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OPINION

REVIEWS IN Aquaculture

The need for proactive environmental management of offshore aquaculture

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The aquaculture industry produces 52% of the global aquatic food budget (FAO, 2020), with the growing global human population increasing demand for its expansion. At present, most marine fish farming activities occur in sheltered coastal waters where conditions are favourable for the infrastructure and farmers have ease of access to stock for daily maintenance and harvest. However, the scale of coastal fish farming is constrained by the space available, interactions with other users of inshore waters, climatic conditions, and the rate at which the local seafloor biological communities can assimilate and remineralise settled organic 'farm waste' (faeces and excess fish feed).[1] In shallow water, these constraints are tightened as a result of the low water turnover and close proximity of the seafloor, where farm-derived antifouling contaminants, therapeutics and dissolved nutrients can concentrate and affect benthic and pelagic ecosystems[1] and potentially cause concerns for industrial and recreational activities. The close proximity of the seafloor also supports the accumulation of organic farm waste underneath and around the fish farm. This accumulation increases both the oxygen demand of the benthic community and the release of reduced metabolic products from the sediment into the bottom seawater.[2] Finally, climate-driven warming of shallow coastal ecosystems[3] may further limit inshore habitat suitability for fish production through a reduction of stock fitness,[4] and reduce the aerobic capacity of the seafloor to efficiently remineralise and assimilate farm waste.[5] This raises concerns about the fiscal and environmental sustainability of industry expansion in inshore waters, forcing farmers to consider expanding their operations into deeper and more energetic offshore waters.

Fish farms in deep, offshore waters will disperse their organic waste over a larger area than fish farms in shallow, sheltered waters. That is, the amount of waste that settles on the seafloor per unit area and time underneath an offshore farm will be less than that below a shallow water farm.[6] In addition, since waste released in deeper water requires more time to reach the seabed, a larger fraction will be consumed[7] or remineralised[8] in the water column, further attenuating the waste as it settles.[9] For these reasons, an offshore farm is likely to create a less intense, albeit larger, organic enrichment 'footprint' in the seafloor ecosystem than a similar-sized shallow water farm.[6] In this regard, we note that offshore benthos are conditioned to low levels of organic deposition,[10] and, unlike the benthos of sheltered coastal waters, may be sensitive to even minor organic enrichment. Ecosystem monitoring is therefore necessary to ensure that offshore fish farms can operate sustainably.

This new venture offshore provides a timely opportunity for the industry to re-evaluate environmental management standards. In this piece, we wish to demonstrate the value of coupling measurements of the benthic metabolism with predictive depositional and metabolic response modelling. We argue that environmental monitoring should adopt such an approach to enable *proactive* farm management and give farmers confidence that they are operating within the metabolic capacity of the receiving seafloor ecosystem. We will begin by acknowledging questions that researchers, farmers and regulators of the industry should be asking:

Will the amount of waste that settles on the seafloor below a dispersive offshore farm exceed the metabolic capacity of the receiving sedimentary environment? Will organic farm waste accumulate over time and alter benthic ecosystem function and trophic diversity? How do we quantify and predict such changes?

1 | DEFINING THE METABOLIC CAPACITY OF THE RECEIVING ENVIRONMENT

Here, we define the capacity of the seafloor ecosystem to assimilate organic waste as its ability to maintain ecosystem functions and trophic diversity while remineralising the added organic material. Knowing the metabolic rates of the benthos and oxidant availability is key to understanding the pathways and associated thermodynamic efficiency of labile organic matter remineralisation at the seafloor. These variables will also determine whether the degradation of organic matter leads to eutrophication[11] and environmental conditions unsuitable for large infauna.[12,13]

While the remineralisation of organic matter is not limited to the oxic zone of the sediment, maintaining an oxic surface layer is 'desirable' because aerobic respiration is the most thermodynamically efficient remineralisation process.[14] Furthermore, oxic conditions at the sediment surface support the settlement of burrowing fauna,[12,13] which increases the remineralisation capacity of the sediment through pore water irrigation and particle mixing,[15,16] expanding the surface area for diffusive sediment–seawater solute exchange, and enhancing the structural and functional diversity of the sedimentary ecosystem.[17]

2 | WASTE SETTLING RATES CAN EXCEED METABOLIC CAPACITY OF RECEIVING SEDIMENTS

Organic matter fuels various heterotrophic metabolic pathways. However, the relative contributions of these pathways to the remineralisation of organic waste, and ultimately the ability of the sedimentary ecosystem to maintain an oxic surface layer, depends on the rate at which waste settles.[2,18,19] Porewater oxygen is often depleted within the top few millimetres to centimetres of the sediment column, and below this depth anaerobic microbes continue to remineralise organic matter with less thermodynamically favourable oxidants (in succession: nitrate/nitrite, iron and manganese oxides, sulphate, CO_2). The oxidation of the resulting reduced anaerobic metabolic products adds to the benthic oxygen demand, often dominating the total oxygen consumption in organically enriched sediment.[20] Therefore, as the rate at which waste settles on the seafloor increases, the sediment oxygen demand will also increase and eventually exceed the rate of oxygen supply from the bottom water. This depletion of porewater oxygen shifts the subsurface oxic–anoxic boundary (chemocline) to the surface of the sediment.

The migration of the chemocline towards the sediment surface forces aerobic infauna to emerge from the sediment,[12] ultimately changing the structure of the infaunal community and, as a result, ecosystem functioning.[2] This shift to hypoxic or anoxic conditions at the sediment surface also increases the diffusive loss of reduced metabolic products into the overlying bottom water.[2] Moreover, surface sediments are more susceptible to lower oxygen concentrations in warmer seasons and during ocean heat waves[21,22] because warming acts to both increase metabolic reaction rates[23] and decrease oxygen solubility in seawater.[24] As the climate warms, hypoxia in surface sediments may occur more often[25] and make the seafloor ecosystem more sensitive to the introduction of farm waste. This potential for climate warming to limit the metabolic capacity of the seafloor ecosystem, emphasises the need to quantify waste settlement and better understand the metabolic functioning of the sediments that receive the settled waste.

3 | QUANTIFYING THE ORGANIC MATTER ASSIMILATION CAPACITY OF THE SEAFLOOR

Depositional models describing the transport of organic waste in the water column coupled with mechanistic biogeochemical models of the degradation of organic waste[18] can be used to predict the capacity of the seafloor ecosystem to accommodate settled farm waste. That is, modelled metabolic solute exchange rates can be used to determine the maximum amount of farm waste that the seafloor can degrade per unit area and time without shifting to different trophic conditions.[18] The use of such predictive models will be invaluable for the *proactive* management of future offshore fish farms. Such models will need to be informed by (pelagic and benthic) monitoring programs that can quantify the sediment-solute exchange rates of the receiving environment. For example, the relative sediment–seawater exchanges of dissolved oxygen, and inorganic carbon and nitrogen species, can be used to infer the metabolic pathways likely occurring in the sediments,[11,26,27] and whether sediments are retaining, remineralising, or removing carbon and nitrogen from the ecosystem.[11] Environmental managers may then use such measures of metabolic activity to define the limits of the seafloor ecosystem for accommodating organic waste.[18]

4 | INCORPORATING METABOLIC FUNCTIONING MEASUREMENTS FOR *PROACTIVE* MANAGEMENT

Currently, 'desired' conditions at the seafloor are commonly defined by the absence of anaerobic metabolic products in the porewater of the surface sediment and/or derived from the composition of the resident faunal community.[28,29] The concentrations of dissolved sulphides and other sediment characteristics are often used in monitoring efforts to provide discrete, geochemical proxies of organic enrichment,[29] evaluated relative to reference/control sites and/or to pre-farming conditions (see detailed review in the report by International Council for the Exploration of the Sea[1]). These monitoring approaches are based on observations showing that an accumulation of dissolved sulphides from anaerobic organic matter remineralisation creates undesirable benthic conditions where macrofaunal diversity is affected[13,28] and, at which point, environmental mitigation tends to be necessary and often costly. Alternatively, sediment profile imagery or sediment surface video or photography have been proposed as tools to identify more biogeochemically integrative proxies than porewater solute concentrations alone.[30–32] For instance, in soft sediments, an integrative measure of change, such as the depth of the apparent redox potential discontinuity,[33] can be incorporated with other visual indicators (e.g., *Beggiatoa* sp. coverage[34]) to detect a response of the sedimentary ecosystem to enrichment,[30] and if necessary, trigger mitigation actions. We recognise the obvious value in these visual and geochemical measures as proxies of biological responses to organic enrichment. However, these are not measures of benthic function or metabolic efficiency that would be needed to inform predictive models.

Techniques that measure the sediment–seawater exchange of metabolic solutes provide a starting point for a *proactive* management framework. For instance, ex situ sediment core incubations are a common tool that has been used for decades to measure the sediment–seawater exchange of dissolved oxygen, carbon and nitrogen, revealing sediment metabolic functions.[27,35–37] Such incubations have also been used to study the seafloor near fish farms.[38–40] Similarly, in situ techniques such as non-invasive gradient flux,[41] eddy covariance measurements[42,43] and benthic chamber incubations,[44–46] are well-established methods that may prove useful in an environmental monitoring framework.

We foresee many benefits to considering in situ techniques for measuring the sediment–seawater exchange of metabolic solutes in offshore environments. Moreover, replicating in situ conditions for ex situ sediment incubations will prove increasingly difficult the farther offshore and deeper sediments are extracted.

5 | LIMITATIONS AND HURDLES

Although, gradient flux, eddy covariance, and benthic chambers landers can be deployed in deep waters (up to 6000 m[46]), with the technology used for these deployments becoming more robust, available and accessible (e.g., Berg et al.[42] and Granville et al.[47]), there is an apparent need to refine these tools to make them complement each other and have them fit for purpose in a monitoring framework. For example, despite benthic chambers having a limited footprint size (e.g., ~900 cm^2), they have the ability to repeatedly measure solute fluxes in a physically controlled in situ chamber that allows for reproducible, albeit successional, sediment–seawater solute exchange measurements along potential enrichment gradients. In contrast, eddy covariance techniques sample over a larger area (~10–100 m^2[48]), but the location of the area changes with the current direction. Consequently, eddy covariance measurements incorporate the heterogeneity of sediment conditions in the near vicinity of the sensor, revealing the natural variability of sediment–seawater solute exchange rates that would otherwise require multiple chamber deployments to capture. While individually, these two techniques may not provide all the information ecosystem modelling may require, the coupling of these two technologies can provide a metabolic map of the seafloor ecosystem surrounding fish farms. That is, eddy covariance measurements can provide the context of natural spatial and temporal variations in the sediment–seawater solute exchange in which a sediment–seawater solute exchange gradient detected by chamber measurements can be assessed.

It is important to acknowledge that an approach based on sediment–seawater solute exchange rates may be less common in management practices than *reactive* approaches that measure accumulated solutes or biological community structures[1,2,29] for a reason. This is likely due, at least in part, to logistical and technical limitations of conducting accurate rate measurements. For instance, in situ benthic chambers (e.g., Kononets et al.[46]) and eddy covariance measurements (e.g., Reimer and Smith[49]), require sensors to remain at the seafloor for some time to collect sufficient data. This makes any monitoring involving multiple sites time-consuming, and thus, expensive. However, these solute exchange measurements are needed to build and maintain the diagenetic models required for predicting the receiving environment's capacity to maintain ecological function and trophic diversity when accommodating farm waste. As such, this tradeoff for time seems to be an environmentally conscious decision and creates an opportunity in research and development sectors to optimise such techniques for *proactive* management purposes.

6 | CONCLUSION

We argued here that the incorporation of solute exchange measurements that can inform benthic biogeochemical models of the receiving seafloor ecosystem is essential for *proactive* ecological management of fish farms. Such predictive modelling will inform environmental managers about the seafloor's capacity for additional organic loading and its ability to support existing fisheries and/or culturally significant species. This ability to quantify the effects of organic enrichment can be used to show that farms operate within the metabolic capacity of the site. Not only will this help support the social acceptability of offshore fish farming, but it will also give farmers confidence to expand their production sustainably.

Finally, while this article focused on the opinion that new research for environmental monitoring of aquaculture should incorporate predictive models for *proactive* management, we see the undeniable value in the existing proxies. As such, an approach that can combine a broad suite of measurements, such as geochemical and macrofauna community metrics,[28] and gradients using diagenetic models,[18] will provide the most comprehensive understanding of the effects of settled farm waste. By incorporating the *proactive* strategies proposed here, we can not only work towards better defining 'acceptable limits' of waste deposition, but also help quantify the relationships between various organic enrichment metrics[28] that will go towards strengthening benthic response models, and advancing our understanding of the complexity of soft-sediment ecosystems.

AUTHOR CONTRIBUTIONS

Michelle N. Simone: Conceptualization; writing – original draft; writing – review and editing; investigation. **Kay Vopel:** Writing – review and editing; funding acquisition.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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