VERSION 1.0

A global monitoring, evaluation and learning framework for regenerative and restorative aquaculture: Helping nature thrive through aquaculture

SEAWEED (MACROALGAE), MOLLUSCS AND ECHINODERMS, AND FINFISH FARMED IN MARINE AND ESTUARINE ENVIRONMENTS

February 2024

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TNC seaweed trainer Mondy Muhando near Pemba Island. © Roshni Lodhia

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SUGGESTED CITATION

The Nature Conservancy. 2024. *A global monitoring, evaluation and learning framework for regenerative and restorative aquaculture: Helping nature thrive through aquaculture.* Arlington, Virginia, USA.

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Acknowledgements

We acknowledge and thank the many people who have facilitated the development of this framework and report, especially Junning Cai, and others contributing to our working group. We also thank the many other individuals who have supported this project more broadly, including the authors of the Global Principles of Restorative Aquaculture, who encouraged our focus on regenerative opportunities in aquaculture and putting tools into the hands of farmers. Finally, we thank Builders Initiative for generously supporting the creation of this framework.

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CONTENTS

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Preface

Aquaculture's capacity to achieve environmental goals is twofold: not only can it provide a natural, resource-efficient source of food, raw materials and products, but it can also accelerate ecosystem restoration. The challenge is getting this nature-positive future right.

Because of aquaculture's environmental, social, and economic potential, many nations are seeking to expand production and further develop the commercial sector. As they do so, it is critical that all parties are armed with the best available science and the right decision support tools to ensure the industry is managed with restorative and regenerative practices.

The ecosystem benefits that aquaculture can provide are already substantiated through robust evidence from around the world. Many farmers today are operating in a manner that delivers valuable habitat, water quality, climate, and social benefits. However, the extent of available data is limited, and to date, monitoring and evaluation approaches remain unharmonized.

A global monitoring, evaluation, and learning framework for regenerative and restorative aquaculture: Helping nature thrive through aquaculture, is a key step forward for aquaculture. This framework creates a shared language and supportive network that will help farmers, researchers, government, and non-government organizations come together to understand, value, and communicate these benefits. This framework, if applied globally, can help deliver the information needed to chart a course towards continuous improvement and the right policies and market incentives for these sectors to flourish economically while providing environmental benefits.

The Nature Conservancy's vision for regenerative food systems is to improve the health of ecosystems, biodiversity, and climate, moving beyond sustaining natural resources to embrace large-scale restoration of the lands, waters, and oceans that supply our food. Aquaculture plays a critically important role in our food future, and we look forward to working alongside each of you as partners in this endeavour.

Robert Jones
Global Aquaculture Lead

Introduction

When developed in the right locations and with practices that minimize the risk of environmental harm, aquaculture – one of the fastest growing forms of food production worldwide – can generate a range of benefits for surrounding ecosystems. From improving water quality by filtering nutrients to increasing biodiversity by providing habitat, aquaculture is emerging as a pathway to support the resilience and recovery of coastal and marine areas. These environmental benefits occur in addition to the food or resources produced and the economic opportunities created, representing co-benefits of an industry that already plays a pivotal role in the provision of food, nutrition, livelihood and cultural values. Given ocean biodiversity loss due to the continued exploitation of natural resources, pollution, and increasing impacts of climate change (Jaureguiberry et al., 2022) aquaculture could be a much needed support for aquatic environments.

The capacity for aquaculture to generate co-benefits (hereafter referred to generically as benefits or environmental benefits) builds on a now well-established basis of best practice in the industry. While aquaculture can also present a significant threat to the environment through the introduction and spread of disease and invasive species, disturbance of wildlife and habitat, and pollution from chemicals and waste, (Naylor et al., 2000, 2021; Diana, 2009) in recent decades, progress has been made in addressing these challenges (Shumway, 2011; Naylor et al., 2021). Global, national, and sector-level sustainability safeguards as well as better jurisdictional management (i.e., regulation and policy) are also increasing the efficacy of efforts to mitigate these effects. There is momentum to collectively realize a strong, sustainable aquaculture industry in all nations, as evidenced by the recent development of Guidelines for Sustainable Aquaculture, led by the Food and Agriculture Organization of the United Nations[1].

Alongside a sustainable future for the aquaculture industry, there is an enormous opportunity to expand practices and aquaculture systems that are nature positive. Empowering the aquaculture industry to produce enough seafood to meet anticipated demand (Gann et al., 2019; Newton et al., 2020) with regenerative and restorative practices (Alleway et al., 2023) will contribute to transformation of the global food system to address its role as a major driver of greenhouse gas emissions, deforestation, and freshwater use. It will also help us meet the world's **Sustainable Development Goals**

[1] The Guidelines for Sustainable Aquaculture (GSA) will provide practical guidance to government authorities and policymakers in their efforts promoting the implementation of Code of Conduct for Responsible Fisheries, and engaging and enabling aquaculture to effectively participate in the implementation of the 2030 Agenda for Sustainable Development. **https://www.fao.org/in-action/gsa/background/en/**

(SDGs) and support critical initiatives in this defining decade for climate action, including the **United Nations Decades on Ecosystem Restoration (2021-2030) and Ocean Science for Sustainable Development (2021-2030)**.

A sustainable aquaculture industry is uniquely placed to make a globally relevant contribution because it covers all aquatic ecosystems (freshwater, estuarine or brackish, and marine) and can generate diverse values at multiple spatial and temporal scales (Troell et al., (2023). For example, seaweed cultivation can directly contribute to goals for climate action (SDG 13), ocean health and biodiversity protection (SDG 14), zero hunger (SDG 2), human health and well-being SDG3), and affordable, clean energy (SDG 7), and indirectly contribute to myriad other goals and community and environmental needs (Duarte, Bruhn and Krause-Jensen, 2022; Spillias et al., 2022).

This dynamic, nature-positive role is also increasingly sought by consumers and investors. Seafood sustainability standards help consumers better understand the products available to them, enabling informed purchasing decisions. There are several existing environmental and sustainability standards in the seafood industry that provide important consumer-facing frameworks and tools. However, demonstrating that a business or industry sector is operating not just sustainably but regeneratively is a nature+ or sustainability+ model not yet adopted within any certification approach. In many instances, certain types of aquaculture may already be providing environmental benefits that are not factored into the value of the product or business. Where a farm, practice, or product goes 'above and beyond' basic requirements for ecologically sustainable development, intentionally or passively deploying a regenerative or restorative approach, this information should be available to and valued by markets.

To identify, value, and legitimize the benefits of regenerative and restorative aquaculture, there is a need for a consistent, evidence-based approach to monitor those benefits and a clear, common definition of the goals and objectives of this approach. It is important to recognize the contribution of species and practices to the ecosystem in which they are placed. We can then use this information to make adaptations that maximize the co-benefits provided and manage unanticipated negative effects, if they arise. ***The global monitoring, evaluation, and learning framework for regenerative and restorative aquaculture: Helping nature thrive through aquaculture*** **establishes a generic, data-driven approach to understand the local environmental benefits of aquaculture practices and recommends practical methods to measure and value these benefits in a standardized way.**

Purpose of the Framework

The degree to which aquaculture practices can provide environmental benefits is influenced by inherent ecological factors. This includes species-specific characteristics and local environmental variables, such as the seasonal presence and needs of wild populations of fish, and biophysical aspects of the local environment, including sea surface temperature, water currents, and turbulence, which effect the dispersion and direction of waste and nutrients (Verdegem, 2013; Lester et al., 2018; Theuerkauf et al., 2022). Benefits are also influenced by farm and regional-scale practices and management (e.g. the timing of harvest, frequency of maintenance activities; The Nature Conservancy, 2021) and, therefore, the regulatory or best practice framework in place that sets these expectations (Fletcher et al., 2004; Lauer et al., 2015). Where these benefits are known, they are also often measured or valued in isolation or using different techniques, limiting the opportunity to build an evidence base for understanding these effects.

This document, hereafter referred to as the Framework, establishes a generic framework for monitoring, evaluating, and learning for regenerative and restorative aquaculture. The Framework can be used by aquaculture industry operators, sector associations, and supporting organizations, such as research institutes, government authorities and non-government organizations (NGOs), to take an evidence-based approach in identifying, quantifying, and establishing a

Data being collected to support development of an oyster reef restoration site.

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monitoring program for the environmental benefits and several intersecting socioeconomic outcomes from aquaculture in a consistent way. It identifies recommended goals, objectives, and indicators, and a suite of sampling methods for monitoring and evaluation. It is a base model that can applied in full or adapted, and it can be used across varied spatial scales.

THE FRAMEWORK DOES:

- ✓ Support farmers to identify and measure the environmental benefits they may or may not be providing on their farm.
- ✓ Provide a consistent approach to measuring environmental benefits from similar species, systems, and/or practices across locations and from year to year.
- ✓ Align a quantitative understanding of the environmental benefits provided to broader environmental goals that will support ecosystem resilience, conservation, or repair.
- ✓ Recognize the potential for several key socioeconomic benefits that can be associated with these environmental benefits.

THE FRAMEWORK DOES NOT:

- ✗ Replace any standard environmental monitoring procedures required by regulatory bodies, agreed Best Management Practice, or industry Codes of Practice (e.g. monitoring of infrastructure for adverse effects on habitat or fauna, monitoring of marine debris).
- ✗ Implement a basis for comparing the environmental performance of individual operations or sectors to one another.
- ✗ Establish a credential or certification scheme for environmental performance and sustainability.
- ✗ Support extensive assessment of socioeconomic benefits from aquaculture and aligned challenges, such as achieving food and nutritional security and equality.

User	Example use
Farmers	• Explore existing benefits their farm may provide or may be able to provide through practices (e.g. modifying the timing of harvest or maintenance) • Use the methods described to begin recording data that can be used to quantify benefits on their farm • Monitor their farm and practices to measure benefits from year to year and changes over time • Share observations, data, or equipment with other farmers in the area to build a shared understanding of the benefits to the broader local environment
Sector Associations (sector co-operatives or formal industry associations)	• Identify shared goals and objectives of interest to the sector and use the framework to monitor what benefits are provided • Establish partnerships or approaches to enable collaboration on data collection and analysis, such as research partnerships and funding • Use the data collected to build community understanding of aquaculture or consumer awareness and market-based opportunities
Research Institutes and NGOs	• Support farmers to build a robust evidence base of benefits on their farm or in their sector or area by collecting, analysing, and interpreting data they collect • Undertake more difficult sampling and monitoring methods • Develop ongoing datasets that can work toward comparing benefits across farms locations, species, and systems • Develop data management systems and complementary data collection and analysis tools
Government Agencies	• Enable the positive impacts of aquaculture to be more widely understood and regenerative and restorative practices applied by supporting farmers to monitor their benefits • Support the development of monitoring and data collection that can be used in support of regulated monitoring requirements, e.g. annual environmental compliance reports • Partner with research institutions and NGOs to support data collection and analysis that can be used to improve existing policy or develop new policy • Use the information gathered to develop evidence-based policy support, such as streamlining of regulatory requirements or formation of approaches for payment for ecosystem services • Use the framework to monitor efficacy of aquaculture practices and encourage consumer awareness of the benefits provided and/or adapt incentive programs • Use the framework to encourage investment in a credible approach to regenerative and restorative aquaculture and monitoring returns on investment

Scope of the Framework

The Framework applies specifically to three overarching aquaculture sectors and farming in marine (including coastal) or estuarine environments:

1. Seaweed (macroalgae)—brown, red, and green macroalgae, consistent with 'aquatic plants' in the current International Standard Statistical Classification of Aquatic Animals and Plants (ISSCAAP)[2] terminology that is also often used in national or state legislation and policy.

2. Molluscs and echinoderms—including bivalves and gastropods, but excluding cephalopods because of a current lack of information about the potential for cephalopod farming to generate environmental benefits.

3. Finfish—identified in the ISSCAAP as 'fishes'.

While environmental benefits from restorative aquaculture also occur in inland environments connected to or affecting natural water courses (i.e., excluding tanks and recirculating systems), marine and inland aquaculture systems are functionally different and can impact ecological processes and wild species in different ways. **It is intended that future versions of the Framework will be developed for other sectors, farming practices, and ecosystems systems, such as finfish and shrimp farming in inland waters.**

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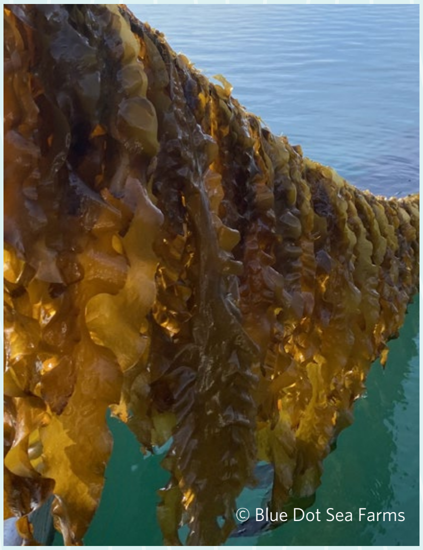
[2] AnnexSIIlistISSCAAP2000.doc (fao.org)



Seaweed (macroalgae)

Molluscs and echinoderms

Finfish

How can aquaculture help nature?

Aquaculture is one of the fastest growing forms of food production globally and is projected to continue to expand to meet increasing demand for seafood.

"By 2030, aquatic food production is forecast to increase by a further 15 percent, mainly by intensifying and expanding sustainable aquaculture production. Such growth must preserve aquatic ecosystem health, prevent pollution, and protect biodiversity and social equality." (FAO, 2022)

A growing body of evidence is showing how, when sited in the right locations and implemented with practices that mitigate and minimize the risk of environmental harm, aquaculture can bring a broad range of intentional and incidental benefits to surrounding ecosystems, from assisting species and habitat recovery by supporting ecological processes or using cultivated organisms for restoration or rehabilitation projects to coastal defence, bioremediation, and biological control (Overton et al., 2023; Ridlon et al., 2023). Many of these benefits arise from the inherent characteristics of certain species, especially bivalves and seaweed, which have a well-known influence on water filtration and nutrient uptake (e.g. Rose et al., 2014; Grebe et al., 2021; Racine et al., 2021; see Figure 1). These benefits can be influential at the farm site and at the scale of an ecosystem or ecoregion. The value of nitrogen removal currently provided by bivalve aquaculture in the EU has been modelled to be an equivalent value of between 15.9 billion to 21.6 billion euros, if other methods were used for waste treatment (Cubillo et al., 2023). If restorative practices are used effectively, the value of nitrogen removal and the value of additional fish production globally from aquaculture could be in the order $17 billion to $56 billion annually in the coming years (Barrett et al., 2022).

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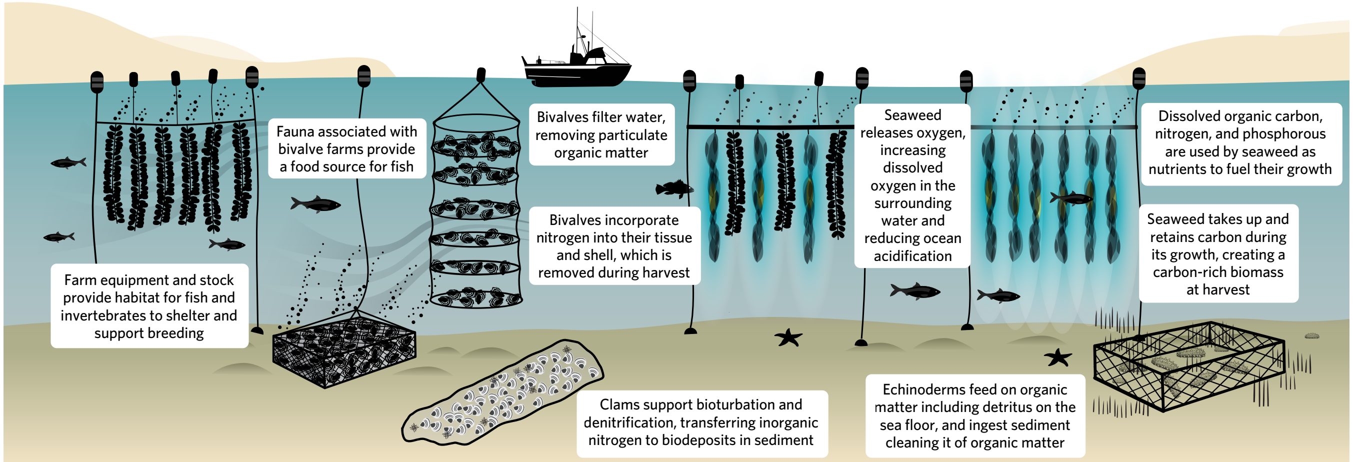
Diver inspecting seaweed lines in Placencia, Belize

Figure 1. **Benefits to the marine environment that can be provided by aquaculture of seaweeds, molluscs, and echinoderms.**



A regenerative and restorative approach

Regenerative and restorative farming practices emphasise the cultivation of species or use of aquaculture systems, infrastructure, and practices to generate direct environmental benefits (The Nature Conservancy, 2021). The pathways through which regenerative approaches create these benefits can be broadly characterized in one of two ways: approaches that can be applied to the farm landscape and surrounding area (e.g. interventions that ensure protection or support rehabilitation of natural habitat), or approaches that are applied to the farming practice itself (e.g. optimizing stock rotation or intentional management of nutrient cycling to benefit farming productivity and the environment; FOLU, 2019; Miralles-Wilhelm, 2021). In aquaculture, these approaches have been recognized as also being potential Nature-based Solutions (NbS), including solutions that meet the objectives and criteria of the Global NbS Standard™ (IUCN, 2020; Le Gouvello et al., 2023).

The environmental benefits of the farming practice or species may have an immediate positive effect (e.g. increasing water filtration rates and capacity) or an incremental effect, with the outcomes of this effect accruing over time to generate a broader value for nature (e.g. improved water quality due to increasing water filtration capacity and reducing excess particulate matter and dissolved nutrients). The benefits that arise can also be classified as ecosystem services – the many and varied benefits to people provided by the natural environment – resulting in intersecting social-ecological and socioeconomic outcomes, such as increased opportunities for livelihood, including employment and economic opportunities that assist people to access necessities and recreation and its benefits for mental health, physical health, and spiritual well-being (Table 1).

The benefits created by aquaculture, using a nature-positive approach, can generally be attributed to four categories, three of which are specifically associated with ecological outcomes and the fourth an overarching category encompassing several opportunities in support of linked equitable and sustainable social and economic outcomes:

- Habitat and biodiversity
- Water quality
- Climate change
- Sustainable food, resources, and livelihood

Some farmed species have inherent characteristics that lend to the provision of certain benefits more than other species. For example, the benefit of water filtration provided by bivalve molluscs is an intrinsic value, when compared to the benefits that finfish aquaculture may and may not be able to provide for water quality. The benefits that can be provided also reflect a spectrum, where some modes of culture may be expected to return greater benefits than others (The Nature Conservancy, 2021; Theuerkauf et al., 2021). For example, aquaculture equipment that provides habitat in areas where hard bottom habitat has been lost could provide a greater benefit for biodiversity than comparable systems in areas where structured habitat hasn't been lost.

In comparison to seaweeds and bivalve molluscs, the potential for fed aquaculture systems, including finfish and fed molluscs, to generate environmental benefits is not as well resolved and remains to be tested. Potential positive environmental interactions are known to occur, such as the attraction of wild fish, crustaceans, and echinoderms, which if managed to avoid ecological traps or other negative impacts, such as the transfer of pathogens or parasites, can provide a benefit by enhancing local wild fish populations (Barrett, Swearer and Dempster, 2019). The dependence of this sector on feed and the consequent concentration of waste means, however, that in comparison to seaweeds and unfed molluscs, there are some fundamental differences in the way these species are farmed that likely negate the capacity for specific services to be provided, such as improving nutrient cycling and waste treatment.

While the effects of some farm practices are becoming clear, such as water filtration from bivalve molluscs, others remain unresolved. The effect of seaweeds on effective carbon sequestration (carbon sequestration is the secure storage of carbon containing molecules, especially atmospheric CO_2, for more than 100 years) is currently uncertain and difficult to account for (Hurd et al., 2022). While bivalve molluscs may play an important role in carbon cycling in the water, calcifying organisms don't positively influence carbon sequestration over a time scale that is relevant to addressing climate change (Howard et al., 2023). There could also be valuable benefits from aquaculture for reducing wave energy and the intensity of storm surges in coastal environments (Zhu et al., 2020, 2021; Bodycomb, Pomeroy and Morris, 2023); however, these benefits need to be more widely understood in commercial settings because of their potential to have secondary effects, both positive and negative, on ambient hydrodynamics (Hanley, 2023). Continued research into the full range of ways that aquaculture species and systems may be able to have positive effects on the surrounding ecosystem and communities is needed and will help to resolve the practical application – and limitations – of regenerative and restorative practices.

Importantly, many of these practices are founded on or improved by the knowledge and management of Indigenous communities. Ensuring that customary and Indigenous practices and their peoples' stewardship is centred in our approach to contemporary food production and food systems will lead to better outcomes from ecosystem services. It will also foster food sovereignty and social outcomes for Indigenous communities, including greater equality and cultural reconciliation. The inclusion of such practices and pathways alongside learning from Indigenous peoples is and should be maintained as an active intention in regenerative and restorative aquaculture.

Data on oysters being collected to support development of a restoration site.

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Table 1. **Examples of environmental co-benefits that can be associated with aquaculture in marine environments and the social and economic values that can be directly and indirectly associated with regenerative and restorative practices.**

Benefit category	Potential outcome or impact	Example	Method used and data collected
Habitat and biodiversity	Habitat provided by farm stock and equipment is used by wild fauna for shelter and feeding, from microbiota to megafauna	Snapper associated with mussel farms consumed different prey in comparison to non-farm sites, including biofouling and nuisance species (a nuisance to farming operations), with the diet provided potentially supplying more nutritious prey and reducing foraging effort (Underwood, van der Reis and Jeffs, 2023)	Gut contents analysis of snapper found within and outside mussel farms, Esk Point, Coromandel Harbour, New Zealand
		Species abundance and richness higher on submerged aquaculture gear (SAG) versus submerged aquatic vegetation and shallow non-vegetated seabed because the SAG habitat provided more surface area than the other habitats, potentially protecting juvenile fish from predation and providing substrate for sessile organisms as a food source for fish (Dealteris, Kilpatrick and Rheault, 2004)	Enclosure gear used to sample the SAG and non-aquaculture habitats for associated fauna, Point Judith Pond estuary, Rhode Island, New England, USA
		Fish consumption rates were highest near off-bottom floating oyster bags, greater for both off- and on-bottom oyster aquaculture relative to bare sediment, and for off-bottom aquaculture relative to on-bottom (Lefcheck et al., 2021)	Dried squid used as a prey item in the three structured settings and reference sites (unstructured habitats), repeated across three seasons at twelve locations spanning 900 km of coastline, North Carolina and Virginia, USA
	Area provided by the aquaculture site is used by fish and other fauna for shelter	Seaweed farms in Maine found to have fish and invertebrates sheltering with the framed biomass (Schutt et al., 2023) Finfish farming in marine areas contributed to increases in local fisheries activity and landings (Machias et al., 2006)	Visual surveys using GoPro cameras to collect video footage paired with sampling and analysis of environmental DNA, Saco and Casco Bays, Maine, USA Data from time series of landings, fish farming production, fishing fleet, temperature, and rainfall from 1984-2001 to model the effects of fish farming, Greece

Benefit category	Potential outcome or impact	Example	Method used and data collected
Habitat and biodiversity	Fauna attracted to aquaculture infrastructure provides a supplementary food source for other wild populations	Seal populations are attracted to net pen aquaculture for habitat and foraging, feeding on wild mackerel and trevally that are attracted to aquaculture sites (Goldsworthy et al., 2019)	Dietary assessment of seal populations using DNA and hard part analysis paired with GPS tracking of individual seals and sea lions along the coast of South Australia, Australia
	Provision of habitat for different life stages, e.g. spawning and recruitment	Mussel farms provided habitat for fish settlement and recruitment of some fish species equivalent to natural habitats (Underwood and Jeffs, 2023)	Standard monitoring units for the recruitment of fish (SMURFs) at farm and non-farm reference sites with similar habitat, Coromandel Harbour, Firth of Thames, New Zealand
		Oyster farms contained higher densities of black sea bream eggs than historical spawning sites, indicating farms provide habitat for successful spawning (Kawai et al., 2021)	Sampled planktonic eggs at 14 sites, including oyster farms and non-farm historical spawning sites, Hiroshima Bay, Japan
		Fish abundance similar or greater around oyster cages than rocky reef habitat, with young-of-year fish found in both habitats, suggesting oysters farms may have acted as nursery habitat (Mercaldo-Allen et al., 2023)	Underwater video census of fish abundance and community composition within off-bottom oyster cages and rocky reef habitat, Milford, Connecticut, USA
	Protecting or enhancing productivity or the function of wild habitats and communities	Seaweeds produce detritus (Particulate Organic Carbon) through frond erosion and breakage that can 'donated' to other habitats, such as seagrasses, enhancing nutrient transfer and their productivity or the cycling and retention of carbon (Hyndes GA, Lavery PS, and Doropoulos C, 2012)	Experimental addition and tracing of isotopically-labelled (15N) kelp in laboratory and field setting, Shoalwater Islands Marine Park, southern Western Australia
	Habitat and species recovery and resilience	Aquaculture methods such as selective breeding and stock enhancement could assist species resilience, conservation, and restoration, including challenging species and habitats such as coral reefs (Ridlon et al., 2023)	Conduct small scale of proof trials on stock enhancement, drawing on experience with coral and oyster reef restoration approaches (global), so that efforts can be scaled up before significant ecosystem decline
		Disease resistance in hatchery-produced populations of European flat oysters supported by selective breeding of cultured oysters, with some culture systems also supporting genetic diversity (Lallias et al., 2010)	Sampling of wild and managed populations (pond produced) for genetic analysis of stock across Scotland, France, the Netherlands, Denmark, Norway, and Portugal

Benefit category	Potential outcome or impact	Example	Method used and data collected
Water quality	Increased water clarity through filtration	Bivalves filter water to feed, reducing suspended material in water column (Barr, 2022)	Field experiments conducted seasonally using a flow-through filtration chamber with ambient water to calculate individual oyster filtration physiology, Delaware Bay, New Jersey, USA
	Excess nitrogen removal through denitrification enhancement	Oyster aquaculture using suspended mesh bags increased net denitrification rates, quantified by sediment denitrification and Sediment Oxygen Demand (Humphries et al., 2016)	Field experiments using in situ environmental chambers across four oyster habitat and reference sites: restored oyster reefs, oyster aquaculture, oyster cultch (shell), and bare sediment, Ninigret Pond, Rhode Island, USA
	Excess nutrient removal through bioextraction (assimilation of nutrients in tissue and shell)	Sugar kelp cultivation and harvest estimated to remove 19.2 (± 4.8) – 176.0 (± 7.7) kg N ha−1 after 6 to 7 months of culture, depending on the density of longlines (Grebe et al., 2021)	Elemental and stable isotope analysis of tissue paired with periodic estimates of farmed biomass (using mean biomass of samples extrapolated for the full farming area), Western Gulf of Maine, Maine, USA
		Mussel cultivation estimated to remove 0.6-0.9 t ha-1 yr-1 of N and 0.03-0.04 t ha-1 yr-1 of P (Petersen et al., 2014)	Full-scale mussel farm optimized for nutrient removal with biological and economic parameters measured for 1 year, Skive Fjord, Denmark
	Reducing excess non-organic minerals heavy metals	Pearl oysters can extract notable quantities of organic nutrients but also heavy metals, with each tonne of pearl oyster material harvested removing approximately 703 g metals, 7452 g N, and 545 g P (Gifford et al., 2005)	Collection of samples from aquaculture facility with laboratory analysis of nutrient and metal content in shell and tissue, Port Stephens, New South Wales, Australia
Climate change	Regulation through carbon cycling	Cultivated seaweed that retains C in its biomass can deposit particulate organic carbon in sediments underneath, adjacent to, and away from farms (Duarte et al., 2017)	Modelled estimates of CO_2 use a C uptake in farmed seaweed, based on rates of C cycling and uptake in wild seaweed habitat globally
	Regulation through water flow and sediment stabilization, resulting in erosion prevention and moderation of extreme events	Suspended aquaculture farms attenuated shorter peak period waves and high frequency waves more than submerged aquatic vegetation, providing higher degree of wave attenuation during high tide, storm surges, or storm tides (Zhu et al., 2020)	System model for wave attenuation with application to a case study site and mussel farm, Saco Bay, Maine, USA

Associated social and economic co-benefits through sustainable food, resources, and livelihood

Provision of food	Aquatic foods are a valuable source of health and nutrition, often having high concentrations of minerals, vitamins, essential fatty acids, and protein (Thilsted et al., 2016; Raja, Kadirvel and Subramaniyan, 2022)
Provision of raw materials	Seaweeds can be used for a range of bioproducts and have a lower environmental footprint than other sources, such as biofuels, bioplastics, biomaterials, and agricultural fertilizers or biostimulants (United Nations Environment Programme, 2023)
Provision of medicinal resources	Shell and meat of mussels are an accessible source of a range of bioactive compounds, including carbohydrates, lipids, and peptides that have health and medicinal properties (Grienke, Silke and Tasdemir, 2014)
Sense of place through livelihood and support for employment, including gendered employment	Employment in aquaculture can include gendered employment and increased opportunities for women's participation. For example, women's participation has recently been identified as highest within the fast-growing though relatively low-value seaweed aquaculture sector in Maine, northeast USA, in comparison to other sectors, such as oyster farming, providing the potential to increase gender equity in the seafood industry (McClenachan and Moulton, 2022)
	Seaweed aquaculture in Indonesia can provide income for rural households and women to the extent that social outcomes can be increased through better access to transport, housing, and education (Rimmer et al., 2021)
Supporting Indigenous culture, heritage, values, and wellbeing	Indigenous economic and social wellbeing can be important benefits of aquaculture, and Indigenous-centred monitoring methods often provide better pathways for valuing sustainability. For example, **loko iʻa (Hawaiian fish ponds)** are unique aquaculture systems that exist throughout Hawaiʻi, developed to optimize natural patterns of watersheds, nutrient cycles, and fish biology, and their restoration and management can be an important component of the ahupuaʻa (traditional land stewardship framework) that contributes to a present-day healthy and robust food system. Also, the **mauriOmeter**, used in Aotearoa, is a decision-making framework that combines a stakeholder assessment of worldviews with an impact assessment of indicators to determine sustainability and trends over time, using the concept of mauri as the measure of sustainability instead of the conventional monetary-based assessment, allowing for a more accurate representation of the impacts of certain actions or options.
Contribute synonymously to multiple social and human development goals	Seaweed farming and products can contribute to multiple Sustainable Development Goals, including SDGs 2 (Zero Hunger), 8 (Decent Work and Economic Growth), 9 (Industry, Innovation, and Infrastructure), 12 (Sustainable Production and Consumption), 14 (Life Below Water), and 15 (Life on Land) (Spillias et al., 2022)

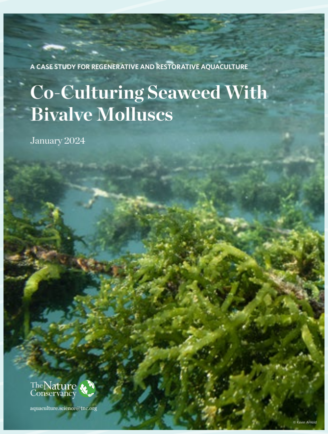
Case studies

In the Global Principles of Restorative Aquaculture (The Nature Conservancy, 2021), three case studies were used to explore how aquaculture systems and practices may or may not be considered restorative. Those case studies reflected on the impact of filter-feeding carp on lake water quality in China freshwater environments, the potential for farm-scale practices to contribute to ecosystem-scale goals through oyster aquaculture's contribution to water quality in the Chesapeake Bay, and the habitat benefits of the emergent seaweed industry in Belize and how these benefits could shape farm and sector-wide approaches to continued industry growth and development.

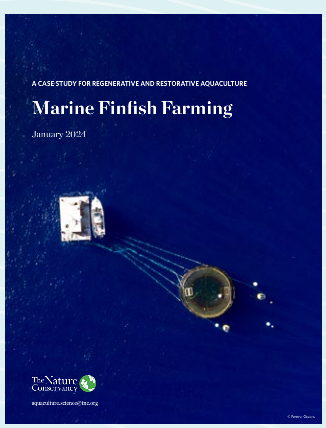
Case studies are useful to continue building our understanding of the many ways regenerative practices could create environmental benefits and how these will vary across a wider range of sectors, growing environments, and species.

To support development of the Framework, three new case studies of aquaculture in marine environments have been explored. These case studies intersect with known potential restorative aquaculture approaches but intentionally extend this knowledge in new ways to better resolve some of the ecological principles that may apply across farming species and systems and the monitoring methods that will be needed to adequately assess impacts at a sector-level.

A first case study explored the unique interactions that could exist in systems **co-culturing seaweed with bivalves**. While co-culture of these species represents a mature farming system in China (Mao et al., 2019), the approach isn't common in many other areas. Co-culturing these species may have the potential to enhance certain environmental benefits and ecological outcomes, such as providing a refuge from



Co-Culturing Seaweed With Bivalve Molluscs



Marine Finfish Farming

Marine Pearl Farming

Barge harvesting oysters at Hama Hama Oyster Company on Washington's Olympic Peninsula.

ocean acidification (Fernández, Leal and Henríquez, 2019), and could have reciprocal benefits to the production of each.

A second case study looked specifically at the dynamics of **pearl oyster farming** and how its environmental benefits may differ from food-based oyster production. While these systems are largely similar, variations in growing systems and equipment, species-specific characteristics, and impacts associated with product utilization could result in higher or lower restorative outcomes for some benefits. Understanding these differences will provide insights into the system or context-dependent outcomes that will arise for pearl farming specifically, and general ecological principles for the mollusc sector more broadly.

A third case exploring the extent to which **marine finfish farming** may be able to apply regenerative and restorative practices and finfish species and farming systems may be able to generate environmental benefits.

The Framework

The global monitoring, evaluation and learning framework for regenerative and restorative aquaculture is a strategy-based framework. It identifies why a restorative approach matters within the context of global environmental issues (the vision), what the aquaculture industry and individual farmers can realistically do to help address these issues (the strategy), and how this can be carried out and assessed (the tactics).

The aim of establishing a framework is to guide a common and consistent approach that can enable data and knowledge on the environmental benefits generated by aquaculture to be collected and monitored for change over time. This will assist in more accurate assessment and valuation of the ecosystem services aquaculture can provide as well as the exchange of information among farmers, farms, sectors, and stakeholders. The Framework has been designed to be adoptable and adaptable, meaning it can be used 'as is' or customized to serve a range of purposes and more localized MEL plans.

The Framework provides this guidance through a hierarchical approach that identifies environmental and social goals which can be achieved through certain objectives. Indicators and metrics to consistently assess the contribution of a farm or farm practice to

Figure 2. **The strategy-based approach to monitoring and evaluation of environmental benefits from aquaculture.**

these objectives are described along with a suite of methods that could be used to quantify and repeatedly monitor benefits (see Figure 2). Goals, objectives, indicators, and methods are described according to the environmental benefit categories (habitat and biodiversity, water quality, climate change) for each of the three aquaculture sectors considered in Version 1.0 (i.e., seaweed, molluscs and echinoderms, and finfish farmed in marine or estuarine environments).

Opportunities to implement monitoring and evaluation are similarly described for the provision of sustainable food, resources, and livelihood. The social benefits that can arise from regenerative and restorative aquaculture differ from environmental benefits, but are an important part of a just and equitable food system. Regenerative food systems go beyond sustainability and create positive growth for communities, economies, and the planet. Conversely, sustainable business models and food production are the basis of regenerative practices. These benefits are increasingly sought by investors and the community, such as expectations for genuine corporate environmental, social, and governance practices. The opportunities highlighted are not intended to be exhaustive; rather, they are suggested examples for industry, companies, or governments to consider for further development.

This approach is consistent with the established principles of the International Society for Ecological Restoration (Gann et al., 2019) and current best practice methods for bivalve shellfish reef restoration (e.g. zu Ermgassen et al., 2016). A hierarchal framework emphasises the importance of the planning phase for effective implementation of regenerative and restorative approaches, having high level goals underpinned by measurable objectives to assess success against, a plan for monitoring, and a pathway for analysing, adapting, and sharing learnings.

How can this Framework be used?

As a global framework, this approach establishes a comprehensive but generalized evidence-based platform. The Framework can be used 'as is', as a supplement to other monitoring approaches, or it can be integrated into existing aquaculture monitoring strategies to support consideration of environmental benefits from aquaculture. This includes integration with conservation strategies and plans, such as management plans for marine protected areas. In developing the Framework, the aims and indicators used in other assessment processes have been considered (e.g. the World Aquaculture Performance Indicators, the aims of certification schemes and benchmarking frameworks, such as the Global Sustainable Seafood Initiative).

The Framework can also be adapted. Additional goals, objectives, or indicators could be included to create a comprehensive local or regional MEL plan. **The Framework does not, and should not, be used to replace basic requirements for monitoring of environmental interactions and impacts from aquaculture, (e.g. negative impacts to benthic habitats through nutrient enhancement, negative interactions with**

marine fauna, testing for food safety [for all species including seaweed]) or for the purposes of compliance with regulation and management. Restorative and regenerative aquaculture emphasizes the provision of environmental benefits and intersecting socioeconomic benefits, recognizing that healthy and functioning ecosystems are the basis of not just nature but also human well-being. Benefits, therefore, cannot occur at the expense of negative environmental or social impacts in other ways. **Ecologically sustainable development and management is, effectively, a pre-condition for regenerative and restorative aquaculture**.

The Framework can be used to support a quantitative assessment of a farm or farm practice, following higher level guidance in the **Global Principles of Restorative Aquaculture roadmaps**, which help farmers and practitioners understand at a high level whether a farm is likely or not to be 'restorative'. The questions asked within those roadmaps are qualitative and quantitative. Where relevant, a quantitative assessment of the questions provides a more precise appraisal of whether a farm is engaging in restorative aquaculture. For example, a farm may be operating within the limits of ecological carrying capacity, which could be understood by compliance with local regulations, but quantitative information could better answer the question, "does the site have appropriate flushing?"

While the Framework has been developed with the intent of supporting monitoring and evaluation by any user group that has an interest in regenerative and restorative aquaculture, there are several most likely use cases in the short term, which will be influenced by the size and capacity of a farmer or organization. Depending on their capacity or goals, a farmer, researcher, government, or NGO may choose to monitor for one benefit, a small number of benefits in one or two categories, or a larger number of benefits across all categories to develop a more comprehensive understanding.


© Jonathan Mackay

Off-bottom oyster culture in South Australia

The indicators and methods recommended to support monitoring and evaluation reflect a range in their ease of implementation and therefore, in many cases, their accuracy. Low cost, accessible, and readily repeated methods have been recommended alongside more complex methods that will likely require assistance from researchers with access to specialized equipment and infrastructure. While accuracy is important, sampling methods that may not be as precise but can be adopted at low cost and deployed immediately are necessary to make progress on data collection, rather than waiting for funding or resources for more complex methods. They are also important for inclusion of farmers who may not have support from research institutions.

Monitoring

Effective monitoring enables performance to be measured against a set of predetermined objectives. Consistent collection of monitoring data using the same methods enables the information collected to be built over time, creating a robust evidence base. Knowing which indicators assist in measuring progress toward a particular goal also helps to define the resources that are needed (e.g. equipment, time, science support).

The Framework recommends a repeated measures design for sampling, on the basis that most users interested in applying the Framework will already be undertaking aquaculture activities, which precludes the opportunity to sample the ecosystem before a farm was developed. The efficacy of a repeated measures design is dependent on sampling specific, individual ecosystems services regularly and at comparable times (e.g. seasonally) in successive years. This means, for example, collecting data at the same point within an aquaculture site at the same or similar times each year. Where data is consistently collected, the comprehensiveness and confidence in the data will improve over time. The exception to this approach would be where a decision is made to change a management practice, type of infrastructure, or other activity on the farm (e.g. to add a species to the farm or modify the timing of harvest) with the probability that environmental benefits will be enhanced.

Where there is the opportunity to sample an aquaculture farm or practice prior to it being introduced, the use of a before-after-control-impact (BACI) design should be used.

Many of the indicators identified require sampling of the farm environment only. To adequately sample and assess the benefits of farm versus non-farm sites, however, the use of control or reference sites may be necessary. To assess farm and reference sites, collaborative monitoring efforts may be needed. Dedicated regional monitoring programs supported by shared resourcing or funding could also be required for sampling non-farm sites. Collaboration should increase and centre regional and local interests and needs, including Indigenous knowledge and science capacity.

Control or reference locations are those of similar biophysical characteristics (e.g. depth, water flow, habitat type, sediment biogeochemistry, salinity and temperature, and range of variation) that don't have aquaculture activities occurring. The distances between farm and non-farm reference sites will need to consider local environmental conditions (e.g. currents and ecosystem connectivity) and the species that is being farmed. This is because of the continuum in potential effects from aquaculture activities that can occur, from no effects being seen off a farm site through to pronounced effects several hundred metres away, depending on the species and intensity of farming (at the farm site and through multiple farm sites). As a guide, distances of more than 100 metres for seaweed and mollusc and echinoderm farms and between 500 metres to 1 kilometre for finfish (potentially more in dispersive environments, such as offshore open oceans) will likely be needed between farm and control or reference sites to reduce the potential for farm activities to influence non-farm samples, while keeping the conditions at the sites as similar as possible.

ARCHETYPES OF RESTORATIVE AQUACULTURE

Environmental and farm-based factors determine the degree to which aquaculture activities generate environmental benefits (Theuerkauf et al., 2022; Alleway et al., 2023). As well as these conditions, the current state and trajectory of ecosystem health in the local area influences the extent to which a farm may be able to have a 'restorative' effect. For example, where water quality or habitat has been degraded, there may be a greater effect from regenerative practices, whereas in areas where no declines have occurred, certain practices or the spatial expansion of aquaculture activities and production may present a risk for negative impacts. Four archetypes for restorative aquaculture characterise this intersection and can inform both the monitoring approach that might be most effective in a particular area (see Figure 3) as well as the sampling design that might be needed to adequately assess environmental benefits (see Figure 4).

When sampling across these archetypes, there will be a need to make choices about the use and location of control or reference sites. Selecting an appropriate reference site depends on the indicator you are measuring and the nature of the ecosystem. In areas where there is structured habitat – 3D habitats such as kelp forests, seagrasses or oyster reefs that have more complex structure that aquaculture gear and stock then simulates – it may be most relevant to locate reference sites within those habitats so that an understanding of the quality of aquaculture habitat can be gained (e.g. how does the abundance and richness of species associated with aquaculture habitat compare to other similarly structured habitats?).

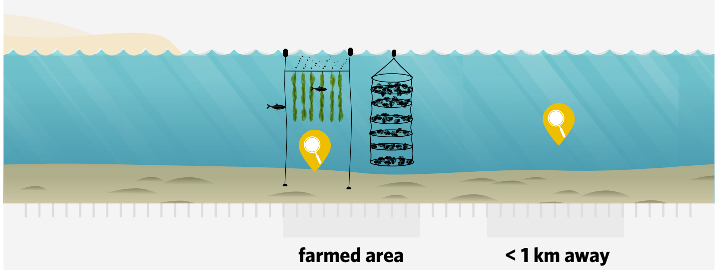
In contrast, in areas where there is a lack of structured habitat – the area is characterised by sediment or soft sediment bottom – it may be most relevant to use these natural habitats to specifically assess the how fauna is enhanced by the addition of the structured aquaculture habitat to that ecosystem (e.g. how does fauna respond to the addition of structured habitat to that environment?).

Figure 3. **Archetypes of farming and sampling regimes to establish the extent of benefits provided, depending on the state of environmental health.**

Where should sampling occur to best understand environmental benefits?

Archetype 1

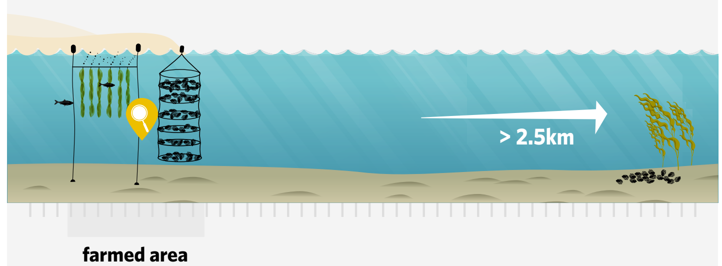
Farm is sited in an area where there is widespread lack of structured habitat, e.g. farms over soft sediment or low relief rocky bottom



Sample in the farmed area and maybe within the vicinity of the farm (e.g., < 1 km away from farm edge) if measuring enhancement

Archetype 2

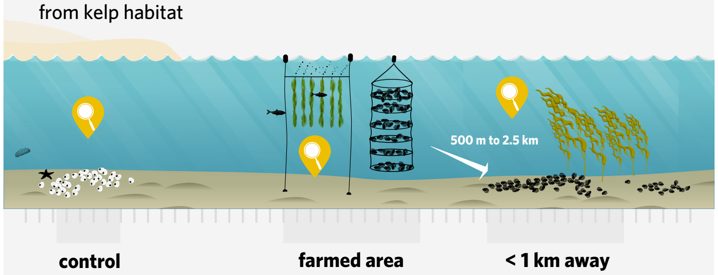
Farm is sited away from similar wild habitat, e.g. oyster aquaculture > 2.5 km from oyster reefs, kelp farms > 2.5 km from kelp habitat



Sample in the farmed area, samples could be compared to data collected from nearby similar wild habitat

Archetype 3

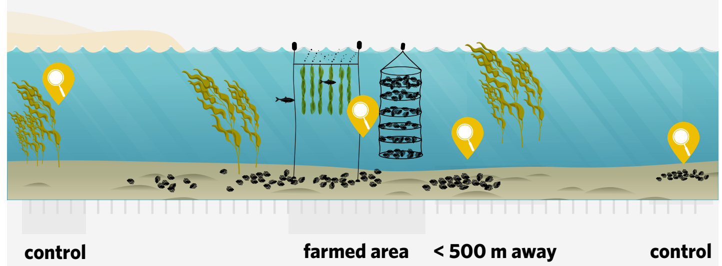
Farm is sited near to similar wild habitat, e.g. oyster aquaculture between 500 m and 2.5 km from oyster reefs, kelp farms between 500 m and 2.5 km from kelp habitat



Sample in the farmed area and within the vicinity of the farm (e.g. < 1 km away from farm edge) and at appropriate reference sites that have similar structure but may be habitat formed by different species

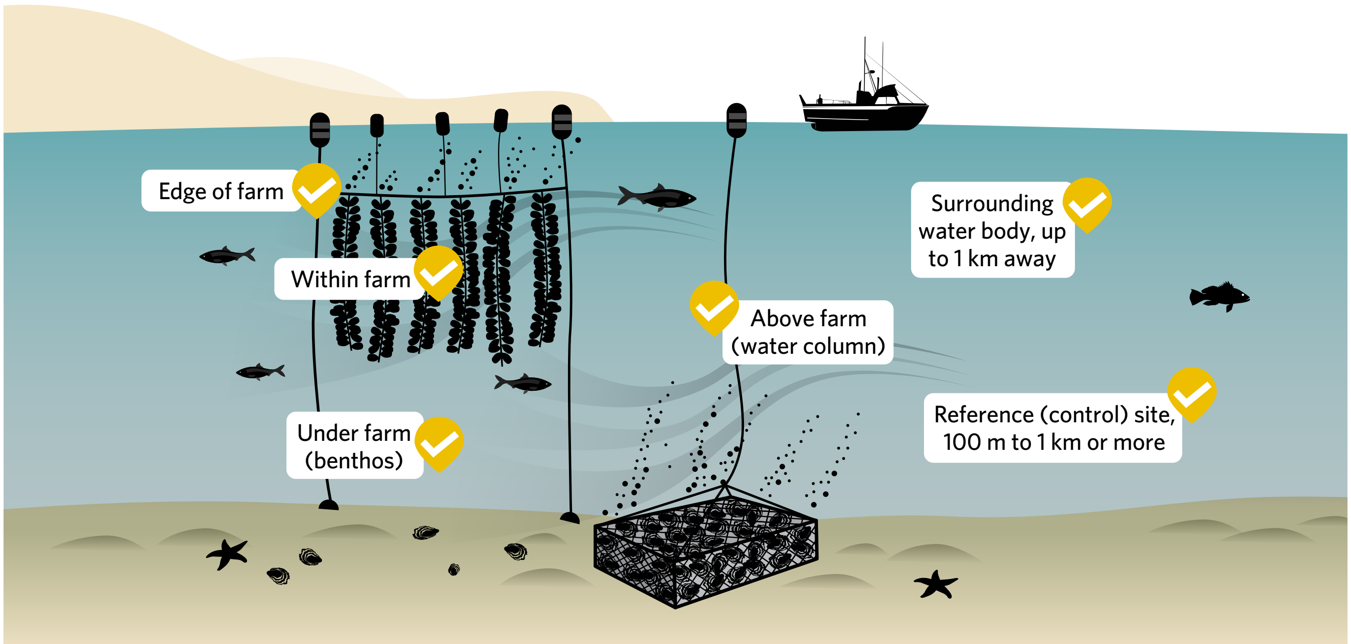
Archetype 4

Farm is sited within similar wild habitat, e.g. oyster aquaculture < 500 m from oyster reefs, kelp farms < 500 m from kelp habitat



Sample in the farmed area and within the vicinity of the farm (e.g. < 500 m from the farm edge) and at appropriate control sites that are within similar wild habitat (e.g. oyster reefs for oyster aquaculture, kelp beds for kelp aquaculture)

Figure 4. **Farm sampling positions. (Note control sites must be distinct from the aquaculture farm and any potential impacts, e.g. upstream or a sufficient distance away.)**



Evaluation

Evaluation is the analysis of information collected to understand if, and to what extent, progress is being made toward identified goals and objectives. The emphasis of this Framework is on measuring the type and degree of benefit of interest. However, there may be flow-on values and outcomes from evaluation that will assist the industry more broadly. For example, for some sectors there will be instances in which farms are already providing benefits. The indicators and methods identified in the Framework provide a way for farmers to validate these benefits. Using the data and information gathered, this evidence could then be actively communicated to communities, supporting greater social understanding and acceptance for aquaculture and creating a more encouraging environment for regenerative and restorative businesses.

The Framework identifies suggested metrics to assess each indicator, objective, and goal. For each of the metrics, information is provided regarding

- Preferred units for the data collected
- A primary suggested method and potential alternative methods
- Recommended frequency of sampling, noting that most instrumentation used should be deployed at intervals sufficient to build an accurate depiction of processes over time
- Recommended locations and positions of sampling, noting that most instrumentation used should be consistently deployed across sites to assist accurate analysis and reduce the influence of confounding factors, such as differences in the depth and availability of light

For each sector and benefit category, several initial resources or tools are listed that will assist farmers, researchers, practitioners, and/or policy makers with evaluation. However, individual farmers or organizations will need to analyse the data they collect and retain this information in an appropriate database. **There is a need to develop resources and tools that can make monitoring, evaluation, and data visualization and retention more accessible to farmers and policy makers. Resourcing the development of open access technology tools could be an influential role for research institutes, NGOs, and investors in working toward a regenerative and restorative aquaculture industry.**

In Version 1.0, focus has been given to basic monitoring methods while also highlighting more complex but valuable approaches. For more complex methods or experimentation, such as the use of flow-through chambers to measure denitrification or mesocosms to validate changes in ocean acidification on farms, the support of research institutions will be needed. Where possible, the use of these more complex approaches in conjunction with basic measurements is encouraged because they provide the most appropriate means to resolve local environmental variability and the contextual benefits a farm or farms may provide. For example, while oyster aquaculture has been shown to play a role in enhancing denitrification, this influence can be highly variable. It can change from season to season and be influenced by other factors affecting productivity (Ray and Fulweiler, 2020). It can also change over time in response to broader shifts in the local ecosystem and the pressure on sediment biogeochemical processes exerted by the aquaculture activity itself (Ray, Al-Haj, and Fulweiler, 2020). Also, the characteristics of a water body will determine the ecological carrying capacity for bivalve species (Byron et al., 2011). The use of phytoplankton by these species, for instance, has the potential to substantially alter primary ecological processes (Souchu et al., 2001), thereby positively or negatively affecting the local environment.

To support implementation of the Framework or specific projects, it may be useful to develop an agreed RACI (Responsible, Accountable, Consulted, and Informed) matrix identifying who has responsibility for each component of the MEL process. A RACI matrix would be particularly useful where a collaborative approach is being used. (For example, where industry and government are working together with a research institution to sample, assess, and monitor nutrient cycling and improvements in water quality, with a view to develop a nutrient trading policy and monitoring program [Table 2].)

Fox Point Oysters in Little Bay, NH

© Jonathan MacKay

Table 2. **Base RACI matrix for a collaborative approach to monitoring and evaluation. (Note: in this example, accountability has not been assigned because the example is theoretical. In any actual project, accountability should be identified.)**

	Roles			
Task or Activity	**Farmer**	**Industry Association**	**Research Institution**	**Government**
PHASE ONE				
Deploy sampling equipment	R	R	C	I
Record data	R	I	C	I
Analyse data	I	I	R	I
Review and interpret results	C	I	R	R
Translate implications of results into action (e.g. consumer awareness materials or policy)	C	R	I	R
Implement ongoing monitoring approach	R	R	I	C

Responsible: the individual or group with responsibility for delivering the task or activity

Accountable: leads accountability for effective delivery of the task or activity, and ultimately the work or project

Consulted: individuals or groups whose opinions need to be considered throughout the process; their input helps guide the course of the work or project

Informed: those who need to or are beneficial to stay in the loop during the work or project

Within a collaborative approach, there may also be an important role for NGOs. Many NGOs can support the recording of data and potentially the deployment of sampling equipment. Industry and government entities that play a supporting role in production chains could also support monitoring, evaluation, and extension, such as food safety or quality assurance programs, (which might have existing equipment and datasets of use) dockside wholesalers that weigh harvested product, or fish health surveillance networks that support passive disease monitoring and detection.

EVALUATING SOCIAL AND ECONOMIC CO-BENEFITS

Some of the indicators and metrics identified in the Framework could be used to advance understanding and evaluation of ecosystem services. The Framework does not establish a structure for monetary valuation of these services (e.g. a framework for a nutrient trading scheme) but does provide guidance on goals, objectives, and monitoring methods that would be relevant to evaluating benefits, such as regional water quality improvements through a reduction in eutrophication, which would be informed by the quantity (in kg) of nitrogen and/or phosphorous removed from a water body. Viable opportunities for nutrient trading as a mechanism for direct payments to farmers have been identified for the USA, Europe, and China (Ferreira and Bricker, 2016, 2019; Rose et al., 2021). These mechanisms should be further investigated and developed. Other opportunities for payment for ecosystem services, such as the enhancement of fish production or biodiversity, should also be explored.

As well as potentially enabling an additional revenue stream, payment for ecosystem services provided by aquaculture (Box 1) will assist with broader recognition of the full range of benefits from aquaculture to society. In many countries, there is a need to increase societal understanding of aquaculture beyond the risks it presents, as this influences public acceptance of current and future aquaculture development. It can also inform social carrying capacity, which is 'the amount of aquaculture that can be developed without adverse social impacts' (McKindsey et al., 2006; Byron and Costa-Pierce, 2013). At an individual level, people may also be willing to pay more for aquaculture products that provide an ecosystem service (Bolduc, Griffin and Byron, 2023), further incentivising the use of regenerative and restorative practices.

Box 1. What are ecosystem services?

Ecosystem services are the many benefits provided to people by the natural environment. Across all biomes, these services yield a net benefit nearly twice as large as the global gross domestic product, an estimated $124.8 trillion yr^{-1} (based on 2011 estimates in 2007) (Costanza et al., 2014). The basis of this valuation is clear articulation of the services that ecosystems can provide in support of human well-being and the capacity to measure their relative contribution. Because of this clear articulation, the different processes that generate benefits can be distinguished and the relative contribution of ecosystem services can be expressed in multiple units, including monetary units (de Groot, Wilson and Boumans, 2002; Costanza et al., 2014). Assessment of ecosystem services can also support alignment of ecologically, socially, and economically centred practices with other environmental objectives, such as Ecologically Sustainable Development (ESD), or conservation or restoration targets. The **UN Environment**

Programme the Economics of Ecosystems and Biodiversity (TEEB) initiative has developed a comprehensive categorization of ecosystem services. Ecosystem services associated with aquaculture may be numerous and advantageous in circumstances that require a focus on a specific service or service category, such as the provision of food in areas where the same or similar food sources have been lost due to overexploitation (Alleway et al., 2018).

Learning

Knowledge exchange, education, and learning will be a critical step in ensuring that regenerative and restorative practices can be effectively and consistently implemented and create a positive outcome for nature. An active approach to learning as a part of monitoring and evaluation can be supported through the dissemination of data and information gathered amongst farmers, researchers, government, and communities, so that new knowledge and capabilities can be acquired by these groups. Data sharing also helps to identify if/when a monitoring method is not providing the desired information, enabling learning and evolution of the monitoring and evaluation approach itself.

It may not be cost-effective to evaluate environmental benefits for every farm. Instead, information and knowledge generated for standard farm types could form an initial basis for assessment of environmental benefits across similar farms at the industry level or across geographies, building momentum for further research and monitoring.

By having a plan for learning, farmers will be able to adjust their practices to enhance benefits, and government or supporting organizations will be able to make evidence-based decisions to better support policy and management. Two primary streams for learning are identified for the Framework: centralized learning, which are formally organized and recognized modes, and decentralized learning, which are the informal practices that can be adopted to exchange and benefit from shared knowledge. Within each, there are actions best implemented by industry and supporting organizations or by government. There are also actions that will be best pursued at a specific scale: globally or regionally, nationally, or locally.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Seaweed farming training in Tanzania

ACTIONS THAT CAN BE TAKEN FOR CENTRALIZED EDUCATION AND EXTENSION:

- Farmers make a commitment to regularly discuss observations and farm practices or approaches at industry meetings.
- Sector-associations develop shared data hubs or data repositories or support the development of monitoring networks (formal or informal).
- Government provides a structured process for reviewing and reporting results of monitoring and a process for integrating this information into policy and management, e.g. including the results in policy review processes; ESD risk assessments for new permit/lease/licence applications; aligning results with management requirements, such as the terms for leasing; or committing to publishing the results to increase awareness of environmental benefits in the broader community.
- Government and/or industry associations host targeted knowledge exchange forums, such as seminars or workshops.

ACTIONS THAT CAN BE TAKEN FOR DECENTRALIZED LEARNING:

- Farmers discuss their observations and share data.
- Farmers and sector-associations or collectives intentionally compare data and observations across farms and locations.
- NGOs engage with industry by supporting research and discussing observations of environmental benefits and what practices might be influencing these benefits.

When handling and sharing data, attention must be given to sensitive information, including confidential or business information as well as personal information associated with employees. The protection of intellectual property and commercial data should be considered and ensured. Any information that could be linked to personal data should not be collected, and if it must, it should be handled in a way that ensures personal security and privacy.

To assist effective learning, digital technologies are needed that can simplify data collection, analysis, and storage. For example, applications allowing a farmer to upload a photograph or video taken from their phone for assessment at a later time would make sampling easier to fit into the daily farming routine. Machine-learning platforms that automate data and statistical analyses will also be valuable. Rapid development of software and hardware is occurring, providing a range of options for farmers to more readily analyse the data they collect. These platforms should

Farmer working with seaweed lines in Tawi Tawi, Philippines

automate the display of measurements taken in an area through time or across locations and systems. They should also strive to make the software and results open access. The use of web-based approaches on farms could also have ancillary benefits and should be factored into the development of digital technologies for regenerative and restorative aquaculture. The collection of production data, for example, could assist more efficient handling of stock or help to monitor stock losses more accurately, so that increases in mortality can be pre-empted or the survival of selectively bred stock tracked.

Evaluating the quality and impact of the data collected with a view to methodological advancement of the indicators in the Framework should also form a component of learning. Many of the indicators recommended in Version 1.0 represent basic calculations that can be more readily used. By increasing the amount of data available through these initial methods, it will be possible to increase confidence in these basic metrics, which will then facilitate an extension into more comprehensive measurements and modelling that is more accessible to a wider range of users and beneficiaries. For example, the assimilation and extraction of nitrogen by seaweed can be estimated from existing published species or genus-specific estimates of nutrient composition of the tissue. These estimates do not, however, account for local environmental conditions and the effect they may have on assimilation and the quantity of nitrogen, phosphorous, or carbon extracted. Collecting information that can contribute to refining estimates will improve confidence in conclusions and support continued development of the MEL approach.

The Framework will use an adaptive response to learning and be periodically updated to incorporate feedback from industry, government, and other users and to encompass new ideas and opportunities that emerge.

MEL Framework: Seaweed (Macroalgae)

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MEL Framework: Seaweed (Macroalgae)

Habitat & Biodiversity

Goal	**GOAL 1 - HABITAT & BIODIVERSITY** Seaweed is farmed in a way that supports an abundance and diversity of associated native species				**GOAL 2 - HABITAT & BIODIVERSITY** Seaweed is farmed in a way that enhances* the abundance or diversity of associated native species (species associated with farmed biomass and farm site is greater than non-farm sites)	
Objective	**OBJECTIVE 1.1** Farming of seaweed supports an abundance and diversity of native epibiota (organisms that live on the surface of another living organism)	**OBJECTIVE 1.2** Farming of seaweed supports an abundance and diversity of native mobile fauna, such as fish and crustacea, without increasing negative impacts, such as fishing pressure	**OBJECTIVE 1.3** Farming of seaweed supports an abundance and diversity of native benthic infauna	**OBJECTIVE 1.4** Farming of seaweed maintains sediment characteristics and biogeochemistry comparable to or better than surrounding non-farm areas	**OBJECTIVE 2.1** Farming of seaweed increases the abundance and diversity of associated native species, epibiota, mobile and benthic, in comparison to nearby, similarly structured non-farm habitat (e.g. wild seaweed habitat or seagrasses)	**OBJECTIVE 2.2** Farming of seaweed enhances the abundance of associated native fauna (epibiota and mobile) by supporting spawning or recruitment
Indicator	**INDICATOR 1.1.1** Abundance and diversity of native epibiota associated with farmed biomass	**INDICATOR 1.2.1** Abundance and diversity of mobile fauna associated with farm site	**INDICATOR 1.3.1** Abundance and diversity of benthic infauna associated with farm site	**INDICATOR 1.4.1** Sediment characteristics and biogeochemistry are consistent with normal functions, in comparison to nearby healthy sediments	**INDICATOR 2.1.1** Abundance, diversity, and community composition of epibiota, mobile and benthic infauna associated with farmed biomass and farm site	**INDICATOR 2.2.1** Spawning or recruitment identified within the farm site
Complexity	**Moderate** - Sampling using invertebrate collectors requiring immediate ID and counting or preservation for processing of samples at a later date	**Easy** - Collection of video footage with ID and counting at a later date	**Moderate** - Sampling using sediment collectors requiring immediate ID and counting or preservation for processing of samples at a later date	**Difficult** - Sampling using sediment collectors requiring immediate ID and counting or preservation for processing of samples at a later date	**Difficult** - Sampling using multiple methods of areas outside the lease as well as within the farm with preservation of samples required for processing at a later date and statistical analysis of data collected	**Moderate** - Deployment of equipment for an extended period with successive sampling
Metric	**Abundance** - Number of individuals or total mass per species/species group **Diversity** - Number of species, genus, families and/or functional groups, Shannon Diversity Index	**Abundance** - Number of individuals or total mass per species/species group **Diversity** - Number of species, genus, families and/or functional groups, Shannon Diversity Index	**Abundance** - Number of individuals or total mass per species/species group **Diversity** - Number of species, genus, families and/or functional groups, Shannon Diversity Index	Sediment profile including organic content, oxygen concentrations, hydrogen sulfide concentrations, and ammonia	Snapshot of community biodiversity using a range of metrics including taxonomic (e.g. species abundance and diversity) and the number and range of functional groups	Detection of the presence of spawning or recruitment of epibiota or mobile fauna
Suggested method	In situ invertebrate collectors or collection and inspection of farmed biomass	In situ/remote video	Sediment 'grab' samples (e.g. Smith-Mac or Ponar samplers) or collection of sediment cores	Photos to establish benthic quality	Biodiversity survey, including data on species abundance, diversity, sizes of individuals, and functional group or guild	Remote video in stereo, to determine fish sizes/age classes
Proxy or additional method	Visual surveys and on the spot ID (diver/snorkelling)	Visual surveys and on the spot ID (diver/snorkelling)	Photos or video for e.g. benthic index, index requires quadrats	Sediment 'grab' samples (e.g. Smith-Mac or Ponar samplers) or collection of sediment cores	N/A	SMURFs
Frequency/ Timing	Once per season	Once per season	Once per season	Biannual	Annual	Seasonal
Location of sampling (e.g. within farm/ environment)	Within the farm (amongst the farmed biomass) and at the edge of the farm area	Within the farm (amongst the farmed biomass) and at the edge of the farm area	Underneath the farm, within and at the edge of the farm area	Within the farm, underneath and at the edge of the farmed area, and 'offsite' in sediment near to the farm	Within the farm, underneath and at the edge of the farmed area, and 'offsite' in similar structured non-farm habitat	Within the farm

* 'Enhances' refers to higher biomass and rates of abundance or diversity as result of the presence of the farm, as a opposed to 'support' whereby a farm might provide shelter or food for local fauna but does not provide habitat for spawning or recruitment.

MEL Framework: Seaweed (Macroalgae)

Tools & Resources (Habitat & Biodiversity)

Description of use	Title	URL
Detailed list of sampling methods for measuring specific seaweed habitat interactions and benefits and their pros and cons	Corrigan et al., (2022) ‘Quantifying habitat provisioning at macroalgal cultivation sites’. *Reviews in Aquaculture*	**https://doi.org/10.1111/raq.12669**
NOAA citizen science guide to help growers capture high quality underwater footage of their aquaculture gear and monitor ecosystem interactions	Phillips et al., (2022) ‘*Using underwater video to observe aquaculture gear in Long Island Sound – A Citizen Science Guide*’	**https://media.fisheries.noaa.gov/2022-03/Citizen_Science_Doc_2022.pdf**
Online processing and software/applications for identification of organisms in video footage	FishID, The Global Wetlands Project (GLOW) from Griffith University Video and Image Analytics for Marine Environments (VIAME)	**https://fishid.org/** **https://www.viametoolkit.org/**

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MEL Framework: Seaweed (Macroalgae)

Water Quality

Goal	GOAL 1 - WATER QUALITY Seaweed farming contributes to a reduction of excess organic nutrients in the local environment		GOAL 2 - WATER QUALITY Seaweed farming improves/enhances local ecosystem primary productivity	
Objective	**OBJECTIVE 1.1** Farmed seaweed biomass takes up more N and P than is released	**OBJECTIVE 1.2** Farmed seaweed supports a reduction in symptoms of eutrophication	**OBJECTIVE 2.1** Farming of seaweed supports microorganism and plankton communities, chlorophyll a concentrations are lower, and microorganism communities similar to or more productive on the farm site without negatively impacting carrying capacity and feed available for wild populations or other farms	
Indicator	**INDICATOR 1.1.1** N and P assimilated and extracted with the farmed biomass	**INDICATOR 1.2.1** Dissolved oxygen at the farm site	**INDICATOR 2.1.1** Chlorophyll a concentration at the farm site	**INDICATOR 2.1.2** Microorganism and plankton community composition at the farm site
Complexity	**Easy** - Estimate of farmed biomass for calculation of estimated bioextraction	**Easy** - Water sensor or collection of water samples for processing by commercial laboratory	**Moderate** - Chlorophyll sensor or collection of water samples for processing by commercial laboratory	**Difficult** - Water sampling, plankton tows, or sediment and light traps with ID required by microscopy or molecular methods (e.g. eDNA)
Metric	N and P (kg) in harvested biomass	Dissolved oxygen concentration (mg/L)	Chlorophyll a concentration (µg/L), as a primary indicator of eutrophication	Microorganism and phytoplankton species presence, abundance (N), and change over time
Suggested method	Established species nutrient composition biomass harvested	Water sensors and data loggers	Chlorophyll sensors	Water sampling, plankton tows, or sediment and light traps
Proxy or additional method	Elemental analysis of N and P concentrations in farmed biomass at harvest	Collection of water samples and laboratory analysis	Collection of water samples and laboratory analysis	Chlorophyll a concentration, as a proxy for productivity
Frequency/ Timing	At time of harvest or at a point in time based on standing biomass	Weekly, monthly, or seasonal, with diurnal measurements over several days	Weekly, monthly, or seasonal, with diurnal measurements over several days	Weekly, monthly, or seasonal, with diurnal measurements over several days
Location of sampling (e.g. within farm/ environment)	Farmed biomass	Within the farm area and adjacent non-farm areas	Within the farm area and adjacent non-farm areas	Within the farm and neighbouring non-farm areas, i.e., not immediately adjacent but some distance away within the same waterbody

MEL Framework: Seaweed (Macroalgae)

Tools & Resources (Water Quality)

Description of use	Title	URL
Detailed list of sampling methods for measuring specific seaweed habitat interactions and benefits and their pros and cons	Corrigan et al., (2022) 'Quantifying habitat provisioning at macroalgal cultivation sites'. *Reviews in Aquaculture*	**https://doi.org/10.1111/raq.12669**
Methods for measuring nutrient bioextraction	Rose et al., (2015) 'Nutrient Bioextraction' in *Encyclopedia of Sustainability Science and Technology*	**https://link.springer.com/referenceworkentry/10.1007/978-1-4939-2493-6_944-1**
Methods to measure nutrient bioextraction in seaweed systems	Kim, Kraemer, and Yarish (2015) 'Use of sugar kelp aquaculture in Long Island Sound and the Bronx River Estuary for nutrient extraction'. *Marine Ecology Progress Series*	**https://www.int-res.com/abstracts/meps/v531/p155-166/**
Methods to measure nutrient bioextraction in seaweed systems	Grebe et al., (2021) 'The nitrogen bioextraction potential of nearshore *Saccharina latissima* cultivation and harvest in the western Gulf of Maine'. *Journal of Applied Phycology*	**https://link.springer.com/article/10.1007/s10811-021-02367-6**

MEL Framework: Seaweed (Macroalgae)

Climate Change

Goal	**GOAL 1 - CLIMAGE CHANGE** Seaweed farming enhances carbon cycling and occurs in a way that can support mitigation of CO_2, with the potential to contribute to a reduction of local CO_2 emissions over an extended period		**GOAL 2 - CLIMATE CHANGE** Seaweed is farmed in a way that reduces stress from local ocean acidification
Objective	**OBJECTIVE 1.1** Farmed seaweed creates a biomass that can be used to replace more GHG emissions-intensive products	**OBJECTIVE 1.2** Seaweed released from the farm through breakage of fronds or as particulate organic carbon (POC) or dissolved organic carbon (DOC), is quantified to improve understanding of carbon cycling	**OBJECTIVE 2.1** Farmed seaweed supports sustained decreases in dissolved CO_2 and increased pH on the farm site in areas where ocean acidification is occurring or a risk
Indicator	**INDICATOR 1.1.1** Quantity of seaweed biomass used in replacement of more emissions-intensive products	**INDICATOR 1.2.1** Cradle to grave GHG emissions	**INDICATOR 2.1.1** pH at the farm site
Complexity	**Moderate** - Estimate of farmed biomass for calculation of estimated carbon content and knowledge of product end point	**Difficult** - Requires tracing carbon through multiple pathways across a range of methods and sites	**Difficult** - Requires high quality water sampling and analysis and repeated measures to detect minor changes
Metric	Life Cycle Analysis (LCA) impact indicators of Global Warming Potential or Climate Change (kg CO_2 equivalent)	Contribution of farmed seaweed biomass to POC and DOC (g C/year) and its likely circulation in the ecosystem	pH, total alkalinity (g/L $CaCO_3$) or dissolved inorganic carbon (µM)
Suggested method	Farmer or operation specific LCA, or existing published carbon content values (species-specific or generic) converted from wet to dry weight of farmed biomass	Net Primary Productivity, or CO_2 influx and outgassing (e.g. see DIC, pH, CO_2, alkalinity, temp and salinity) coupled with modelling of water currents and particle transport	Measurement of pH using in situ buoys for measuring water chemistry
Proxy or additional method	Remotely sensed data for site biomass and species-specific estimates of carbon content. Regional seaweed carbon estimates or modelling, e.g. Regional Services Seaweed Model V2.0.	N/A	N/A
Frequency/ Timing	At time of harvest or at a point in time based on standing biomass, annual assessment for LCA	Regular or real time (e.g. sensors)	Realtime, daily, or weekly with diurnal measurements over several days
Location of sampling (e.g. within farm/ environment)	Farmed biomass, if possible across the life cycle of production, including relevant upstream, on-farm, and downstream processes to produce the biomass and end products	Within the farm and broader ecosystem	Within and adjacent to non-farm areas

MEL Framework: Seaweed (Macroalgae)

Tools & Resources (Climate Change)

Description of use	Title	URL
Sampling needed to accurately quantify carbon cycling and uptake in seaweed systems	Hurd et al. (2022) 'Forensic carbon accounting: assessing the role of seaweeds for carbon sequestration'. *Phycological Society of America*	https://doi.org/10.1111/jpy.13249
Methods and sample metrics for carbon uptake and permanence and their relevance to macroalgae, including advantages and limitations of different methods	Rose & Hemery (2023) 'Methods for measuring carbon dioxide uptake and permanence: review and implications for macroalgae aquaculture'. *Journal of Marine Science and Engineering*	https://doi.org/10.3390/jmse11010175
Global model and calculator allowing users to estimate both potential climate and water quality benefits for a specified seaweed farm in a selected ecoregion of the world	Regional Seaweed Services Model V2.0	https://tnc-aquaculture-science.shinyapps.io/RegionalSeaweedServicesModel/

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MEL Framework: Molluscs and Echinoderms

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MEL Framework: Molluscs and Echinoderms

Habitat & Biodiversity

Goal	GOAL 1 - HABITAT & BIODIVERSITY Molluscs and echinoderms are farmed in a way that supports an abundance and diversity of associated native species				GOAL 2 - HABITAT & BIODIVERSITY Molluscs and echinoderms are farmed in a way that enhances the abundance or diversity of associated native species		GOAL 3 - Molluscs and echinoderms are farmed in a way that can support native wild populations that have declined or are under stress
Objective	**OBJECTIVE 1.1** Farming of molluscs and echinoderms supports an abundance and diversity of native epibiota (organisms that live on the surface of another living organism)	**OBJECTIVE 1.2** Farming of molluscs and echinoderms supports an abundance and diversity of native mobile fauna, such as fish and crustacea, without increasing negative impacts, such as fishing pressure	**OBJECTIVE 1.3** Farming of molluscs and echinoderms supports an abundance and diversity of native benthic infauna	**OBJECTIVE 1.4** Farming of molluscs and echinoderms maintains sediment characteristics and biogeochemistry comparable to or better than surrounding non-farm areas	**OBJECTIVE 2.1** Farming of molluscs and echinoderms enhances (promotes, increases) the abundance and diversity of associated native species in comparison to nearby, similar non-farm areas	**OBJECTIVE 2.2** Farming of molluscs and echinoderms enhances the abundance of associated native fauna (fish, invertebrates or algae) by supporting spawning or recruitment	**OBJECTIVE 3.1** Where native species populations have declined or are at risk of decline, larvae from farming these same species increases larval abundance and recruitment in local wild populations, with stock that is has an appropriate genetic structure (i.e., supports diversity in wild populations, or supports effective restoration through stock with higher thermal tolerances for climate change resilience)
Indicator	**INDICATOR 1.1.1** Abundance and diversity of organisms directly associated with farmed biomass	**INDICATOR 1.2.1** Abundance and diversity of mobile fauna associated with farm site (e.g. fish, crustaceans, birds, marine mammals)	**INDICATOR 1.3.1** Abundance and diversity of infauna associated with the benthic habitat under the farmed biomass	**INDICATOR 1.4.1** Sediment characteristics and biogeochemistry and similarity to nearby sediment characteristics	**INDICATOR 2.1.1** Abundance and diversity of organisms directly associated with farmed biomass and the farm site	**INDICATOR 2.2.1** Species using and extent of spawning or recruitment at the farm site	**INDICATOR 3.1.1** Abundance of larvae or recruits released from farm stock
Complexity	**Moderate** - Sampling using invertebrate collectors requiring immediate ID and counting or preservation for processing post-sampling	**Easy** - but may be time consuming - Collection of video footage with ID and counting post-sampling	**Moderate** - Sampling using sediment collectors requiring immediate ID and counting or preservation for processing post-sampling	**Difficult** - Sampling using sediment collectors requiring immediate ID and counting or effective preservation for processing post-sampling	**Difficult** - sampling using multiple methods of areas outside the farm and within the farm, with preservation of samples required for processing post-sampling and statistical analysis of data collected	**Moderate** - Deployment of equipment for an extended period with successive sampling	**Difficult** - tracking of larvae with sampling of wild populations preferred to differentiate farm and wild stock
Metric	**Abundance** - Number (N) of individuals or total mass per species/species group (g) **Diversity** - Shannon Diversity Index (H), or number of species, genus, families and/or functional groups	**Abundance** - Number (N) of individuals or total mass per species/species group (g) **Diversity** - Shannon Diversity Index (H), or number of species, genus, families and/or functional groups	**Abundance** - Number (N) of individuals or total mass per species/species group (g) **Diversity** - Shannon Diversity Index (H), or number of species, genus, families and/or functional groups	Sediment profile encompassing a range of biogeochemical characteristics (e.g. organic content, oxygen concentrations, hydrogen sulfide concentrations, ammonia)	Profile of community biodiversity (includes data on a range of characteristics, e.g. abundance, species richness, diversity, age classes, functional groupings)	Presence of spawning or recruitment of fauna or algae	Detection of spawning and recruitment of farmed stock in wild populations
Suggested method	Stationary invertebrate collectors or collection and inspection of farmed biomass	Stationary remote video	Sediment 'grab' samples (e.g. Smith-Mac or Ponar samplers, devices used to scoop sediment from the seafloor) or collection of sediment cores	Sediment 'grab' samples (e.g. Smith-Mac or Ponar samplers, devices used to scoop sediment from the seafloor) or collection of sediment cores	Biodiversity survey	Remote stereo-video	Trace element fingerprinting and tracking of cultured stock
Proxy or additional method	Visual surveys and on the spot ID (diver/snorkelling), eDNA for detecting presence/absence of species	Visual surveys and on the spot ID (diver/snorkelling), trapping, lift nets, mark-recapture studies, eDNA for detecting presence/absence of species	Photos or video for (e.g. benthic index, index requires quadrats)	Sediment imaging and visual classification of apparent redox potential	NA	Standard monitoring units for the recruitment of fish (SMURFs), constructed artificial habitats (e.g. hanging baskets)	Biophysical particle tracking (produces modelled results only)
Frequency/ Timing	Seasonal	Seasonal	Seasonal	Seasonal or biannual	Seasonal	Seasonal	Seasonal, depending on timing of spawning and recruitment
Location of sampling (e.g. within farm/ environment)	Amongst the farmed biomass, within and at the edge of the farmed area	Amongst the farmed biomass, within and at the edge of the farmed area	Underneath the farm, within and at the edge of the farm area	Within the farm, underneath and at the edge of the farmed area, and nearby similarly structured non-farm sediment to assess similarity	Within the farm, underneath and at the edge of the farmed area, and nearby similarly structured non-farm habitat to assess quality of farm habitat	Within the farm	Within the farm and within nearby wild populations of the same species to differentiate farmed and wild stock

MEL Framework: Molluscs and Echinoderms

Tools & Resources (Habitat & Biodiversity)

Description of use	**Title**	**URL**
Comprehensive text on the environmental, social, and economic benefits of marine bivalves	Smaal et al., (2018) *'Goods and Services of Marine Bivalves'*	Online ISBN 978-3-319-96776-9
Methods to measure habitat provisioning	Mercaldo-Allen et al., (2021). 'Exploring video and eDNA metabarcoding methods to assess oyster aquaculture cages as fish habitat'. *Aquaculture Environment Interactions*	**https://www.int-res.com/articles/aei2021/13/q013p277.pdf**
Methods to measure habitat provisioning	Ferriss et al., (2021) 'Characterizing the habitat function of bivalve aquaculture using underwater video'. *Aquaculture Environment Interactions*	**https://www.int-res.com/articles/aei2021/13/q013p439.pdf**
Online processing and software/applications for identification of organisms in video footage	FishID, The Global Wetlands Project (GLOW) from Griffith University Video and Image Analytics for Marine Environments (VIAME)	**https://fishid.org/** **https://www.viametoolkit.org/**

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MEL Framework: Molluscs and Echinoderms

Water Quality

Goal	**GOAL 1 - WATER QUALITY** Mollusc and echinoderm farming contributes to a reduction of excess organic nutrients in the local environment				**GOAL 2 - WATER QUALITY** Mollusc and echinoderm farming improves/enhances local ecosystem primary productivity	
Objective	**OBJECTIVE 1.1** Farmed bivalves biomass takes up more N and P than is released		**OBJECTIVE 1.2** Unfed farmed molluscs and echinoderms support a reduction in symptoms of eutrophication	**OBJECTIVE 1.3** Farmed biomass contributes to water filtration within the estuary/embayment/coastal area that improves light penetration and reduces hypoxia	**OBJECTIVE 2.1** Farming of molluscs and echinoderms supports regulation of phytoplankton arising from eutrophication, chlorophyll a concentrations are lower, and microorganism communities similar to or more productive on the farm site without negatively impacting carrying capacity and feed available for wild populations or other farms	
Indicator	**INDICATOR 1.1.1** Quantity of N and P assimilated and extracted	**INDICATOR 1.1.2** Rate of denitrification	**INDICATOR 1.2.1** Dissolved oxygen concentration at the farm site	**INDICATOR 1.3.1** Rate of water filtration	**INDICATOR 2.1.1** Chlorophyll a concentration on the farm site	**INDICATOR 2.1.2** Microorganism and plankton community on the farm site
Complexity	**Easy** - Estimate of farmed biomass for calculation of estimated bioextraction	**Easy** - Placement of incubation chamber on the farm	**Easy** - Water sensor or collection of water samples for processing by commercial laboratory	**Easy** - Estimate of farmed biomass according to several size classes	**Moderate** - Chlorophyll sensor or collection of water samples for processing by commercial laboratory	**Difficult** - Water sampling, plankton tows, or sediment and light traps with ID required by microscopy or molecular methods (e.g. eDNA)
Metric	N and P (kg) in harvested biomass	Net N2 flux (μmol/m2/hour) and/or total N removed (Mg N/year)	Dissolved oxygen concentration (mg/L)	Filtration rate (L/hour)	Chlorophyll a concentration (μg/L), as a primary indicator of eutrophication	Microorganism and phytoplankton species presence, abundance (N), and change over time
Suggested method	Established species nutrient composition biomass harvested	Incubation chamber	Water sensors and data loggers	Species specific filtration models or ShellSIM	Chlorophyll sensors	Water sampling, plankton tows, or sediment and light traps
Proxy or additional method	Elemental analysis of N and P concentrations in farmed biomass at harvest	Modelling of environmental characteristics	Collection of water samples and laboratory analysis	Incubation chamber, upstream and downstream fluorescence measurements, Farm Aquaculture Resource Management (FARM) model	Collection of water samples and laboratory analysis	Chlorophyll a concentration, as a proxy for productivity
Frequency/ Timing	At time of harvest or at a point in time based on standing biomass	Point in time based on standing biomass	Weekly, monthly, or seasonal, with diurnal measurements over several days	Point in time based on standing biomass	Weekly, monthly, or seasonal, with diurnal measurements over several days	Weekly, monthly, or seasonal, with diurnal measurements over several days
Location of sampling (e.g. within farm/ environment)	Farmed biomass	Within farm and at nearby non-farm control site	Within the farm area and adjacent non-farm areas	Farmed biomass	Within the farm area and adjacent non-farm areas	Within the farm and neighbouring non-farm areas, i.e., not immediately adjacent but some distance away within the same waterbody

MEL Framework: Molluscs and Echinoderms

Tools & Resources (Water Quality)

Description of use	Title	URL
Methods for measuring nutrient bioextraction	Rose et al., (2015) 'Nutrient Bioextraction' in *Encyclopedia of Sustainability Science and Technology*	http://link.springer.com/referenceworkentry/10.1007/978-1-4939-2493-6_944-1
Methods for measuring denitrification	Ray et al., (2021) 'A review of how to assess denitrification in oyster habitats and proposed guidelines for future studies'. *Limnology and Oceanography: Methods*	https://aslopubs.onlinelibrary.wiley.com/doi/10.1002/lom3.10456
Method to measure nutrient assimilation	Higgins, Stephenson and Brown, (2011) 'Nutrient bioassimilation capacity of aquacultured oysters: quantification of an ecosystem service'. Journal of Environmental Quality	https://acsess.onlinelibrary.wiley.com/doi/abs/10.2134/jeq2010.0203
Tool simulating farm dynamics within a specific environment (based on environmental characteristics)	Farm Aquaculture Resource Management (FARM)	www.farmscale.org
Tool simulating farm dynamics within a specific environment (based on environmental characteristics)	ShellSIM	http://www.shellsim.com/

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MEL Framework: Molluscs and Echinoderms

Climate Change

Goal	GOAL 1 - CLIMATE CHANGE Mollusc and echinoderm farming occurs in a way that can support mitigation of CO_2 by providing a comparatively low or net neutral GHG emissions product	GOAL 2 - CLIMATE CHANGE Mollusc and echinoderm farming enhances carbon cycling in the water and shells, pearls, and other hard materials with a long life span are directed toward circular solutions for carbon management	GOAL 3 - CLIMATE CHANGE Nearshore molluscs farms support broader efforts to reduce the threat of coastal erosion and storm damage
Objective	**OBJECTIVE 1.1** Farmed molluscs and echinoderms are produced with fewer GHG emissions than similar products (e.g. other seafood) produced in comparable systems and geographies, and emissions continue to decrease over time	**OBJECTIVE 2.1** Farmed shell, pearls, and other materials retain more carbon than is respired by bivalves during farming	**OBJECTIVE 3.1** Mollusc farms contribute to reducing wave energy and coastal erosion during severe weather events
Indicator	**INDICATOR 1.1.1** Cradle to grave GHG emissions	**INDICATOR 2.1.1** Quantity of shell, pearls, and other materials directed toward appropriate storage or disposal pathways	**INDICATOR 3.1.1** Wave attenuation or decay across the footprint of farming infrastructure and stock
Complexity	**Easy to moderate** - Estimate of farmed biomass for calculation of estimated carbon content and knowledge of product end point and farm-specific LCA or GHG emissions footprint assessment	**Easy** - Estimate of farmed biomass for calculation of estimated carbon content and knowledge of product end point	**Difficult** - Requires modelling of wave energy around the farm and its influence on changing wave energy or direction along shoreline, with consideration of primary and secondary effects
Metric	Life Cycle Analysis (LCA) impact indicators of Global Warming Potential or Climate Change (kg CO_2 equivalent)	Quantity of carbon (kg) assimilated and retained in farmed biomass	Wave decay coefficients (k_D)
Suggested method	Farm or operation specific LCA	Existing published carbon content values (species-specific or generic) converted from wet to dry weight of farmed biomass	Tethered wave buoys to measure wave spectra and other oceanographic and atmospheric variables (e.g. tidal variation, atmospheric pressure)
Proxy or additional method	Sector-wide LCA meta-analyses of GHG emissions data, from similar geographies and/or farming systems and products		
Frequency/ Timing	Annual	At time of harvest or at a point in time based on standing biomass	Realtime, daily, or weekly with diurnal measurements over several days
Location of sampling (e.g. within farm/ environment)	Life cycle of production, including relevant upstream, on-farm, and downstream processes to produce the biomass and end products	Farmed biomass	Within the farm or at the edge of the farm

MEL Framework: Marine Finfish

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MEL Framework: Marine Finfish

Habitat & Biodiversity

Goal	GOAL 1 - HABITAT & BIODIVERSITY Permitted farm area contributes to effective regional marine conservation, e.g. for specific species of marine mammals, migratory, or larger bodied fish		GOAL 2 - HABITAT & BIODIVERSITY Net pens and stock are maintained in a way that supports the attraction of fish without causing negative impacts by creating ecological traps	
Objective	**OBJECTIVE 1.1** Permitted farm area is managed in such a way that it provides an effective refuge for fauna	**OBJECTIVE 1.2** Fish attracted to net pens or using the permitted area enhance wild stocks or support the resilience of wild stocks	**OBJECTIVE 2.1** Net pens attract and support the health of fish populations, contribute to regional wild populations, and do not display increased incidence or prevalence of parasites, pathogens, and diseases (in wild populations and farmed fish stock)	
Indicator	**INDICATOR 1.1.1** Fauna use the permitted area without experiencing disturbance	**INDICATOR 1.2.1** Proportion of fish associated with permitted area contributing regional wild stocks	**INDICATOR 2.1.1** Species and abundance of fish attracted to net pens	
Complexity	**Easy to moderate** - Incidental observation combined with targeted visual or surveys	**Difficult** - Requires assessment of stock enhancement as a result of farming and alignment with regional fisheries stock assessments and management	**Easy** - Routine monitoring of farmed stock	**Moderate** - Requires sampling or surveillance of wild populations
Metric	Presence, abundance, and behaviour of fauna in the permitted area	Biomass (kg or tons) of wild fisheries stock enhanced as a result of the permitted area	Proportion of farmed stock (%) without parasites etc. above anticipated baseline/background loads	Proportion of wild fish stock (%) without parasites etc. above anticipated baseline/background loads
Suggested method	Recording of incidental observations and targeted visual census, imaging, or sound sonar	Fisheries stock assessment or inclusion in fisheries stock assessment	Monitoring of parasites, pathogens, and diseases in farmed stock (e.g. sea lice counting)	Monitoring of parasites, pathogens, and diseases in wild fish populations
Proxy or additional method	NA	Monitoring of wild fish populations in the permitted through in situ/remote video	NA	NA
Frequency/Timing	Ongoing, through recording of sightings combined with seasonal intentional surveys across the permitted area	Annual	Real time monitoring or weekly manual	Ongoing with annual reporting
Location of sampling (e.g. within farm/environment)	Extent of the permitted area	Wild fish populations within the permitted area and outside, locally and/or regionally	Stock in net pens	Wild fish populations within the vicinity of the farm and up to 2.5 km away

MEL Framework: Marine Finfish

Tools & Resources (Habitat & Biodiversity)

Description of use	Title	URL
IUCN guidance on the use of marine concessions as other effective area-based measures (OECMs)	IUCN (2019) *'Recognising and reporting other effective area-based conservation measures'*	https://portals.iucn.org/library/node/48773
IUCN guidance on how to assess sites as constituting an OECM	IUCN (2023) *'Site-level tool for identifying other effective area-based conservation measures (OECMs)'*, first edition	https://www.iucn.org/story/202308/site-level-tool-identifying-other-effective-area-based-conservation-measures-oecms
Online processing and software/applications for identification of organisms in video footage	FishID, The Global Wetlands Project (GLOW) from Griffith University Video and Image Analytics for Marine Environments (VIAME)	https://fishid.org/ https://www.viametoolkit.org/
Environmental indicators for salmon aquaculture	Rector et al., (2022) 'Environmental indicators in salmon aquaculture research: A systematic review'. *Reviews in Aquaculture*	https://aquacultureindicators.shinyapps.io/EnviroIndicatorsAquaculture/

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MEL Framework: Marine Finfish

Water Quality

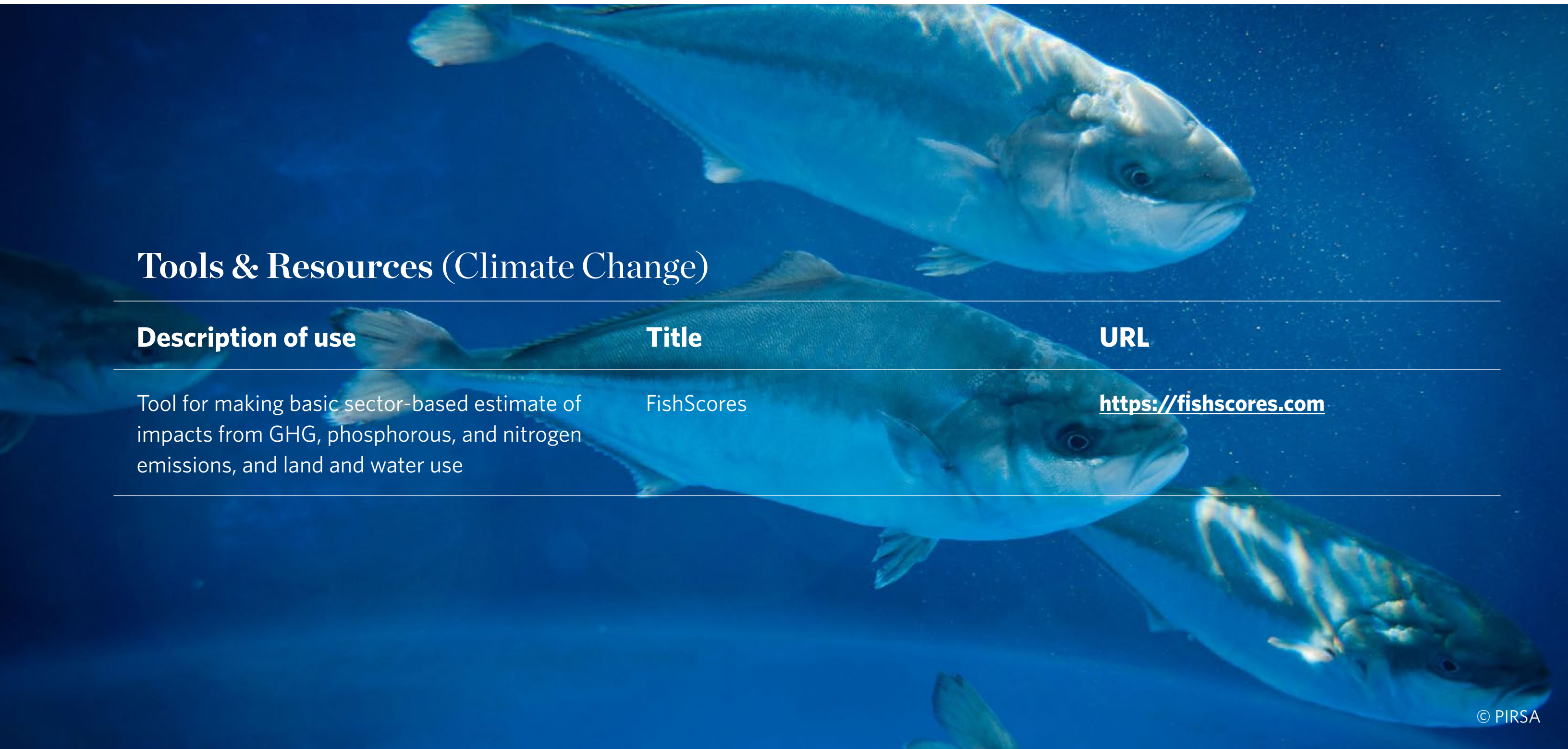
Objective	WATER QUALITY
NA, marine finfish species and monoculture farming systems are unlikely to directly provide ecosystem services associated with improving water quality through waste treatment. They may, however, provide a pathway for the addition of seaweeds and molluscs that could provide a water quality benefit to a farm site.	

Salmon Farming Cages in Golfo de Corcovado in Chile. © Tom Crowley

MEL Framework: Marine Finfish

Climate Change

Goal	**GOAL 1 - CLIMATE CHANGE** Finfish farming occurs in a way that can support mitigation of CO_2 by providing a comparatively low GHG emissions product, either in isolation as a monoculture or in co-culture or IMTA that includes farming of seaweeds
Objective	**OBJECTIVE 1.1** Farmed finfish are produced with fewer GHG emissions than similar products (e.g. other seafood, agricultural animal products of similar nutritional value), targeting local distribution and markets (to reduce transport GHG emissions), and emissions continue to decrease over time
Indicator	**INDICATOR 1.1.1** Cradle to grave GHG emissions
Complexity	**Easy to moderate** - Estimate of farmed biomass and calculation of CO_2 emissions throughout the lifecycle of farming
Metric	Life Cycle Analysis (LCA) impact indicators of Global Warming Potential or Climate Change (kg CO_2 equivalent)
Suggested method	Farm or operation specific LCA or environmental footprint assessment
Proxy or additional method	Sector-wide LCA meta-analyses of GHG emissions data, encompassing similar geographies and/or farming systems and products
Frequency/Timing	Annual
Location of sampling (e.g. within farm/ environment)	Life cycle of production, including relevant upstream, on-farm, and downstream processes to produce the biomass and end products



Tools & Resources (Climate Change)

Description of use	Title	URL
Tool for making basic sector-based estimate of impacts from GHG, phosphorous, and nitrogen emissions, and land and water use	FishScores	**https://fishscores.com**

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Opportunities for MEL for Sustainable Food, Resources & Livelihood

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Opportunities for MEL for Sustainable Food, Resources & Livelihood

Potential Goals, Objectives & Indicators for Sustainable Food, Resources & Livelihood, all sectors

Potential Goal	GOAL 1 - SUSTAINABLE FOOD, RESOURCES & LIVELIHOOD Aquaculture sustainably increases accessibility of nutritious food	GOAL 2 - SUSTAINABLE FOOD, RESOURCES & LIVELIHOOD Employment provided on the farm and in supporting operations (e.g. business administration) is equitable and meaningful	GOAL 3 - SUSTAINABLE FOOD, RESOURCES & LIVELIHOOD Company operations are consistent with a high impact approach to environmental, social, and corporate governance (ESG)	GOAL 4 - SUSTAINABLE FOOD, RESOURCES & LIVELIHOOD Communities understand and accurately perceive the risks and values of aquaculture
Potential Objective	**OBJECTIVE 1.1** Food products from regional aquaculture activities are available in local markets	**OBJECTIVE 2.1** Jobs and employment practices (e.g. recruitment, workplace policies) improve Diversity, Equity and Inclusion (DEI)	**OBJECTIVE 3.1** Company operations are consistent with the highest standard of environmental, social, and corporate governance (ESG)	**OBJECTIVE 4.1** Communities have an accurate and positive response toward sustainable aquaculture activities
Potential Indicator	**INDICATOR 1.1.1** Number, consistency, and affordability of regional aquaculture food products available to consumers	**INDICATOR 2.1.1** Company or sector-wide Diversity, Equity and Inclusion (DEI) approach or policy leads to improvements in inclusion or quality of work	**INDICATOR 3.1.1** Company ESG approach or policy leads to improvements in inclusion or quality of work	**INDICATOR 4.1.1** Communities recognise management measures to mitigate negative impacts from aquaculture and can recall benefits from regenerative or restorative practices, trends in community awareness, perception, and recognition of aquaculture over time
Complexity	**Easy** - Tracking of products produced, primary markets and distribution to local markets	**Easy** - Internal approach or policy with company or sector-wide implementation	**Easy** - Internal approach or policy with company implementation	**Moderate to difficult** - Requires surveying of community over successive years
Metric	Number of products and price point of each	Meeting and exceeding DEI approach or policy metrics	Meeting and exceeding ESG expectations	Improvement in community recognition and perception of sustainable aquaculture activities over time
Suggested method	Tracking of products, consistency of supply, and price point	A company or sector-wide approach or policy is developed and has executive endorsement and support for implementation, with metrics/targets and appropriate monitoring	A company policy is developed and has executive endorsement and resourcing (e.g. staff time) to support effective implementation	Social science/survey methodology (before and after education treatments, analysis and surveys of community meetings or engagement events, using a standardized survey)
Proxy or additional method	Survey of products in national supermarkets	Regular internal, executive-level discussion on DEI within the company or sector association (e.g. agenda item at board and staff meetings)	B Corp Certification, regular internal and executive-level discussion on ESG within the company (e.g. agenda item at board and staff meetings)	Analysis of content in media coverage and community publications (e.g. newsletters) or assessment of public submissions received on new aquaculture permit applications, including in comparison to other farm types in the same region
Frequency/Timing	Annual	Annual	Annual	Occasionally
Location of sampling (e.g. within farm/ environment)	End markets for products	Farm business	Farm business	Local (geographic) community and sector-based communities

Opportunities for MEL for Sustainable Food, Resources & Livelihood

Tools & Resources (Sustainable Food, Resources & Livelihood, all sectors)

Description of use	Title	URL
Methodologies for calculating living and actual incomes	Living Income Community of Practice Measurement Hub	**https://www.living-income.com/measurementhub**
Standard for design, verification, and scaling of nature-based solutions for human well-being and biodiversity benefits	IUCN Global Standard for Nature-based Solutions	**https://portals.iucn.org/library/sites/library/files/documents/2020-020-En.pdf**
An online assessment tool for marine pearl farmers, supporting self-assessment of environmental, social, and governance factors, including estimates of bioextraction and the impact of GHG emissions from fuel use	PearlPoints	**https://pearlpoints.io/**
Methods for measuring nutrient bioextraction	Rose et al., (2015) 'Nutrient Bioextraction' in *Encyclopedia of Sustainability Science and Technology*	**https://link.springer.com/referenceworkentry/10.1007/978-1-4939-2493-6_944-1**
Comprehensive text on the environmental, social, and economic benefits of marine bivalves	Smaal et al., (2018) *'Goods and Services of Marine Bivalves'*	Online ISBN 978-3-319-96776-9
Environmental indicators for salmon aquaculture	Rector et al., (2022) 'Environmental indicators in salmon aquaculture research: A systematic review', *Reviews in Aquaculture*	**https://aquacultureindicators.shinyapps.io/EnviroIndicatorsAquaculture/**

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