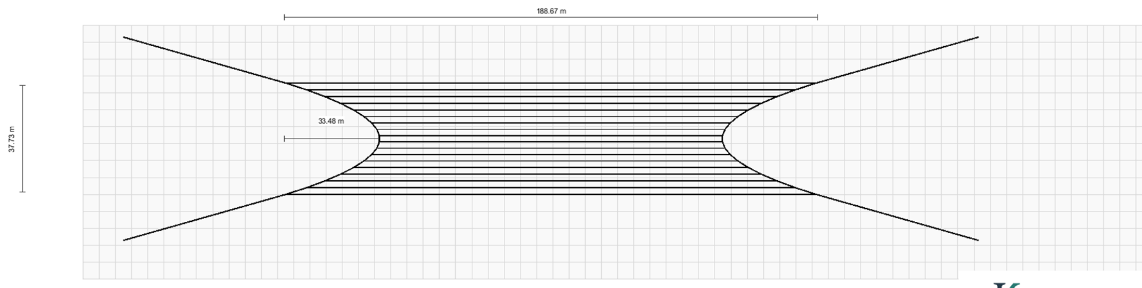

FIGURE 6
Plan view diagram of the macroalgae cultivation system evaluated.

2.4.6 Calculation of required structural capacities

The maximum design loads on all anchoring lines were evaluated based on the results of the dynamic simulations of the cultivation systems at maximum biomass in the 50-year storm conditions. Each of the three farms was simulated for either 900 seconds (finfish) or 1800 seconds (seaweed and shellfish) at each representative site and with three incident wave/current directions. The expected 1-hour extreme loads were calculated from these results using a Peaks-Over-Threshold statistical approach (Coles, 2001). The maximum design load at each representative site is reported as a normalized required capacity (NRC), or

$$NRC = T/T_{max} \tag{7}$$

where T is the maximum 1-hour extreme loads from each load case at the site and T_{max} is the maximum load over all sites and load cases.

2.5 Calculation of exposure indices

Exposure indices were computed for each selected aquaculture site. Calculations employed the regional data products described in Section 2.2.2 and 2.2.3 using the mean depths, design hydrodynamic variables defined by the 50-year return values, structure solidity $S = 0.25$, and structure characteristic length/diameter D = 1.0 m. The z coordinate for the evaluation of the current velocity and wave-induced horizontal orbital velocity amplitudes was set based on the aquaculture structure geometry (see Section 2.4.2, 2.4.3, 2.4.4). The finfish system z coordinate was set halfway down the net-pen to $z = -3$ m, the shellfish z coordinate was set to be the backbone depth and the macroalgae z coordinate was set to a constant depth of the growline or $z = -2$ m. An example map showing the SEE at the surface evaluated over the German Bight is provided in Figure 1. For maps of the full list of proposed indices, see Lojek et al. (2024).

2.6 Linear regression: exploring linear predictors of required structural capacities

The efficacy of exposure indices as a single metric that is approximately proportional to loads on aquaculture structures was evaluated through simple linear regression. Simple linear regression considered the relationships between site specific exposure indices or hydrodynamic variables (i.e. the independent variable or predictor) and sampled normalized required capacities

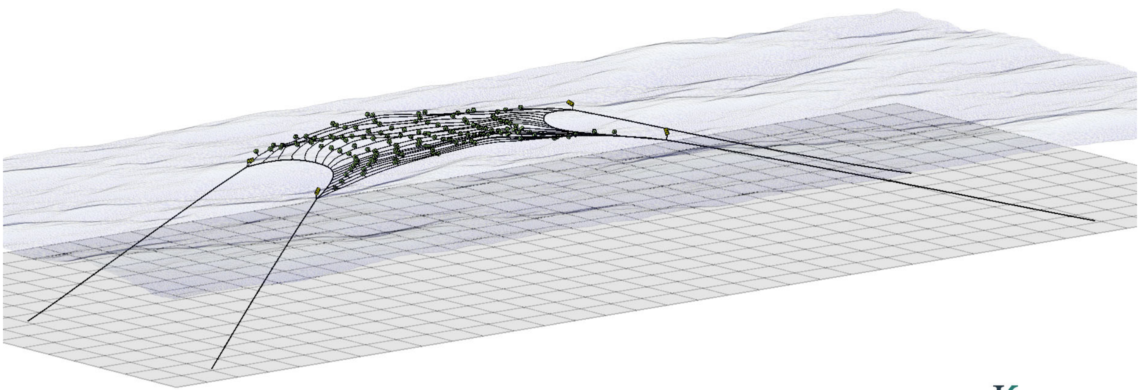

FIGURE 7
Dynamic HS-DFEA simulation of the macroalgae cultivation system in 50-year storm conditions at Site 18.

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TABLE 2 Parameters of finfish net pen system evaluated.

Parameter	Value
Cage diameter [m]	12
Cage depth [m]	6
Net solidity [Sn]	0.27

Component	Type	Dimension
Net, sides	Nylon (Egersund Net Nr 20)	15 mm (half mesh), 2 mm (thread diameter)
Net, bottom	Nylon (Egersund Net Nr 20)	15 mm (half mesh), 2 mm (thread diameter)
Top rope	Danline	14 mm
Main rope	Danline	14 mm
Bottom rope	Lead-line	0.5 kg
Cross rope	Danline	14 mm
Side rope	Danline	14 mm
Weight tethers	N/K	10 mm
Weights	Concrete	8 x 35 kg in water

(i.e. the dependent variable or response) (Montgomery et al., 2012; The MathWorks, 2024). Each combination of independent variable $x = \{x_1, x_2, \ldots, x_n\}$ and dependent variable $y = \{y_1, y_2, \ldots, y_n\}$ was fit to the linear model,

$$y = \beta_0 + \beta_1 x + \varepsilon \tag{8}$$

for model coefficients β_0 and β_1 through minimizing sum of squared residuals in $\varepsilon = \{\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_n\}$. This assumes: (1) a linear $x - y$ relationship, (2) homoscedasticity or equal variance of residuals, (3) normality of residuals, (4) independence of residuals, and (5) absence of outliers. To assess the quality of each regression, results were visualized, the coefficient of determination R^2 was calculated to assess the proportion of variance in NRC that is explained by the linear regression with x, and bootstrapped confidence interval estimates of regression coefficients and of the line of best fit were calculated. Nonparametric bootstrapping utilized percentile interval confidence intervals at a 0.05 significance level through case resampling (n=1000) to avoid breaking assumptions (3)–(5) (Fox, 2002). Assessment of the normality of the residuals was facilitated by the Anderson-Darling test at a 0.05 significance level (Stephens, 1974; Trujillo-Ortiz, 2007).

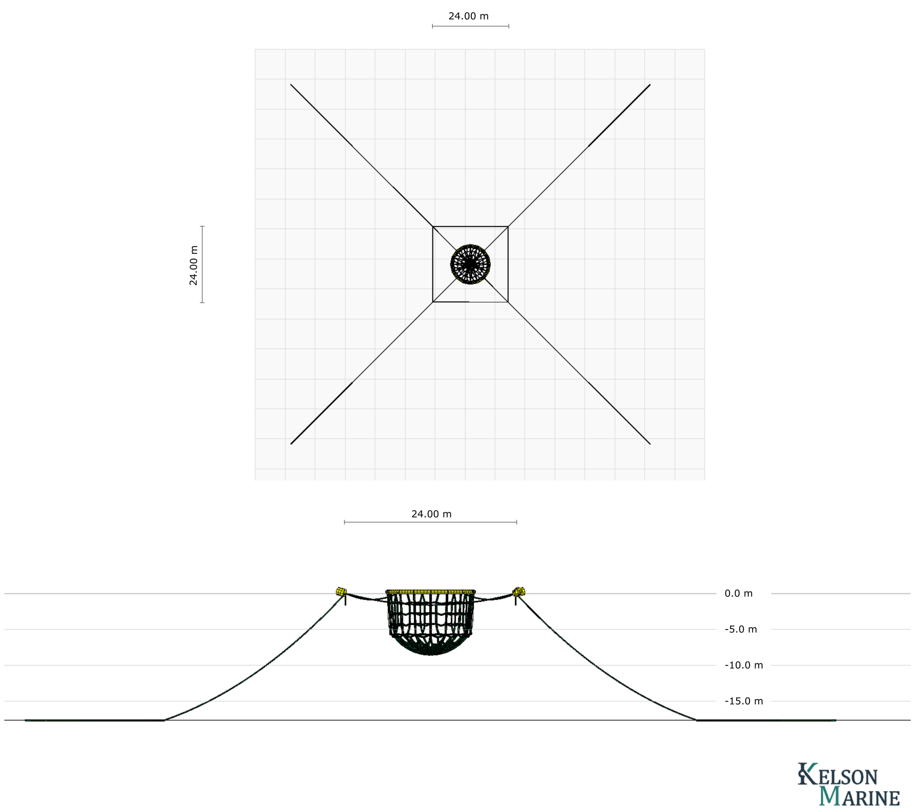

FIGURE 8
Finfish net-pen and mooring layout considered, showing the design in plan view and in profile view.

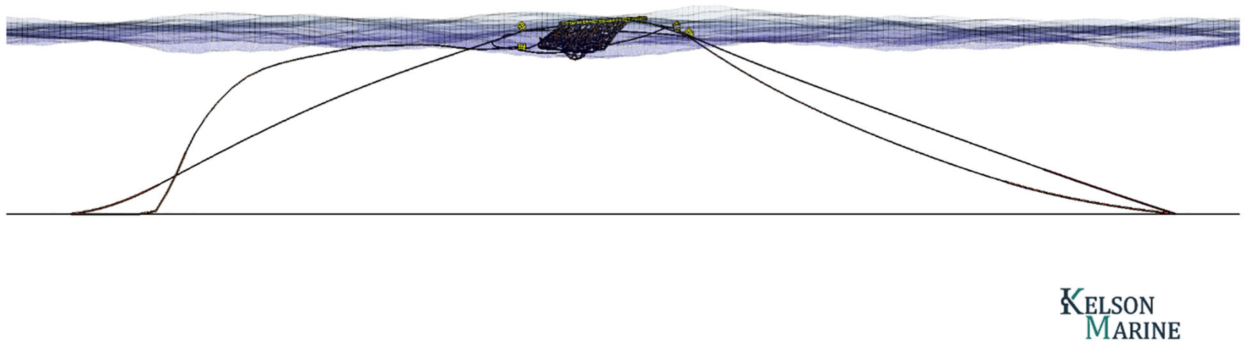

FIGURE 9
Dynamic HS-DFEA simulation of the finfish net-pen in 50-year storm conditions at Site 19.

TABLE 3 Site hydrodynamic parameters and aquaculture structure normalized required capacity.

Site	U_c	H_s	T_p	u_w	d	Distance to coast	Normalized required capacity		
							Finfish	Shellfish	Seaweed
–	*m/s*	*m*	*s*	*m/s*	*m*	*km*	–	–	–
Calm Water	0.00	0.0	0.0	0.00	17.6	–	0.00	–	0.01
					45.6		–	0.02	–
1	1.41	5.7	7.5	2.45	29.3	26	0.82	0.8	0.84
2	1.18	4.9	7.3	2.38	16.8	4	0.69	0.74	0.8
3	0.85	5.8	7.7	2.52	24.0	110	0.64	0.56	0.71
4	1.91	3.2	5.7	1.85	15.7	3	0.30	0.93	0.97
5	0.97	6.1	7.7	2.52	39.0	104	0.50	0.62	0.72
6	1.05	6.5	7.9	2.59	40.5	1	0.78	0.67	0.74
7	2.14	2.4	4.8	1.57	17.6	9	0.47	1	1
8	1.24	4.9	7.8	2.55	12.3	31	0.68	0.77	0.87
9	1.13	6.0	7.6	2.49	42.4	78	0.61	0.67	0.76
10	1.05	5.7	8.0	2.61	17.5	4	0.59	0.74	0.83
11	0.91	5.4	7.6	2.49	18.6	54	0.41	0.61	0.74
12	1.17	5.9	7.6	2.48	34.9	51	0.78	0.68	0.77
13	1.02	5.7	7.4	2.43	36.4	20	0.65	0.58	0.73
14	1.04	6.7	8.1	2.62	45.6	78	0.75	0.67	0.74
15	1.39	4.8	7.4	2.40	14.4	15	1.00	0.85	0.89
16	0.81	6.4	7.9	2.58	41.9	6	0.42	0.55	0.67
17	1.18	5.2	7.3	2.37	23.6	88	0.67	0.71	0.78
18	0.89	6.3	7.8	2.55	39.9	27	0.67	0.56	0.69
19	1.50	5.5	7.4	2.41	25.9	22	0.42	0.86	0.88
20	1.13	5.3	8.1	2.63	13.7	31	0.72	0.79	0.86
21	0.96	5.9	7.9	2.59	21.1	41	0.68	0.65	0.76
22	1.06	6.1	7.7	2.52	36.5	40	0.69	0.61	0.74
23	1.61	2.2	4.6	1.51	13.5	16	0.33	0.73	0.84

(Continued)

TABLE 3 Continued

Site	U_c	H_s	T_p	u_w	d	Distance to coast	Normalized required capacity		
							Finfish	Shellfish	Seaweed
–	m/s	m	s	m/s	m	km	–	–	–
24	0.88	6.7	8.1	2.63	44.4	49	0.68	0.61	0.7
25	0.96	6.3	7.9	2.57	33.0	37	0.71	0.62	0.72
26	1.53	3.9	6.4	2.09	14.3	0	0.48	0.81	0.89
27	1.13	5.4	7.3	2.38	29.0	16	0.61	0.65	0.76
28	1.00	5.0	7.5	2.46	14.4	2	0.58	0.7	0.77
29	1.31	5.8	7.6	2.47	32.1	49	0.58	0.72	0.81
30	0.81	6.0	7.7	2.52	29.6	32	0.63	0.55	0.68
31	0.97	6.1	7.8	2.56	27.3	8	0.71	0.62	0.73
32	1.35	5.2	7.2	2.37	22.1	55	0.75	0.78	0.84
33	0.76	1.5	3.9	1.27	7.1	2	0.26	–	0.54
34	0.78	2.0	4.5	1.49	7.7	3	0.31	–	0.66
35	0.80	1.5	3.8	1.26	7.8	2	0.30	–	0.54
36	0.72	2.1	4.7	1.54	7.5	4	0.30	–	0.67

Sites 1–32 and 33–36 correspond to the first phase and second phase of k-means sampling. Normalized required capacity with no data means that the site exceeded the minimum tolerable depth of the aquaculture structure.

3 Results

3.1 Site selection: hydrodynamic parameters and normalized required capacities

Selected mean depths and 50-year hydrodynamic parameters that define representative sites within the German Bight span a range of depths, surface current speeds, and wave environments. These values and the resultant normalized required capacity for each aquaculture structure are reported in Table 3. To place the sites in context from the perspectives of farm operations and to decouple the ideas of "offshore" and "exposed", the representative distance to coast of the site is reported as well. Normalized required capacities are not reported for sites where the minimum depth exceeds the characteristic length of the aquaculture structure in the z-dimension.

Figure 3 visualizes the representative selected sites with respect to the German Bight, including normalized histograms and kernel density estimates of the probability distribution functions of the German Bight dataset and representative sites.

Across sites 1–36, depth and hydrodynamic parameter sample distributions are further described by sample means, standard deviations, and measures of skewness. Mean seabed depths across sites range from 7.05 to 45.64 m with a sample mean, standard deviation and skewness of 24.73 m, 11.73 m, and 0.21. Significant wave heights across sites range from 1.5 to 6.7 m with a sample mean, standard deviation and skewness of 5.0 m, 1.6 m and −1.2. The associated peak wave periods range from 3.8 to 8.1 s with a sample mean, standard deviation and skewness of 7.0 s, 0.4 s and −1.3. Wave-induced horizontal wave orbital velocity amplitudes—which depend on depth, significant wave height, and peak wave period—range from 1.26 to 2.63 m/s with a sample mean, standard deviation and skewness of 2.39 m/s, 0.42 m/s and −1.4. Surface current speeds range from 0.72 to 2.14 m/s across sites, with a sample mean, standard deviation and skewness of 1.28 m/s, 0.32 m/s, 1.3. The distance to coastline of representative sites extend from the nearshore to offshore settings, ranging from 0.1 to 110.4 km with a sample mean of 31.1 km, standard deviation of 30.4 km, and positive sample skewness of 1.1.

Across sites 1–32, surface current speeds generally increase with decreasing significant wave heights while the greatest surface current speeds occur at sites with a depth less than 20 m. The associated peak wave periods align with the wave steepness limit.

3.2 Linear regression results: assessing linear predictors of required structural capacities

Linear regression of individual combinations of finfish, shellfish, and seaweed NRCs against H_s, d, distance to coast, EV, EVRD, SEE, DEF, SDE, and SDBR yielded varying results (Table 4; Figures 10, 11). Presentation of linear regression results are grouped based on linear predictors; results in Section 3.2.1 cover H_s, d, and distance to coast and Section 3.2.2 cover EV, EVRD, SEE, DEF, SDE, and SDBR. The

TABLE 4 Linear regression coefficients and associated statistics for finfish, shellfish, and seaweed structures NRCs for each independent variable considered.

	Hs	depth	Distance To Coast	EV	EVRD	SEE	DEF	SDE	SDBR
Finfish									
n	37	37	36	37	37	37	37	37	37
R^2	0.60	0.19	0.09	0.60	0.61	0.60	0.51	0.51	0.60
β_0(*best-fit*)	0.14	0.39	0.53	−0.03	−0.00	0.13	0.28	0.26	0.13
β_0(*lower*)	0.07	0.25	0.45	−0.18	−0.13	0.04	0.19	0.17	0.02
β_0(*upper*)	0.26	0.55	0.63	0.04	0.07	0.23	0.40	0.40	0.23
β_1(*best-fit*)	0.09	7.43e-03	1.73e-06	0.21	0.22	0.10	2.86e-06	0.03	1.03
β_1(*lower*)	0.06	2.56e-03	2.29e-07	0.18	0.19	0.08	1.89e-06	0.02	0.78
β_1(*upper*)	0.10	1.17e-02	3.86e-06	0.27	0.28	0.13	3.69e-06	0.04	1.29
AD-test p-value	0.02	0.44	0.06	<0.01	<0.01	<0.01	0.02	0.04	<0.01
Shellfish									
n	33	33	32	33	33	33	33	33	33
R^2	0.01	0.36	0.12	0.76	0.59	0.61	0.00	0.03	0.61
β_0(*best-fit*)	0.61	0.93	0.74	0.05	0.03	0.29	0.66	0.60	0.29
β_0(*lower*)	0.22	0.81	0.69	−0.08	−0.66	0.13	0.35	0.28	0.12
β_0(*upper*)	1.27	1.06	0.81	0.24	0.52	0.48	1.06	1.05	0.49
β_1(*best-fit*)	0.01	−8.90e-03	−1.28e-06	0.24	0.24	0.11	2.02e-07	0.01	1.03
(*lower*)	−0.11	−1.45e-02	−2.30e-06	0.17	0.07	0.06	−2.98e-06	−0.03	0.55
β_1(*upper*)	0.08	−4.59e-03	−2.79e-07	0.29	0.48	0.16	2.67e-06	0.03	1.55
AD-test p-value	0.02	0.04	0.88	0.01	<0.01	0.09	<0.01	0.04	0.09
Seaweed									
n	37	37	36	37	37	37	37	37	37
R^2	0.16	0.00	0.00	0.71	0.64	0.58	0.11	0.16	0.58
β_0(*best-fit*)	0.57	0.75	0.77	0.20	0.27	0.38	0.64	0.61	0.38
β_0(*lower*)	0.31	0.61	0.71	0.04	0.09	0.16	0.46	0.43	0.15
β_0(*upper*)	0.96	0.88	0.83	0.47	0.55	0.58	0.86	0.84	0.59
β_1(*best-fit*)	0.04	−3.13e-05	−2.05e-07	0.18	0.18	0.08	1.05e-06	0.01	0.77
β_1(*lower*)	−0.03	−3.82e-03	−1.08e-06	0.10	0.09	0.04	−7.21e-07	−0.00	0.37
β_1(*upper*)	0.08	3.51e-03	8.78e-07	0.23	0.25	0.12	2.55e-06	0.03	1.18
AD-test p-value	<0.01	<0.01	0.35	0.02	0.01	<0.01	<0.01	<0.01	<0.01

In the rows of the table, n is sample size, R^2 is the coefficient of determination, β_0 and β_1 are reported for the best-fit and for the lower and upper 95% confidence interval, and the normality of the residuals is assessed by the Anderson-Darling test statistic p-value (>0.05 indicates residuals are normal).

quality of best-fit regression coefficients β_0 and β_1 in Table 4 is qualitatively assessed by their lower and upper confidence interval estimates. The 95% confidence interval estimates for β_0 and β_1 indicate the uncertainty and the significance of coefficients to the linear regression model. Generally, linear regressions fail to satisfy the assumptions of the homoscedasticity (not shown) and normality of residuals (Table 4 p-values of the Anderson-Darling test for the normality residuals).

3.2.1 Significant wave height, depth, and distance to coast as NRC linear predictors

Overall, across the sample sites and structure designs considered, H_s, d, and distance to coast were not found to be linear predictors of NRC. The relationship between H_s and finfish NRC was the one exception, with the line of best fit explaining up to 60% of the variance. The R^2 of remaining relationships was poor, ranging from 0.00 to 0.36 (Figures 10B–I). Near-zero values of β_1 indicates that

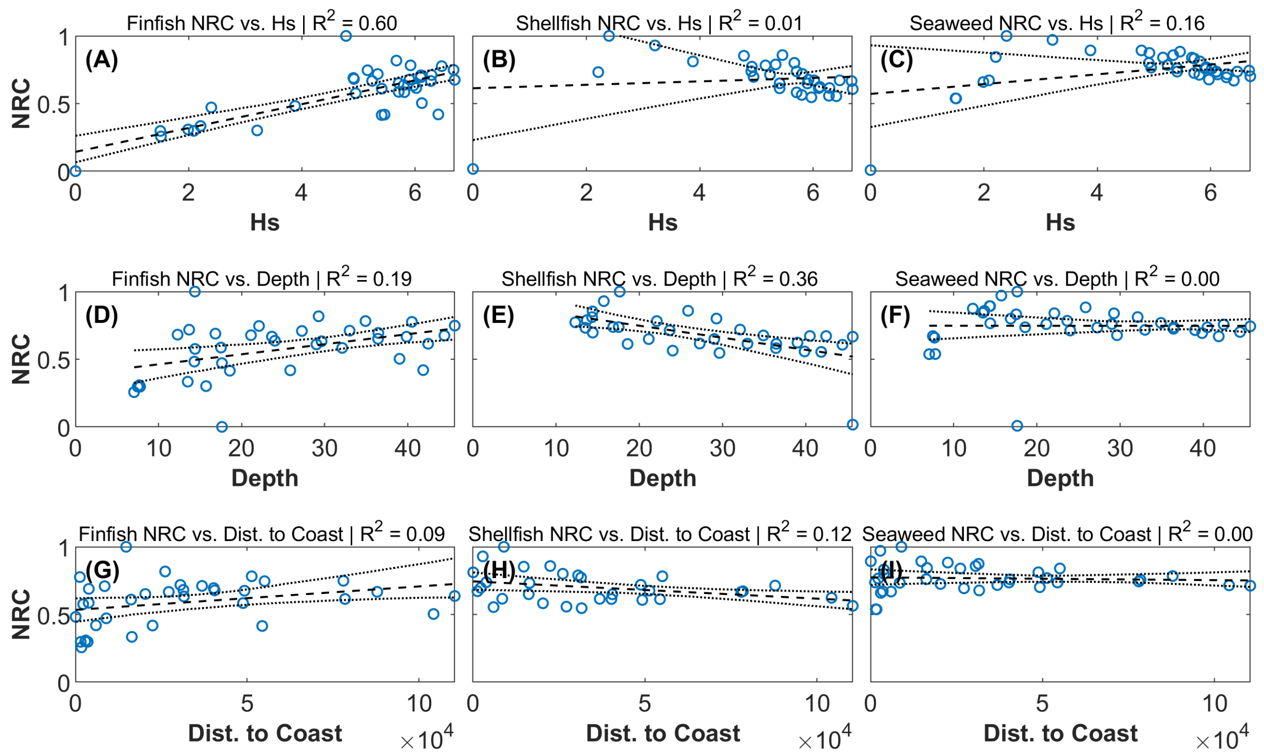

FIGURE 10
Linear regression of NRC against significant wave height H_s , depth d , and distance to coast; in **(A–I)** the samples are blue circles, the line of best fit is the dashed black line, and the bootstrapped 95% confidence interval estimates are the dotted black lines. Results are grouped as: **(A–C)** NRC against *Hs in m*, **(D–F)** NRC against *d in m*, and **(G–I)** NRC against distance to coast in m.

there is not a linear relationship between x and NRC—as shown in Figures 10B, C, F, G, H, I). Further, confidence intervals of β_1 that cross 0 indicates both uncertainty about the nature of the relationship between x and NRC and that the linear model does not describe the relationship between variables adequately. This pattern is present in linear regression results for shellfish NRC against H_s and seaweed NRC against H_s and d. Within the region of German Bight considered, H_s, d, and distance to coast were not found to be good linear predictors of the finfish, shellfish, and seaweed structures NRC.

3.2.2 Exposure indices as NRC linear predictors

The linear relationships between proposed exposure index and the NRC of finfish, shellfish, and seaweed cultivation structures are shown in Figure 11. Linear regression of NRC against EV, EVRD, SEE, and SDBR explained the greatest proportion of the variance. Across structure types, mean R^2 values were 0.69 for EV, 0.61 for EVRD, 0.60 for SEE and SDBR, 0.23 for SDE, and 0.21 for DEF. While all best-fit relationships yielded positive β_1 values, there exists uncertainty about the true values of β_1 as ranges in confidence intervals are of similar magnitudes as the best-fit values. Linear regression of shellfish and seaweed NRC against DEF was not found to generate a suitable model, as noted by the low R^2 values and β_1 estimates alternating sign within the 95% confidence interval. Similarly, there is uncertainty surrounding β_0 estimates, with a suggested lack of significance for regressions of finfish NRC against EV and EVRD and shellfish NRC against EV and EVRD. Visual assessment of residuals (not shown) and the p-values of the Anderson-Darling test for the normality of residuals indicate that the linear regression did not satisfy the assumptions of residual homoscedasticity and normality. Bootstrapped 95% confidence intervals for the line of best fit show considerable uncertainty, with greater ranges associated with lower values of the predictor.

4 Discussion

One purpose of an exposure index is to provide a single metric that is approximately proportional to maximum loads on an aquaculture structure. Thus, the efficacy of such an index depends on its positive linear relation to maximum loads on a structure. While structural and operational costs would be more indicative of the relative implications of selecting one site over another, in the absence of a comprehensive costing analysis, the required structural capacity is a reasonable proxy for relative capital expenditure for aquaculture structures. Often mooring line loads are the highest-loaded structural members of a farm. Because component costs are generally proportional to their load capacity, and installation costs are related to the size of the component, the relative structural costs are approximated by mooring line loads.

Previous attempts to define the challenges of "offshore aquaculture" or site exposure have relied heavily on water depth, significant wave height, and distance from the coast (Ryan, 2004; Lovatelli et al., 2013; Froehlich et al., 2017). While these factors may be more influential with respect to operation and maintenance

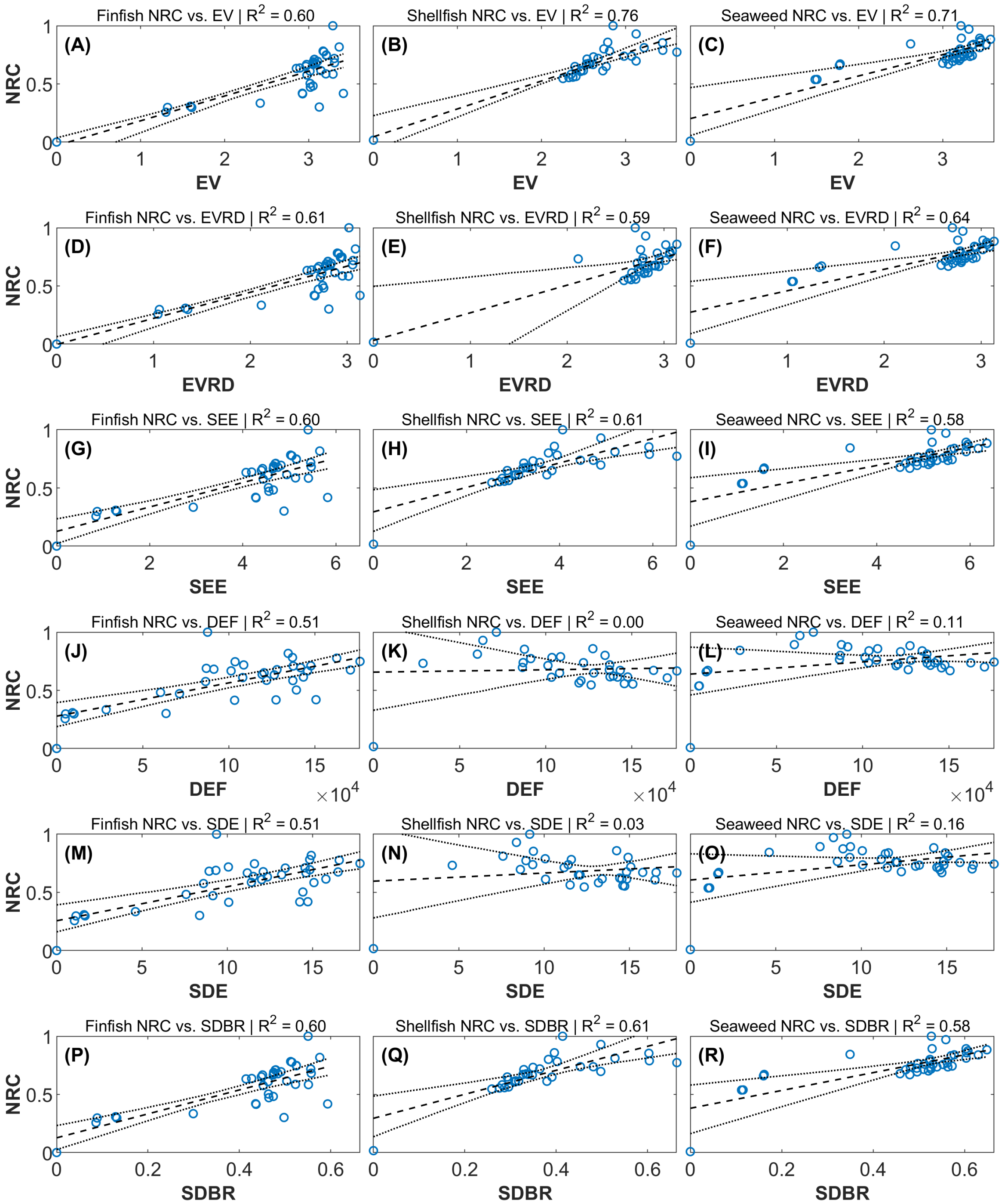

FIGURE 11
Linear regression of NRC against exposure indices; in **(A–R)** the samples are blue circles, the line of best fit is the dashed black line, and the bootstrapped 95% confidence interval estimates are the dotted black lines. Results are grouped as NRC against: **(A–C)** Exposure Velocity *EV* in m/s, **(D–F)**, Exposure Velocity at a Reference Depth *EVRD* in m/s, **(G–I)** Specific Exposure Energy *SEE* in J/kg, **(J–L)** Depth-integrated Energy Flux *DEF* in W/m, **(M–O)** Structure-centered Depth-integrated Energy *SDE* J kg/m^3, **(P–R)** Structure-centered Drag-to-Buoyancy Ratio *SDBR* (non-dimensional).

challenges, these metrics were found to be poor predictors of the structural requirements for aquaculture cultivation structures (Figure 10). Required structural capacity and significant wave height demonstrated a linear relationship for finfish structures, yet the same relationship did not exist for shellfish or seaweed structures. Within the region of the German Bight considered, the required structural capacity was found to be *negatively* related to water depth for shellfish structures, weakly positively related for finfish structures, and independent of depth for seaweed structures. This is because (1) ocean currents are often higher near estuary outlets and nearshore constrictions due to tidal hydrodynamics, and (2) when wind waves with large heights and long wavelengths enter shallow water depths, the resulting horizontal wave-induced particle velocities increase, creating large loads on the cultivation structures considered. The wave shoaling process is captured by the linear relationship between significant wave heights and the required capacities on finfish structures. No similar relation was found for shellfish or seaweed structures, which may be related to the shorter peak wave periods associated with smaller 50-year significant wave heights as defined by the wave steepness limits used in this analysis (DNV, 2010). In regions of the world where extreme wave environments are better characterized by longer peak wave periods, a different relationship may exist. Future work is needed to better define the relationship between the wave environment and structural requirements for aquaculture cultivation structures. Likewise, Depth-integrated Energy Flux (DEF) and Structure-centered Depth-integrated Energy (SDE) were not found to be good predictors of structural requirements and the resulting capital expenditure.

The Exposure Velocity (EV), Exposure Velocity at Reference Depth (EVRD), Specific Exposure Energy (SEE), and Structure-centered Drag-to-Buoyancy Ratio (SDBR) were found to predict design loads on aquaculture structures through a positive linear relationship. Of the sample sites considered in the German Bight, linear models based on EV, EVRD, SEE, or SDBR explained 58% to 76% of the variance in NRC, whereas the classical definitions of offshore sites (greater depths, significant wave heights, and distances to coast) explained 0% to 36% of the variance (with the exception of finfish NRC against H_s which explained 60%). All four of these indices are proportional to the combined wave and current fluid velocities or the square of velocity. The EV was the best predictor of required structural capacity in general, though the uncertainty associated with model coefficients still needs improvement (Table 4). The EV performed better than EVRD since the EV was evaluated at a structure-dependent position in the water column whereas the EVRD was evaluated at the constant reference depth of 5 m. Conversely, depth and distance to coast served as poor predictors for structural load in an easily interpretable way.

The linear relationships between all independent variables and shellfish, finfish, and seaweed structure NRCs reflect the nature of the extreme hydrodynamic conditions of the German Bight. Lower values of the independent variables, such as H_s samples less than 4 m or EV samples less than 2 m/s, implicitly carry more weight in the linear regression. However, all variables considered exist over a continuum; in other seas or coastal ocean regions of the world, extreme values of hydrodynamic variables and their associated exposure indices exist within the lower ranges omitted from this analysis. Further exploration across this full parameter space would better characterize the nature of relationships with NRCs, either through a systematic study of synthetic but feasible site conditions or through repeating this analysis procedure across dynamically different regions of the coastal ocean.

Again—the basis of the exposure indices is such that it should provide a positive linear indication of exposure. In this context, a negative linear relationship is clearly undesirable, as is a non-linear relationship. Hence, the linear regression used for evaluation and the favoring of results that best characterize positive linear relationships. Though more work is needed to more accurately characterize the nature of the relationship of exposure indices with design loads on aquaculture structures, this study provides evidence that the EV, EVRD, SEE, and SDBR can support or improve site suitability assessment methods.

Inherent assumptions of the HS-DFEA analysis method could bias agreement towards certain variables or indices over others. Assumptions about hydrodynamic interaction with the structure and the physics incorporated in these models may be better replicated by some indices. While the aquaculture systems chosen for this analysis were selected based on their representative qualities, the specific design choices inherent to these systems may bias the results of this study. Substantial differences in system characteristics, such as mooring line axial stiffness, can result in significantly different loading in the same environmental conditions. The computational resources required to simulate a wide variety of system designs for all sites and load cases were prohibitive in the context of this study. Further, exposure indices do not account for loads related to system inertia in the dynamic scenarios. Due to these nuances and specific design choices, use of exposure indices to estimate structural load does not replace a true engineering study.

5 Conclusion

The Exposure Velocity (EV), Exposure Velocity at Reference Depth (EVRD), Specific Exposure Energy (SEE), and Structure-centered Drag-to-Buoyancy Ratio (SDBR) can provide a coarse estimate of the required capacity of an aquaculture structure across a range of sites. These exposure indices yielded the strongest performance as a positive linear predictor of the normalized required capacities of finfish, shellfish, and macroalgae aquaculture structures at potential sites within the German Bight of the North Sea, with R^2 values of 0.69, 0.61, 0.60, and 0.60 for EV, EVRD, SEE, and SDBR, respectively. Though none of the linear relationships exhibit adequate precision to be used as the basis for engineering design or detailed cost estimation, the findings suggest that EV, EVRD, SEE, and SDBR and other proposed indices based on fluid speed hold significantly more meaning than depth, distance from shore, or significant wave height when communicating about a site's exposure between developers, regulators, investors, insurers, farmers, and technology providers. Structural loads and costs are only a part of the larger siting process; these factors are often misinterpreted or completely left out of the decision-making framework due to the practical barrier of a comprehensive engineering evaluation of all potential sites and structure designs of interest. Though they do not replace a true engineering study, these indices can be generated quickly from widely available public data to inform siting, risk assessment, and relative costs of aquaculture structures.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

TD: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. SR: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. MM: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. NB: Formal analysis, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. ZM: Formal analysis, Investigation, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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