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Global principles for restorative aquaculture to foster aquaculture practices that benefit the environment

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Abstract
The magnitude of negative environmental impacts generated by food production means it is now imperative we develop food systems in a way that can actively support the recovery of degraded ecosystems, while also meeting increasing demands for food and livelihoods. Aquaculture, when it utilizes the right practices and species and occurs in the right places, can strike this balance, enabling food production that supports the health of aquatic ecosystems. To ensure the efficacy of this approach, however, a clear, common understanding of the ways in which this industry can achieve this outcome is needed. This paper highlights a definition of "restorative aquaculture", identifies global principles for the use and development of restorative practices, and identifies needs for information, data, and tools that, if addressed, would greatly expand our understanding of the ways in which aquaculture and restorative activities can have positive environmental outcomes. This guidance was developed by a working group of representatives from global aquaculture, environment, economic and academic organizations. It can assist industry and government in making decisions about sustainability as well as restoration and rehabilitation strategies that intersect with aquaculture.

KEYWORDS
aquaculture, aquatic conservation, food production, regenerative food systems, restoration

1 | INTRODUCTION

Food production contributes significantly to environmental challenges, accounting for nearly one quarter of global greenhouse gas (GHG) emissions, 70% of freshwater usage, and 80% of habitat degradation (Poore & Nemecek, 2018). Changes in the way we produce food could significantly reduce its resource requirements, making production more efficient at the same time as helping to mitigate the drivers of climate change and biodiversity loss (FOLU, 2019). Ecosystem- and Nature-based Solutions (NbS), such as regenerative agriculture, are establishing a vision for transformation through practices that can generate better outcomes for the environment (Miralles-Wilhelm, 2021). Awareness of the synergies between NbS and aquaculture is growing (Le Gouvello et al., 2021) as is a clearer picture of the ecosystem services that can be associated with aquaculture systems (Alleway et al., 2018; Gentry et al., 2020; Theuerkauf et al., 2021; Weitzman, 2019). However, for aquatic environments, and in fact many food industries, clear description and agreement on the meaning and intent of these practices (Newton et al., 2020), and the extent of the environmental opportunity associated with their use, is lacking.

Aquaculture makes a major contribution to the supply of aquatic food (food from freshwater and marine ecosystems) globally. While China remains the overwhelmingly dominant producer (FAO, 2022) trends in seafood indicate demand for fish worldwide, and therefore demand on supply, could more than double by mid-century (Costello et al., 2020; Naylor, Kishore, et al., 2021). But aquaculture can have considerable negative environmental impact. Expanded production under "business-as-usual" could see further deterioration of aquatic habitats through disturbance, waste pollution, and harmful effects on biodiversity from the introduction of non-native species, which can lead to competition for food and habitat, spread disease, and reduce the genetic fitness of wild populations (Diana, 2009; Naylor, Hardy, et al., 2021). Expansion of aquaculture under these circumstances would also increase industry GHG emissions. As well as direct, operational outputs of GHG emissions there is a heavy dependence on wild-caught fish and extensive terrestrial land-use for feed to support the fed aquaculture sectors of shrimp and finfish; sector's that are contributing an increasing share of the industry's overall production (FAO, 2022). Consequently, while many aquatic foods can be produced with lower environmental resource requirements than their terrestrial counterparts (Gephart et al., 2021; Poore & Nemecek, 2018), going forward, these benefits must be coupled with practices that can actively enable iterative improvements in sustainability, rather than exacerbate environmental threats from the industry (Krause et al., 2022).

When done well, with the right practices and in the right locations, aquaculture can create a range of benefits to the environment, from the provision of habitat and improved water quality, to assisting migration, coastal defense, and biological control (Overton et al., 2023). As such, there is an opportunity to decrease the occurrence or risk of negative impacts from aquaculture and enhance positive impacts, by identifying, acknowledging, and ultimately increasing the use of practices that can provide restorative outcomes. For a restorative approach to be effective, though, a clear and common understanding of this concept specific to aquaculture is needed. This includes understanding of intent and the factors that both drive and limit the capacity of different practices to provide positive environmental outcomes. Here, we highlight a definition of "restorative aquaculture" and describe six global principles for implementation of restorative practices. We also identify a range of needs for information, data, and tools to support further exploration of this approach. The definition and principles were first developed by a working group and published in The Nature Conservancy (2021). This group included participants from global and country government and non-government aquaculture, environment, economic and academic organizations, drawing on extensive experience in industry operations and their design, global, country and enterprise-scale financing, policy, and management (local, national, and global), and science, including the physical, social, and economic sciences. We build on that work by: (1) highlighting the definition; (2) reviewing and revising the global principles; (3) discussing the potential intersecting role of restorative aquaculture as one part of broader conservation literature and initiatives; and (4) identifying needs for information, data, and tools to more comprehensively understand the ways in which restorative activities can create environmental benefits, to support continued development of this approach and its widespread, effective use throughout industry sectors and geographies.

2 | DEFINING RESTORATIVE AQUACULTURE

Restorative aquaculture is defined in The Nature Conservancy (2021) as occurring; "*when commercial or subsistence aquaculture provides direct ecological benefits to the environment, with the potential to generate net positive environmental outcomes*". In forming this definition several other descriptions of restorative aquaculture were evaluated (Table S1). We maintain that it is an appropriate definition, and it aligns with descriptions of restorative aquaculture published since that time (e.g., the definition of Mizuta et al. (2023); "*Commercial or subsistence aquaculture that supports initiatives to provide/or directly provides ecological benefits to the environment, leading to improved environmental sustainability and ecosystem services, in addition to the supply of seafood or other commercial products and opportunities for livelihood*").

Fostering the use of a clear description of restorative aquaculture using this definition is useful, because it can assist to understand where the intent or objectives of different approaches might necessarily diverge. Conversely, a lack of shared understanding around this term could create uncertainty, or misinterpretation, of what different actors mean when discussing restorative aquaculture and its role in regenerative food-systems more broadly (Newton et al., 2020). It could also lead to misunderstanding about aquaculture's potential—the practical limits of what aquaculture can and cannot do—to support important conservation initiatives such as restoration and rehabilitation (Gann et al., 2019). For example, some existing uses of "restorative aquaculture" may be more representative of "conservation aquaculture", which has the much needed intent of achieving species and ecosystem-level conservation improvements (Carranza & zu Ermgassen, 2020; Froehlich et al., 2017; Maynard, 2003; Ridlon et al., 2021; Wasson et al., 2020). Encouraging the use of these terms and clarity in their use adds plurality to our understanding of the full range of ways industry and government may be able to advance the sustainability of food systems, so that they can make informed choices about the approaches they take and for what purpose.

Broader ecological and aquaculture concepts, approaches and terms were also considered in forming this definition (Table 1), specifically: regenerative aquaculture; ecological aquaculture; an Ecosystem Approach to Aquaculture (EAA); carrying capacity; conservation aquaculture; Integrated Multi-Trophic Aquaculture; stock enhancement; restoration and rehabilitation; and NbS. We consider the definition is different to most of these concepts, but similar to regenerative strategies (including regenerative aquaculture). Describing the approach as "restorative" (as opposed to regenerative), however, is thought to be important because it more directly recognizes the role that aquaculture could play in supporting more traditional rehabilitation activities in aquatic environments, especially restoration. The inclusion of "net positive" in the definition aims to be responsive to the ambition that is needed to slow negative environmental impacts and reverse the already significant declines in biodiversity (Maron et al., 2021). It encompasses well established sustainability requirements, specifically the reduction of negative risks and effects through risk mitigation and ecologically sustainable development, to then deliver, and over time accrue, environmental benefits in the surrounding ecosystem (Figure 1).

2.1 | Restorative strategies and approaches

In terrestrial systems restorative practices, termed in these systems regenerative agriculture, are often characterized in two ways; approaches that can be applied to the agricultural landscape and surrounding area (e.g., interventions such as natural habitat and fire risk management), and approaches that are applied to the agricultural practice itself, (e.g., grazing optimization, inclusion of trees in cropland, cropland nutrient management) (FOLU, 2019; Miralles-Wilhelm, 2021). Restorative aquaculture practices can be described in a similar way. There are approaches that generate benefits in the broader environment and approaches that provide an environmental benefit as a direct result of the farming practice (Bossio et al., 2021). These benefits have positive impacts over different time scales, providing immediate effects (e.g., increasing water filtration capacity), or incremental effects that accrue over time to provide ecosystem services and environmental benefits (e.g., waste treatment and improved water quality as a result of increasing water filtration capacity) (Table 2).

When implementing restorative practices, it will be important for industry, government, and community to recognize that restorative aquaculture is context specific, and that it is not an all-encompassing solution. Environmental outcomes from restorative aquaculture will, therefore, require a clear understanding of the potential for trade-offs to occur, based on the choices that will need to be made about the site, design, commercial or subsistence activity that is adopted, and any social and economic implications. It may be necessary, but also valuable, to prioritize one type of restorative benefit over another and a farmer may need to balance the environmental benefits that can be provided with the viability and profitability of production. Also, in modified environments, attention to the implications of restorative aquaculture on the provision of food will be needed, because food safety could be compromised by using aquaculture to address poor water quality. Pre-emptively planning to reduce these risks through a holistic view—a One Health perspective (Stentiford et al., 2020)—should be included in the implementation of restorative strategies. Approaches that can ensure products do not compromise human health might also be needed. These approaches include siting aquaculture operations in a way that they can maximize the environmental benefit without exceeding human health thresholds for product quality or treatment methods post-harvest, such as depuration (in tanks or at other sites where nutrients or contaminants are fewer), which can be used in bivalve farming to purge pathogenic organisms prior to harvesting (e.g., Wright et al., 2018).

3 | GLOBAL PRINCIPLES FOR RESTORATIVE AQUACULTURE

Six global principles have been identified that can guide industry and government in understanding the ways in

TABLE 1 Parallel concepts, practices and terms intersecting with restorative aquaculture.

Concept or practice and its definition	Intersection of restorative aquaculture with the concept
Regenerative aquaculture: "Commercial or subsistence aquaculture performed with focus on social, economic, and ecological responsibility and stability, with minimal external input and impact to the environment" (Mizuta et al., 2023).	This term has a similar intent and is largely synonymous with regenerative agriculture—a term associated with terrestrial ecosystems and production—but was considered different to restorative aquaculture by Mizuta et al. (2023). This study highlights that use of this term has a strong emphasis on social wellbeing and justice, in addition to sustainable livelihoods and food production, and was applied especially in relation to polyculture (restorative aquaculture is equally applicable to monoculture as polyculture), and that it had been largely used in economics and environmental policy literature as well as social awareness.
Ecological aquaculture: a "model of aquaculture development that uses ecological principles and practices as the paradigm for development of aquaculture systems" (Costa-Pierce, 2002, 2021).	The seven principles of Ecological Aquaculture are: designing farms to mimic natural systems; contributing to local society through community development; delivering economic and social profits; practicing nutrient management and not polluting; using only native species and/or strains; and modeling stewardship and innovation for local and global communities. Restorative aquaculture farms that meet these principles would be considered farms practicing ecological aquaculture.
Ecosystem approach to aquaculture (*EAA*): a "strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems" (FAO, 2010; Soto et al., 2007).	EAA is a process (or strategy) for governments and aquaculture sectors to follow that has stakeholder engagement at its core. Restorative aquaculture could be incorporated into an EAA approach.
Carrying capacity: a concept associated with environmental management guiding understanding and measurement of the extent of aquaculture that can be supported, without creating unacceptable changes in ecosystem processes or species, populations, or ecological communities, known specifically as ecological carrying capacity (Filgueira et al., 2015), also the amount of aquaculture that can be developed without adverse social impacts, known specifically as social carrying capacity (Byron & Costa-Pierce, 2013; McKindsey et al., 2006).	Environmental benefits are not likely to achieve a net positive outcome if ecological and social carrying capacity is being consistently exceeded, making this concept a condition determining whether restorative aquaculture is or is not occurring, and guiding how restorative practices should be applied. Conversely, if done in the right way, restorative aquaculture could contribute positively to carrying capacity by increasing the upper limit of ecological capacity or social acceptance.
Conservation aquaculture: the "use of aquaculture for conservation and recovery of endangered fish populations" (Anders, 1998); an expanded definition of conservation aquaculture has also been provided, as "the use of human cultivation of aquatic organisms for the planned management and protection of a natural resource" and includes not only species-level rebuilding but also an ecosystem services view (Froehlich et al., 2017). Ridlon et al. (2021) highlight that this definition (which they adopt in their analysis), emphasizes the use of aquaculture techniques that purposefully align with conservation goals (amongst other objectives), in their work, for example, "the application of conservation aquaculture as a tool to aid the recovery of an imperiled species".	Conservation aquaculture and restorative aquaculture can be distinct or interconnected activities within a waterbody or ecosystem, and target different or similar environmental goals. For example, the intentional cultivation of stock that requires enhancement in the wild could be a conservation aquaculture activity but could also be supported by spawning of this species from farmed aquaculture stock. Restorative aquaculture is best differentiated from conservation aquaculture by its explicit focus on practices in commercial or subsistence aquaculture.
Integrated multi-trophic aquaculture (*IMTA*): is "the integrated culturing of fed species, such as finfish, inorganic extractive species such as seaweeds, and organic extractive species such as suspension and deposit-feeders," often for the intent of improving the sustainability of an aquaculture system, maximizing the use of a system and space, and increasing profits through commercial production of additional species (Troell et al., 2009).	There are processes associated with both restorative aquaculture and IMTA such as the use of extractive species to absorb nutrients that can be common, but the approaches are ultimately distinct because they differ in the primary intent and objectives; IMTA being to treat waste and nutrients generated by aquaculture rather than nutrients in the broader environment to provide a net positive ecosystem outcome (restorative aquaculture).

TABLE 1 (Continued)

Concept or practice and its definition	Intersection of restorative aquaculture with the concept
Stock enhancement: the purpose of stock enhancement is to maintain fishery productivity at a rate that supports capture activities, "to increase stock size, and thereby fishable stock" (De Silva & Funge-Smith, 2005), though enhancement of stocks can also aid in the conservation and rebuilding of populations and/or help mitigate habitat or other losses of fishing (Lorenzen et al., 2010).	Stock enhancement overlaps with conservation aquaculture and could overlap with restorative aquaculture, if the stock enhancement was commercial or subsistence and resulted in a direct environmental benefit to the waterbody.
Restoration and rehabilitation: "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (Society for Ecological Restoration International Science & Policy Working Group, 2004). Ecological restoration is "a solutions-based approach that engages communities, scientists, policymakers, and land managers to repair ecological damage and rebuild a healthier relationship between people and the rest of nature. When combined with conservation and sustainable use, ecological restoration is the link needed to move local, regional, and global environmental conditions from a state of continued degradation, to one of net positive improvement" (Gann et al., 2019).	Restorative aquaculture can be a tool used to assist broader restoration and rehabilitation initiatives. The outcomes from aquatic restoration and restorative aquaculture may be perceived to overlap, and restorative aquaculture can assist rehabilitation, but restoration activities in aquatic environments do not (and should not) always use restorative aquaculture as the approach to rehabilitation. Also, benefits to restoration activities from similar or compatible aquaculture activities should not be assumed as a default outcome of commercial or subsistence aquaculture.
Nature-based Solutions (*NbS*): "actions to protect, manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN, 2020).	There are synergies between aquaculture and NbS used to support marine conservation. Restorative aquaculture employs similar environmental objectives and some similar approaches and may be considered a part of the NbS toolkit.

which restorative activities can be implemented to generate positive ecosystem outcomes. These principles are applicable to both new and expanded aquaculture activities as well as practices and decision-making on existing farms, which may, for example, be able to introduce or modify gear or management approaches to better create the opportunity for environmental benefits to occur. Underlying each of these principles is the expectation that an improved or "net positive" environmental outcome cannot be achieved if environmental benefits happen at the expense of negative impacts, on natural habitats, species, ecosystem functions, or the cultural and economic opportunities they support.

Principle 1: *Site farms where environmental benefits can be generated*. The local environmental characteristics and health of the surrounding ecosystem will affect the type and extent of the benefits that can be generated. For example, while similar aquaculture systems may have the potential to generate comparable benefits for fish stocks, a farm that is sited in an area where habitat availability has declined and is limited due to human stressors may be more likely to be a source of habitat than a farm sited in an area where the availability of natural habitat is not limited.

Principle 2: *Farm species that can provide the environmental benefits intended*. The species cultivated will be a significant driver of the type and extent of benefits that can be provided. Species and species groups have differing natural functions and growth rates, which influence for instance, in the case of extractive species such as bivalves and seaweeds, rates of filtration and nutrient uptake.

Principle 3: *Prioritize farming equipment that enhances the delivery of environmental benefits*. Certain types of cultivation gear and supporting structures can increase foraging, breeding, and refuge habitat for wild fish and other species. Gear can be selected that reduces the risks of negatives effects, such as entanglement or plastic pollution, and enhances positive effects for local fauna.

Principle 4: *Adopt farming management practices that can enhance local environmental benefits*. The timing of construction, seeding, harvesting, maintenance practices, and the configuration of farms can influence the extent to which an operation can generate environmental benefits. Environmental benefits could be reduced, for example, if harvest of farmed biomass occurs at a time that coincides with the seasonal use of the area by fish populations.

Principle 5: *Strive to farm at an intensity or scale that can enhance ecosystem outcomes*. Restorative aquaculture should ideally occur at a scale and intensity that considers the needs of the local water body. While it is not the responsibility of farmers to address, for example, the effects of eutrophication driven by land-based run-off, there may be decisions that could be made that could increase the benefit returned, such as increasing shellfish biomass (without over stocking or exceeding carrying capacity) to intentionally increase water filtration.

Principle 6: *Contribute data, information, knowledge and technical capacity to enable quantification and recognition of*

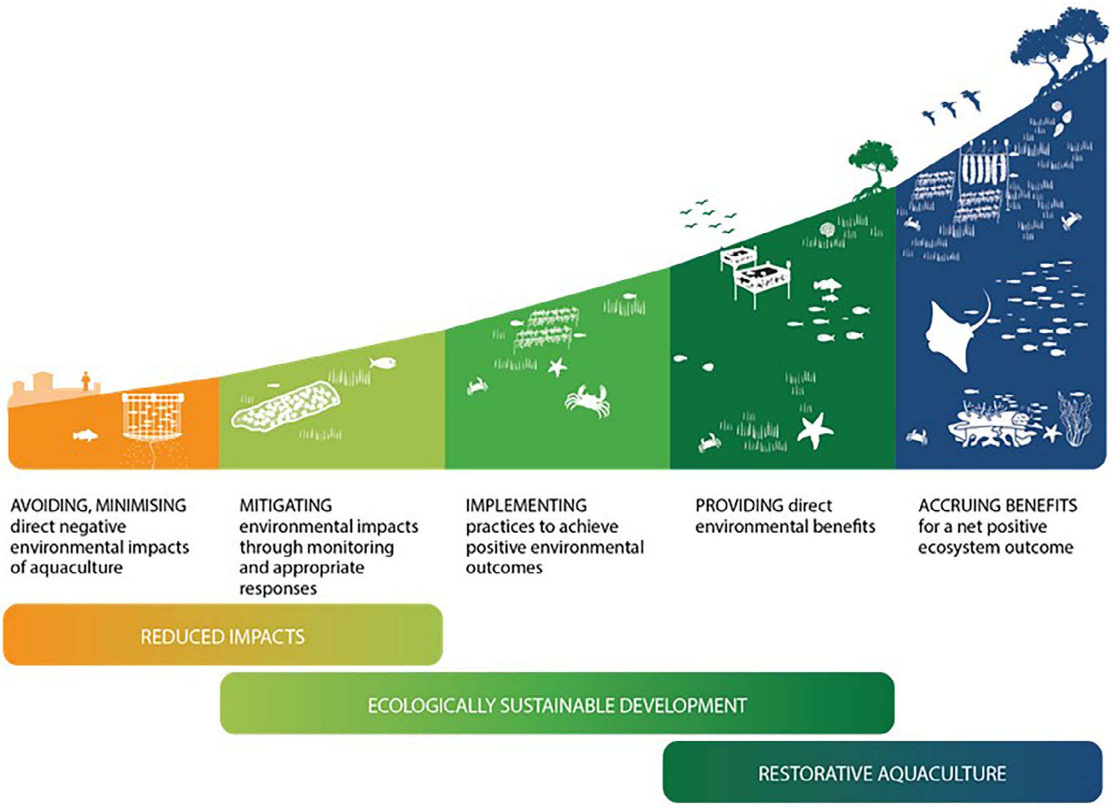

FIGURE 1 The restorative aquaculture "pathway", which builds on sustainable practices in commercial or subsistence aquaculture to also provide and potentially accrue environmental benefits (The Nature Conservancy, 2021). Figure reprinted with permission.

environmental, social and economic benefits. Commercial aquaculture can be constrained by overlap and competition for space or resources and societal concern for negative impacts. In addition to ecological benefits restorative aquaculture should, therefore, also seek to support social and economic benefits in communities, including opportunities for livelihood but also education, inclusion, and equity. However, enabling a positive outcome for restorative aquaculture is ultimately a shared responsibility. To maximize the benefits from restorative practices the social, economic, and environmental benefits will also need to be recognized, encouraged, and appropriately valued by communities and government in their regulatory capacity.

4 | RESTORATIVE AQUACULTURE IN PRACTICE

4.1 | Environmental benefits from aquaculture

Aquaculture-environment interactions are often viewed through a lens that aims to understand the ways in which negative environmental impacts can be mitigated. Yet, there is growing interest in understanding these environmental interactions in a more dynamic way, by, for example, taking an Ecosystem Approach to Aquaculture (Soto et al., 2007) or considering activities as ecological aquaculture; *"aquaculture development that uses ecological principles and practices as the paradigm for development of aquaculture systems"* (Costa-Pierce, 2002, 2021). Restorative aquaculture can occur in marine, fresh, and brackish aquaculture systems and environments, and involve the farming of fed and non-fed species. The capacity to describe and measure the benefits provided is, however, influenced by the data available to understand these benefits and the context in which they occur. In aquaculture systems there are also a range of inherent factors that drive environmental interactions. As such, the environmental outcomes that can be achieved through restorative practices reflect a spectrum where, for instance, some species or modes of culture could be expected to return greater benefits than others (The Nature Conservancy, 2021; Theuerkauf et al., 2021).

At this time, the most developed knowledge base for environmental benefits is associated with bivalve and seaweed aquaculture in open aquatic ecosystems (i.e., excluding tanks and recirculating systems), with studies indicating that environmental benefits can be provided through water quality improvements, the provision of habitat, and

TABLE 2 Examples of restorative aquaculture strategies and practices in marine environments, the nature of the environmental benefit provided, and their effect in enabling an overall, positive ecosystem outcome.

Restorative aquaculture practice	Environmental benefit provided	Short to medium term impact (1–5 years)	Longer term impact (>5 years)	Example study and reported size of effect
1. Siting farming to provide additional capacity for water filtration and denitrification	Water quality—removal of excess (anthropogenic) nutrients, particularly N and P via enhanced biogeochemical cycling	Instantaneous removal of nutrients at the local scale (within a farm), with subsequent cumulative removal of nutrients that can support a reduction at a larger scale (across a farm, or multiple farms)	Quantity of nutrients removed becomes greater than continued anthropogenic inputs, resulting in water quality improvements in surrounding water body	Meta-analysis of the effect of oysters on denitrification (Ray & Fulweiler, 2021) A strong positive effect on sediment denitrification ($g = 0.682 \pm 0.276$ ($p < .001$), $n = 19$), average rate of denitrification from oysters 4.78 ± 2.46 μmol individual^{-1} h^{-1}
				Meta-analysis and valuation of nutrient removal via bioextraction at bivalve and seaweed farms (Barrett et al., 2022) Nitrogen removal by area of farm kg ha^{-1} year^{-1}: clams 107 (−3 to 477), mussels 581 (275–1172), oysters 314 (150–612), scallops 52, seaweeds 275 (96–678)
2. Farming of seaweed to improve water quality	Water quality—increased oxygenation	Instantaneous cycling of oxygen and aragonite, ongoing/enhanced oxygen production continues while seaweed grows	Benefit of increased oxygen ceases once product harvested (seaweed production tends to be seasonal with seaweed biomass fully harvested at the end of a growing season)	Field study in three farms in Shandong, Zhejiang, Guangdong provinces, China (Xiao et al., 2021) Oxygen levels higher inside seaweed farms compared to surrounding waters during the day, with excess O_2 in the farms relative to control areas an average 0.22 ± 0.4 mg L^{-1} (range 0.02–0.35 mg L^{-1}) across farms
				Modeled oxygen release based on quantity of seaweed produced and photosynthesis equivalent to 2.67 tonnes of O_2 for every tonne of carbon in China (Gao et al., 2021) Oxygen production from seven cultivated seaweeds estimated at 2,533,221 tonne year^{-1}
3. Siting farming to provide additional habitat	Habitat—provision of habitat in areas where natural habitat has been lost or degraded	Instantaneous provision of shelter for fauna at a local scale (within a farm) with the potential for enhanced abundance	Farm provides ongoing value for enhanced abundance and potential recruitment enhancement leads to localized increases	Meta-analysis of the abundance of mobile macroinvertebrates associated with aquaculture gear (Theuerkauf et al., 2021)

(Continues)

TABLE 2 (Continued)

Restorative aquaculture practice	Environmental benefit provided	Short to medium term impact (1–5 years)	Longer term impact (>5 years)	Example study and reported size of effect
		and recruitment of fauna	in abundance of associated fauna	Bivalve and seaweed aquaculture associated with higher abundance (0.05× to 473× median lnRR = 0.67) and species richness (0.68× to 4.3×, median lnRR = 0.13). Cultured organism did not significantly predict increases in abundance but did predict an increase in species richness (highest at oyster farms: 0.90× to 2.7× median lnRR = 0.18, $p = .011$)
				Meta-analysis of additional fish production associated with bivalve and seaweed farms (Barrett et al., 2022) Additional fish production by area of farm (kg ha^{-1} $year^{-1}$): oysters 1147 (172–2346), mussels 363 (59–764), seaweeds 529 (−144 to 2452)
4. Siting farming infrastructure where it can reduce wave energy and effects on natural coastal habitats	Habitat—wave attenuation to reduce the risk and effects of erosion	Wave attenuation begins immediately, with ongoing reduction of energy reducing the impacts of mechanical damage to habitat and erosion	Sustained attenuation of energy enables natural habitat to be maintained or recovered	Wave attenuation model (including cantilever-beam, buoy-on-rope, vegetation), validated with laboratory and field data from case study, Maine, USA (Zhu et al., 2020) Suspended aquaculture farms attenuated shorter peak period waves and high frequency wave components more than SAV; provide higher degree of wave attenuation during high tide, storm surges or storm tides (submerged aquatic vegetation decreases dramatically with higher water levels)
5. Siting farming of genetically similar or valuable stock to support restoration of degraded populations of native species	Genetics—Where stock is derived from wild brood stock from the area of farming or is of an acceptable, similar genetic profile, spill over of larvae may add to larval supply for restoration	Benefits limited until spawning of stock occurs. Once spawning occurs aquaculture could be an additional source of larvae for nearby populations and restoration efforts	Spawning of aquaculture stock adds to supplemented population supporting restoration of multiple years classes and population size	Trace elemental fingerprinting and biophysical modeling of *Perna canaliculus*, Firth of Thames, New Zealand (Norrie et al., 2020) Variable contribution of larvae with high rates of supply supported in some locations

TABLE 2 (Continued)

Restorative aquaculture practice	Environmental benefit provided	Short to medium term impact (1–5 years)	Longer term impact (>5 years)	Example study and reported size of effect
6. Farming of seaweed to reduce localized ocean acidification or effects on farming of other species (e.g., in co-culture)	Climate—reduction of ocean acidification	Photosynthetic activity in seaweed (use of CO_2) can maintain elevated pH relative to surrounding waters; effect begins immediately with photosynthesis and continues while seaweed grows	Benefit of increased pH ceases once product harvested	Field study in three farms in Shandong, Zhejiang, Guangdong provinces, China (Xiao et al., 2021) pH consistently elevated in seaweed farms compared to adjacent waters; greatest effect for *Saccharina japonica* farm (mean $\pm$ SE $= 0.10 \pm 0.003$), compared to differences of 0.026 ± 0.003 and 0.036 ± 0.003 in *Porphyra haitanensis* and *Gracilariopsis lemaneiformis* farms
7. Farming of seaweed for carbon capture and storage	Climate—reduction of atmospheric CO_2	Photosynthetic activity in seaweed results in use of dissolved inorganic carbon and conversion to organic carbon, as dissolved (refractory) carbon or transported into benthic habitats or the deep sea where it is sequestered (stored for >100 years)	Carbon "donated" from farming accrues in blue carbon habitats or the deep sea	Modeled sequestration potential based on the ratio of sequestration to harvested POC (sequestration inclusive of POC buried in algal beds, deep sea and refractory pool) of farmed seaweed (model includes counting of lost POC due to remineralization, grazing, detachment, breakoff of farmed seaweed[a]), China (Gao et al., 2021) Carbon removal from seven cultivated seaweeds of 605,830 tonne $year^{-1}$ and carbon sequestration 344,128 tonne $year^{-1}$ Estimated sequestration of farmed seaweed based on equivalent of export from wild seaweed stocks to benthic environments (Duarte et al., 2021) Global seaweed aquaculture sequestration potentially $0.7 TgCO_2$ in 2018; a maximum sustained growth rate of 20% $year^{-1}$ could support sequestration of ~421 $TgCO_2$ $year^{-1}$ in coastal sediments by 2050

[a]Gao et al., 2021 highlight that their study presents higher estimates of NPP most likely as a result of the inclusion of POC and excreted DOC in their calculations which were unaccounted for in earlier studies.

TABLE 3 Information, data, and tools needed to develop the evidence-base for restorative aquaculture, and a supportive environment for industry success.

Area of need	Need
Research and development	• More extensively and thoroughly quantify the environmental and operational factors that influence the environmental benefits provided and their variability (i.e., foundational research on ecosystem services associated with aquaculture in more places, and for more systems, species, and sectors). • Explore the environmental benefits that could be generated through a broader range of aquaculture systems, in particular inland aquaculture, shrimp and marine finfish as well as lesser known or emerging systems, such as silviculture and saltwater "crops". • Evaluate the potential for aquaculture tourism and educational tourism to generate ecosystem services and positive environmental benefits, and the economic, social, and environmental trade-offs that may need to be considered by an operator when engaging in these activities. • Develop effective, low-cost, and accessible tools and technology for monitoring and evaluation (e.g., eDNA, real time data collection, and analysis software). • Run techno-economic feasibility assessments for iterations of species-specific and co-culture farms, at farm and sector-scales. • Develop methodologies and run integrated assessments that include evaluation of resource use and impacts alongside the ecosystem services and environmental benefits provided (e.g., life cycle assessment).
Operational and technical (e.g., farming practices, systems, & management)	• Foundational exploration and development of new native species for aquaculture. • Develop jurisdictional and cross-jurisdictional guidance or frameworks that can harmonize data collection and reporting for monitoring and evaluation of restorative aquaculture practices. • Implement pilot or demonstration sites to test, monitor, evaluate, and learn from restorative practices, supporting farmer capacity building and knowledge sharing on approaches. • Understand social (cultural) and economic contexts and influences associated with implementing restorative practices, and how these could define the efficacy of this approach in a local setting. • Identify likely and potential trade-offs between restorative practices and social and environmental outcomes. • Quantify business costs and approaches to making restorative aquaculture approaches economically profitable. • Identify the best enabling conditions to support Indigenous-led aquaculture, including species, systems, and arrangements for resource access and management (i.e., resource and land use rights).
Governance, policy, and regulation	• Quantify the economic benefits of restorative aquaculture practices and model the effect of different approaches (e.g., siting, choices in species farmed, choices in gear used) on economic outcomes (monetary and employment). • Develop jurisdictional policies that incentivize existing farmers to implement restorative practices (e.g., streamlining of assessment and permitting for restorative practices, recognition for the duration of consent/licenses granted for restorative aquaculture farms). • Develop jurisdictional policies that incentivize appropriate forms of new aquaculture activity, and development of farms in areas where positive environmental impacts can be maximized (e.g., areas of habitat loss). • Develop jurisdictional and cross-jurisdictional crediting or payment for ecosystem services programs. • Develop spatial planning approaches and tools, or incorporate into existing processes and tools, information that can identify areas and approaches that will maximize environmental outcomes from restorative aquaculture at subnational and local levels.

TABLE 3 (Continued)

Area of need	Need
Education and community awareness	• Assess local perceptions and expectations for restorative aquaculture to identify community or government misinterpretations and misconceptions, and therefore potential conflicts. • Explore and develop effective strategies and materials for communicating the benefits as well as the practical limitations of restorative aquaculture. • Quantify consumer willingness to pay for ecosystem services and environmental benefits, across species, systems, practices, and geographies.

climate mitigation (Alleway et al., 2018; Gentry et al., 2020; Weitzman, 2019). Bivalves and seaweeds are extractive species—species that use the organic and inorganic materials and by-products from other species from different levels of the food chain for their own growth—which can increase the cycling and uptake of excess, anthropogenic nutrients from the water (Rose et al., 2014). Shellfish culture systems combined with the stock can also mitigate wave energy and may be able to prevent shoreline erosion (van der Schatte Olivier et al., 2020), and production of seaweed can lead to an uptake of carbon from the atmosphere, which if directed toward effective methods of carbon management may be able to support offsetting of GHG emissions (Duarte et al., 2017; Duarte et al., 2021; Jones et al., 2022). Aquaculture farms also add structure to a water body, which can provide refugia for juvenile fish and invertebrates, sometimes functioning in a similar way to natural nursery grounds (Barrett et al., 2019; Costa-Pierce & Bridger, 2002; Theuerkauf et al., 2021).

It is possible that restorative aquaculture practices will also generate environmental benefits in inland ecosystems connected to or affecting natural water courses (i.e., excluding tanks and recirculating systems). However, understanding of the ways in which positive outcomes may be consistently generated in these systems is not well resolved, likely because many of the strategies that could be adopted are currently coupled with significant trade-offs. For example, while it may be possible to preserve or repair mangrove habitat through integrated mangrove-shrimp farming yields from these systems can often be lower—sometimes considerably lower—in comparison to other shrimp production systems, introducing a trade-off in viability that affects the choice a farmer make when engaging with this approach (Ahmed et al., 2018; Jonell & Henriksson, 2015; Lai et al., 2022). Also in these systems, natural food resources may not always be adequate to support increases in production, which may lead to the need to add feed to maintain production, resulting in negative effects on water quality that detract from the environmental benefit intended (Johnston et al., 2002). In all aquatic environments there is a need to evaluate more extensively the potential environmental benefits of aquaculture practices.

4.2 | Indigenous and customary aquaculture stewardship

Indigenous and cultural aquaculture practices are diverse and widespread and create a rich, globally connected picture of stewardship. Many local and indigenous communities have used aquaculture practices sustainably for food, trade, cultural, and environmental outcomes for millennia (Costa-Pierce, 2022). More than 6000 years ago First Nations in Australia engineered natural water bodies to create sustainable artificial wetlands, where fish were trapped, kept for extended periods of time, and harvested as needed (Jordan, 2012). The co-culture of fish with rice (integrated rice-fish farming) has been practiced for an estimated 2000 years in China (Lu & Li, 2006). In a contemporary setting these integrated systems represent a unique aqua-agricultural landscape that can increase efficiencies in the use of water and land resources at the same time as reducing the need for the use of chemicals in rice production and providing a source of food and livelihood. Rice monoculture relies on the use of chemical fertilizers and pesticides, but the addition of fish and fish waste can replace the need to add nutrients to rice systems via chemical fertilizers and pesticides, supporting the health of faunal biodiversity, and the cultivation of rice can moderate water quality and nutrient cycling providing a favorable growing environment for the fish (Dong et al., 2022; Freed et al., 2020; Li et al., 2021; Xie et al., 2011). In seeking transformation of food systems we must not overlook solutions and management systems created by Indigenous peoples that have fostered sustainable or restorative outcomes for significant periods of time, especially solutions that are rooted in place-based knowledge and traditional management.

5 | FOSTERING A RESTORATIVE APPROACH

Increasing the adoption of restorative aquaculture practices in new aquaculture activities as well as existing sectors and farms has the potential to generate meaningful environmental as well as social and economic outcomes (Barrett et al., 2022; van der Schatte Olivier et al., 2020). To achieve net positive environmental outcomes from restorative aquaculture and contribute to environmental outcomes beyond the scale of an individual farm or farms—thereby enabling this approach to contribute to addressing biodiversity loss, human-driven declines in water quality, and climate change—there is a need to expand our understanding of the ways in which restorative practices can reliably provide environmental benefits. There is also a need to ensure a supportive atmosphere for industry success, socially and economically. Fostering a societal and regulatory environment that rewards the worth of restorative practices through non-market (e.g., social acceptance and appreciation, incentivized licensing approaches), and market mechanisms (e.g., payment for ecosystem services, certification schemes, tax benefits) will empower restorative approaches to be economically viable. For example, research has found that consumers may be willing to pay more for seaweed produced through aquaculture with knowledge of the ecosystem services it can provide (Bolduc et al., 2023).

To assist industry, scientists, government, non-government organizations and individuals to engage with restorative aquaculture, to make their own investigations and to contribute to developing a broader food system approach that is gaining global emphasis (i.e., regenerative food systems, Newton et al., 2020), we identify some key needs for information, data, and tools spanning research, operational considerations, policy and education (Table 3). The needs we identify are not intended to be an exhaustive or prioritized list. Rather they are intended to highlight a range of pressing questions across these topics that, if addressed, would ensure a more comprehensive understanding of "the restorative aquaculture opportunity" and build a foundation for enabling industry to consistently deliver positive environmental outcomes. In addition to these needs, limitations in regulatory frameworks, which by and large treat aquaculture activities solely as a risk for mitigation and currently have little capacity to recognize and account for positive effects from the industry (beyond the provision of food, jobs and economic value), will also need to be overcome (Table S2). Recent analyses and policy approaches have been developed that could be readily built upon to encourage growth of a restorative aquaculture approach at national and sub-national scales. These include integrated social, economic, and ecological analyses (Johnson et al., 2019), methods for forecasting of aquaculture outcomes (Couture et al., 2021), and evidence-base frameworks that describe the ways in which the inclusion of people in decision-making can enable equitable aquaculture outcomes (Krause et al., 2015).

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CONFLICT OF INTEREST STATEMENT

All authors declare they have no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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