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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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