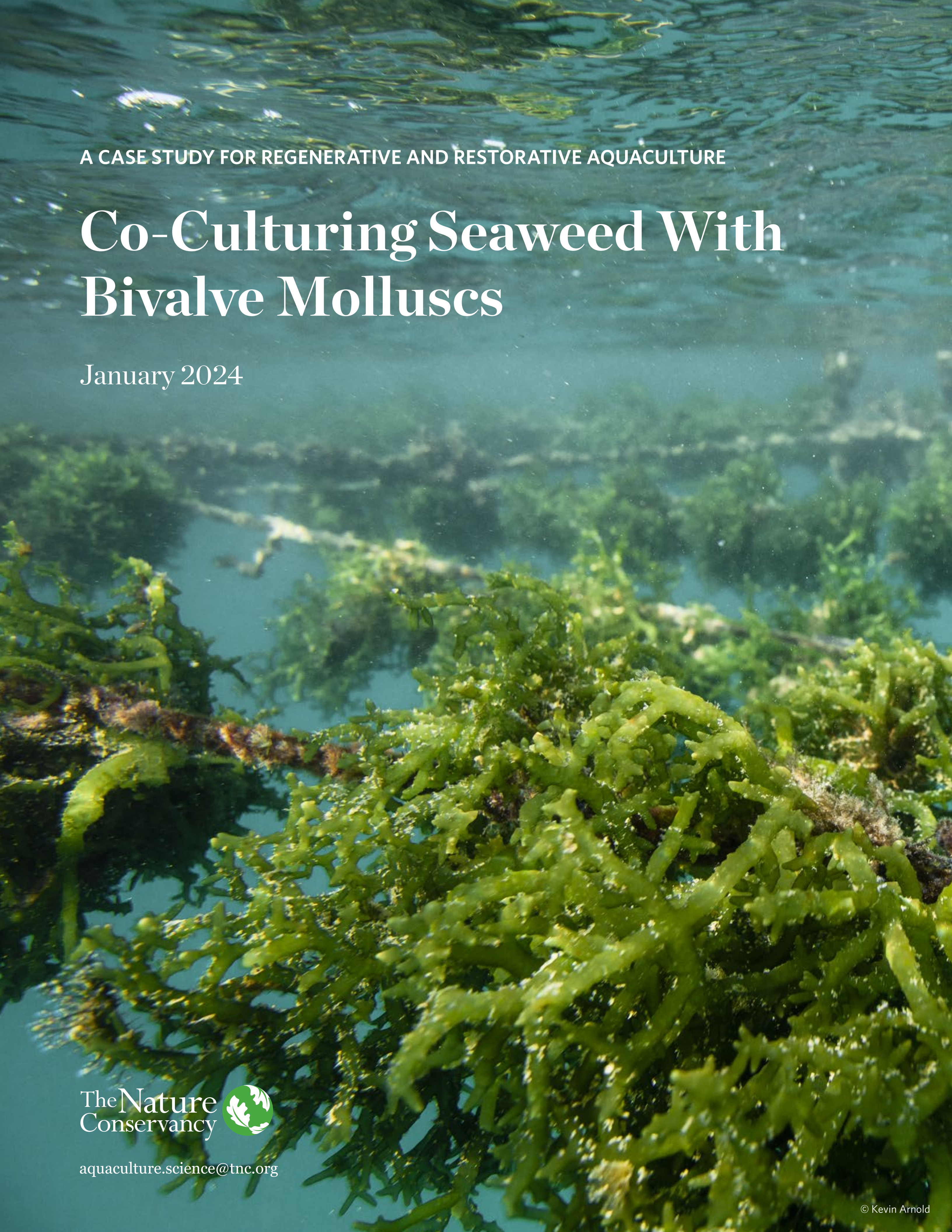

A CASE STUDY FOR REGENERATIVE AND RESTORATIVE AQUACULTURE

Co-Culturing Seaweed With Bivalve Molluscs

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The Nature Conservancy

aquaculture.science@tnc.org

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Mussels and kelp grow together together on a line.

INDUSTRY OVERVIEW

The production of seaweeds and bivalve molluscs (hereafter referred to as "bivalves") via aquaculture are major sectors globally, each contributing approximately half and one quarter, respectively, of total aquaculture production in marine areas and more than 97% and 89% of the total production from marine aquaculture and marine wild harvest combined (Wijsman *et al.*, 2019; FAO, 2022). In 2020, global cultivation of algae – dominated by marine macroalgae, known as seaweeds – grew by half a million tonnes, up by 1.4% from 34.6 million tonnes in 2019 (FAO, 2022). Total global aquaculture production of molluscs, mostly bivalves, was 17.7 million tonnes ($29.8 billion USD in value) (FAO, 2022).

As well as being important sectors by volume and value, farming of seaweeds and bivalve in marine and coastal areas is also relatively widespread. It has been estimated there are more than 51,000 farms across 42 countries for invertebrate mariculture in marine areas, more than any other sector if salmon and marine finfish farms are disaggregated (Clawson *et al.*, 2022). However, the magnitude of farming bivalve molluscs and seaweeds is highly varied and unevenly distributed geographically. Seaweed aquaculture in particular is highly concentrated in a small number of countries; China alone accounts for 59.5% of the production volume of aquatic plants (FAO, 2022; Mair *et al.*, 2023), followed by large production volumes in Indonesia, the Republic of Korea, Philippines, the Democratic People's Republic of Korea, Japan, Malaysia, and the United Republic of Tanzania. In other countries, interest in seaweed aquaculture is increasing rapidly, but commercial scale production remains comparatively low and many operations are at a pilot scale.

While seaweeds and bivalves are collectively the basis of much of global aquaculture production in marine and coastal areas, their co-culture is less common, though it represents a mature farming system in China (Mao *et al.*, 2019) and other parts of Asia. Co-culture – farming of these species side-by-side – and co-location – farming of these species nearby in the same site or area – has a similar ethos to integrated multi-trophic aquaculture (IMTA), where fed species (such as finfish or shrimp) are grown alongside extractive species (such as suspension-feeding bivalves) or deposit-feeding species (such as sea-cucumbers and sea-urchins) and seaweed. However, the intent of IMTA is for the extractive species farmed to use, and therefore mitigate, the organic and inorganic effluent that arises from farming the fed species (Chopin *et al.*, 2008; Troell *et al.*, 2009). The benefits associated with co-culture of extractive species only, such as seaweeds and bivalves, may therefore be similar or different. There is a need to explicitly understand whether benefits across monocultures of seaweed and mollusc species and IMTA versus their co-culture remain the same, or whether their co-culture enhances or even introduces unique benefits that might otherwise not occur.

This explicit understanding could encourage farmers to add species to existing farms for environmental and production-related benefits, including the multiple values of additional revenue streams. A lack of capacity to access markets can be a factor hindering the adoption of integrated systems, and there remain many barriers to effective and viable IMTA, from operational challenges, such as limited availability of seed, to social and regulatory acceptance as well as environmental constraints (Kleitou, Kletou and David, 2018). An evidence-based understanding of the co-benefits of this approach could grow public sector support and investment and consumer interest (e.g., willingness to pay; Bolduc, Griffin and Byron, 2023). It could also inform sector- or government-led operational models over a larger area, such as whether there is value in co-locating independently operated seaweed and bivalve farms within a broader area or region, and the configuration or distance between farms that may be required to maximise benefits at these greater spatial scales.

ENVIRONMENTAL CONTEXT

Seaweed and bivalve species have each been shown to provide a range of environmental benefits and ecosystem services (Weitzman, 2019; Gentry *et al.*, 2020; van der Schatte Olivier *et al.*, 2020). They are extractive species, using organic and inorganic nutrients and matter and by-products from other species to fuel their growth. Bivalves filter water to feed, which can increase the cycling and uptake of excess anthropogenic nutrients from the water

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through bioassimilation and denitrification (Rose *et al.*, 2014). Bivalve culture systems have also been shown to provide habitat for invertebrates and fish for shelter, feeding, and spawning and recruitment (Barrett, Swearer and Dempster, 2019; Underwood and Jeffs, 2023; Underwood, van der Reis and Jeffs, 2023). Similarly, seaweed farms can provide habitat for species ranging from microbiota to large bodied fish, although the benefits can be highly varied, from strong positive responses to negative interactions (Corrigan *et al.*, 2022; Forbes *et al.*, 2022).

Like wild seaweed habitats, farmed seaweed can be highly productive, having high growth rates and net primary productivity (NPP). In addition to taking up phosphorous and nitrogen, seaweed also takes up dissolved inorganic carbon and converts it into biomass that typically retains a high proportion of carbon (Duarte *et al.*, 2017). High rates of productivity can result in these nutrients being removed from surrounding waters in quantities that could make farming of seaweed species a feasible tool for nutrient assimilation and pollution management in waterways (Racine *et al.*, 2021). Aquaculture of bivalve species has also been shown to be a viable pathway for nutrient mitigation (Rose *et al.*, 2021; Cubillo *et al.*, 2023) and nutrient trading schemes are in development in several states in the United States.[1]

Where the negative effects from farming, such as shading, are negated and the ecological and social carrying capacity of local water ways is not exceeded (McKindsey *et al.*, 2006; Byron *et al.*, 2011), environmental benefits could have a valuable economic impact. For instance, the value of nitrogen removal provided by current bivalve aquaculture in the European Union has been estimated to be equivalent to using between 15.9 and 21.6 billion Euro worth of other waste treatment methods (Cubillo *et al.*, 2023). If restorative practices are used effectively, the value of nitrogen removal, and the value of additional fish production from aquaculture that provides habitat, could be in the order $17 to 56 billion USD annually by 2050 (Barrett *et al.*, 2022).

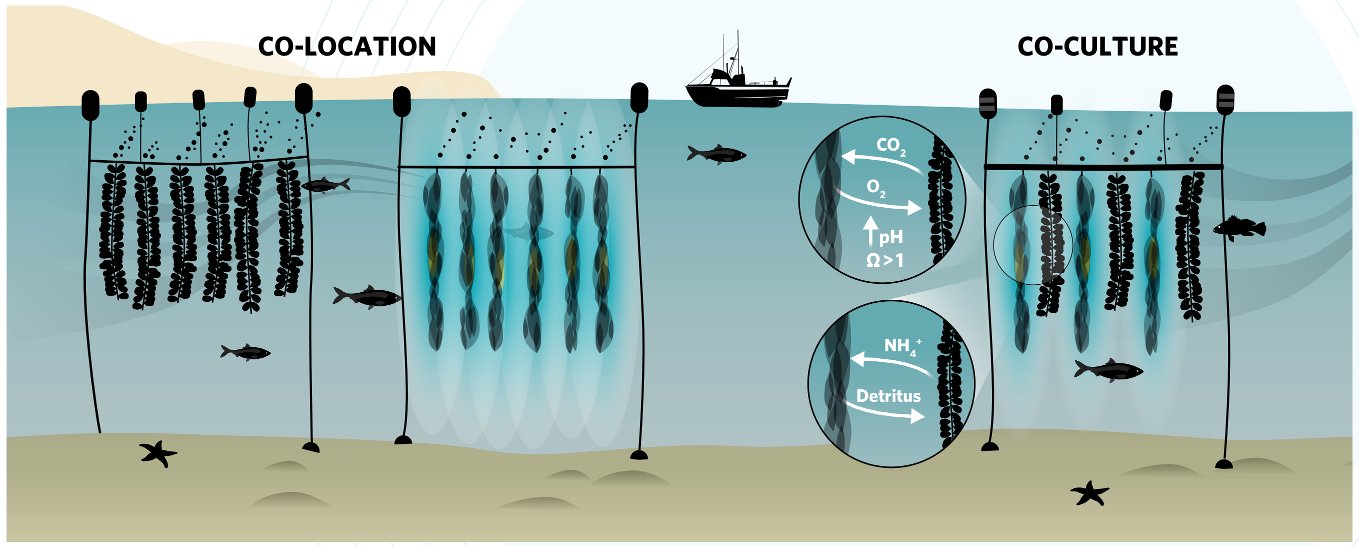
While these benefits exist, seaweed and bivalve farming is also threatened by climate change and associated threats, such as ocean acidification, increasing sea surface temperatures (SST), and severe weather events. These environmental stressors can increase the prevalence of diseases and pathogens, reducing the yield of farmed species. To increase the resilience of the industry, diversification through access to more locations and the development of new production and management practices is needed.

ENVIRONMENTAL BENEFITS

While seaweed and bivalve aquaculture systems can independently generate environmental benefits and ecosystem services, research also shows that there can be unique benefits to their co-culture and that this approach may enhance some benefits for greater effect. In particular, because seaweeds draw on CO_2 for their growth, they can buffer local environments from the negative effects of ocean acidification and reduced water quality (Xiao *et al.*, 2021). Co-culturing seaweeds with bivalves can provide a refuge for shell-forming bivalves from acidification, creating a 'halo effect' (Fernández, Leal and Henríquez, 2019) as well as providing a refuge for other calcifying organisms (Figure 1).

The use of CO_2 by seaweeds could also influence the extent to which bivalve aquaculture contributes to CO_2 emissions. Bivalve farming is generally considered to be a small net source of CO_2, because under most growth conditions, bivalves release more CO_2 through respiration and the calcification process than the amount they store in the resulting accumulation of calcium carbonate shell (Han, *et al.*, 2017). Yet most bivalve aquaculture life cycle assessment (LCA) studies have not incorporated CO_2 production from shell building into greenhouse gas emissions estimates (Jones *et al.*, 2022), and these multiple, step-wise effects suggest there may be instances in which bivalve farms could act as a carbon sink, if the outputs from respiration and supply chain activities can be mitigated (Moore *et al.*, 2023). Seaweeds cultured directly alongside bivalves may be able to absorb and, therefore, offset the CO_2 they release (Xiao *et al.*, 2021). Han *et al.* (2017) suggest a ratio of 4:1 for farming of the Portuguese oyster (*Crassostrea angulata*) and the red seaweed (*Gracilaria lemaneiformis*) as an efficient way to use the dissolved organic carbon within the system and generate a carbon sink. These interactions deserve thorough exploration to better understand the potential of these benefits and the general principles that determine whether positive effects are likely to be enhanced through co-culture (e.g., ambient nutrient availability, spacing between species and infrastructure, biomass, water flow). This will be especially valuable in response to the increasing impacts of climate change and to maximise the potential of restorative practices to support biodiversity (Box 1).

Figure 1. **Co-culturing and co-location of seaweed and shellfish aquaculture systems and potential reciprocal effects in dissolved nutrient cycling.**



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[1] On the Forefront of Nutrient Credit Trading Using Oysters: Lessons Learned (**https://coast.noaa.gov/digitalcoast/training/oyster-aquaculture.html**)

Box 1. **Blue Dot Sea Farms – Washington, USA**

On both coasts of the U.S., climate change is already impacting aquaculture operators through higher sea surface temperatures, increased atmospheric heat exposure during low tides in the summer months, increased exposure to reduced salinities following more frequent flooding, increased hypoxia, and increased local acidification of surface waters (Mills *et al.,* 2023).

Blue Dot Sea Farms operates a 2-hectare bivalve and seaweed farm near Hood Head in the northern part of Hood Canal in Washington, USA. The site benefits from a high flux of natural phytoplankton and ample tidal currents, meaning there is sufficient capacity to carry farming of multiple bivalve species and seaweeds in the local ecosystem. Sugar kelp (*Saccharina latissima*) is farmed on lines at a 3-metre depth with Pacific oysters (*Crassostrea gigas*) grown in surface trays.

The farmer actively supports and runs research projects and collaborations to improve our understanding of how seaweed cultivation can enhance the health of our oceans and communities. This industry-led research includes developing a three-dimensional simulation model of kelp metabolism and biochemical exchange of carbon, nitrogen, and oxygen between the farm and ambient waters, with publication of the results anticipated in early 2024. Further research includes assessing the response of Pacific oysters co-cultured with the sugar kelp. Here, cages of Pacific oysters are suspended on grow lines in proximity (less than 0.25 metres) to the kelp on the same lines. Grow lines in this case consist of stiffened cable manufactured from recycled carbon fibre and enable 0.5 metre spacing between each, with the intent of determining a configuration within the water column that can maximize production of both species. Size at age and survivorship in the Pacific oysters along with estimates of kelp productivity and yield will be assessed within and outside of seaweed lines and compared to control samples and sites.


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Co-culturing seaweeds and bivalves could also have reciprocal benefits on the productivity of farming each organism. Laboratory and field studies of the pearl oyster *Pinctada martensii* and the red algae *Kappaphycus alvarezii* in China have identified higher growth rates for both species when co-cultured, with the implication that the enhanced growth of the algae was due to nitrogenous waste from the pearl oysters, thus supporting productivity in both species (Qian *et al.*, 1996). Cultivation of sugar kelp and the blue mussel (*Mytilus edulis*) in Sweden found kelp yields to be enhanced in the co-culture configuration in comparison to control sites, with a mean increase in biomass of 38% and significant increases in photosynthetic pigment concentrations resulting in improved kelp quality (Hargrave *et al.*, 2022). It may be that even small increases in nutrient availability could result in higher growth rates, greater kelp biomass, and better quality due to increases in total organic content (Rugiu *et al.*, 2021). Significant decreases in ephiphytic cover, which contributes to biofouling, on kelp co-cultured with blue mussels and Pacific oysters have also been observed (Hargrave *et al.*, 2021, 2022). The nature and extent of effects may, however, be dependent on the species farmed. For example, green algae (*Ulva* spp) has been seen to have a negative effect on oyster growth rates and to have a determining role in the microbial community in IMTA (Califano *et al.,* 2020). These investigations should be extended into understanding the unique role of seaweeds cultivated with other molluscs (i.e., comparisons with and without oysters and other species of bivalves), and co-culture with detritovores, such as sea urchins and sea cucumbers on the sea floor or benthic structures. These detritivore species introduce an additional trophic level and unique functional role to co-culture systems by drawing on and reducing detritus and biodeposits from shellfish and other grazers, including other species of high interest for farming, such as abalone.

POTENTIONAL BENEFITS OF SEAWEED-BIVALVE CO-CULTURE

Habitat and biodiversity

Habitat benefits from co-culture could be comparable, or potentially enhanced, in comparison to monocultures of seaweeds and bivalves, given there will be multiple types of habitats formed by culturing each species. This may promote different epibiota and mobile macroinvertebrates by providing different types of food and shelter.

Water quality

Rates of water filtration and bioextraction could be comparable between co-culture and monoculture systems, but co-culture could couple the release of nutrients from bivalve farming with seaweed NPP, resulting in reduced ambient nutrient concentrations and potential eutrophication. This approach may, in some locations, present a more scalable model for increasing the biomass or area of farmed seaweed or bivalves.

Climate change adaptation

Co-culture could provide a unique benefit to carbon cycling, where the farmed seaweed may fuel its growth by using the additional CO_2 generated by mollusc respiration, depending on the configuration of the farm and the potential for the exchange of CO_2 and O_2 between the species.

Farming seaweeds can create a localized 'halo effect,' limiting the potential negative effects of ocean acidification.

Sustainable food, resources, and livelihood

Production of multiple species can be an efficient use of space and provides opportunities to diversify income streams by facilitating access to new markets.

Co-culture farms will be important sites for education, research, and training, particularly as the aquaculture industry and coastal communities work to sustainably increase production and develop supply chains that enable access to multiple markets.

Product quality or volumes may be higher in co-culture systems. For example, mussels may grow larger or more rapidly alongside seaweed, and kelp biomass may be greater when cultured alongside blue mussels. However, co-culture presents unique risks that will need to be managed, such as physical damage to seaweed fronds from bivalves.

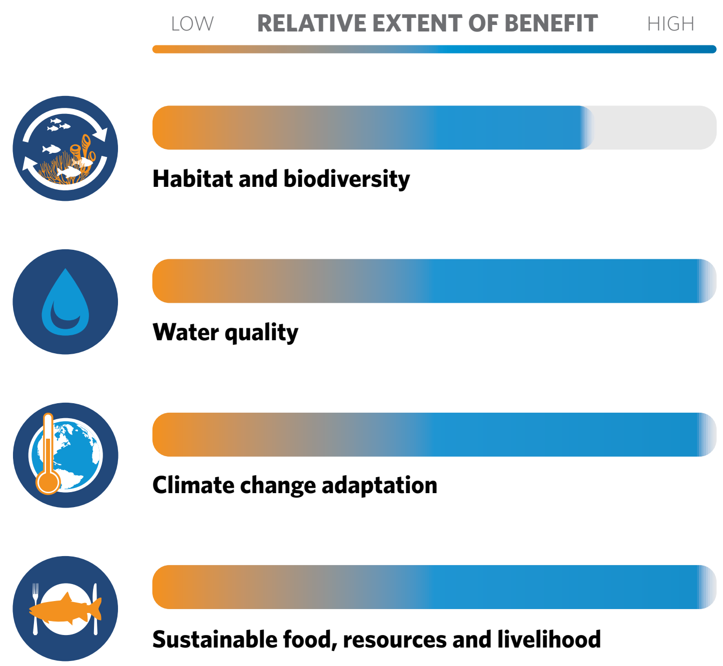


Figure 2. **Potential extent of environmental benefits from co-culturing seaweed with bivalve molluscs.**

Extent of benefits is indicative only and relative to each other and similar systems.

IMPLICATIONS FOR MONITORING AND EVALUATION FOR RESTORATIVE AQUACULTURE

Targeted monitoring of environmental and production characteristics (e.g., growth rates and yields) across co-culture, co-location, monoculture, and non-farm or reference sites will improve our understanding of both the enhanced and the unique benefits of seaweed and bivalve farms systems. These systems should apply the same monitoring and evaluation methods as monocultures as well as methods that can isolate key factors and potential benefits, such as changes in ocean acidification and carbon cycling.

Habitat and biodiversity

The role of co-culture in providing habitat for a range of life stages needs to be assessed and should include sampling and ongoing monitoring of species-specific infrastructure (i.e., shellfish lines and seaweed lines) and areas in between or that are overlapping. Sampling should encompass a range of taxonomic and functional groups, from the microbial community and microorganisms, plankton, epibiota, to finfish and marine mammals.

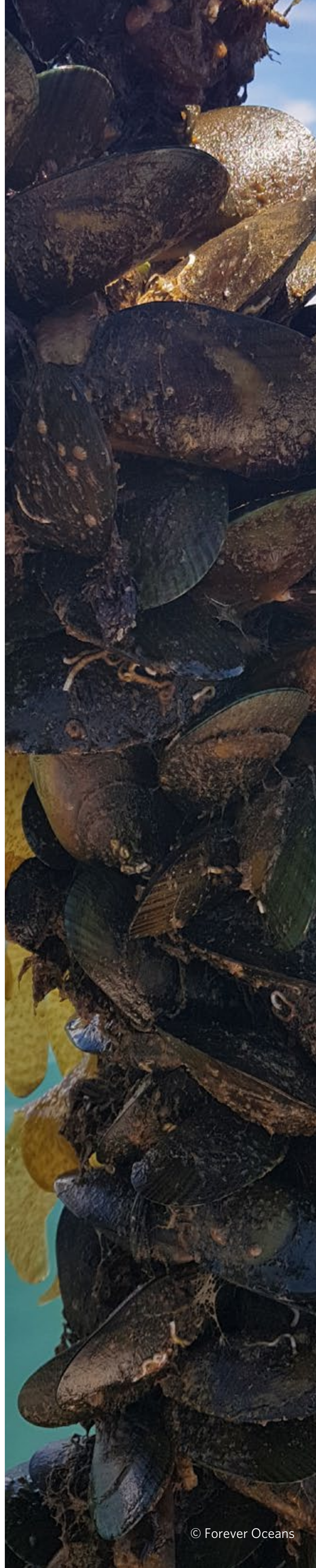
Sampling of associated fauna could target assessing changes in species abundance before and after the addition of seaweed or bivalves to an aquaculture production system to test and monitor for benefits to biodiversity as well as the effects on biofouling.

Water quality

Bivalves' rates of water filtration, bioassimilation and denitrification should be explicitly monitored across co-culture, monoculture, and reference sites to identify differences and better understand the potential advantages of co-culture on the removal of excess nutrients.

Climate change

Monitoring of ocean acidification at a farm will provide important insights into the potential 'buffering' effect of seaweeds on shell forming species, both cultured and wild. This monitoring should be comprehensive across the farm area and measurements should be taken in association with water temperature, salinity, light conditions, and estimates of corresponding stock biomass. It should be done regularly and with consistent methodology that accounts for the distance of the macroalgal canopy and potential diurnal and seasonal variation; coastal environments are characterised by strong diurnal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acidity fluctuations due to photosynthesis and respiration. More complex research studies, such as mesocosm experiments, would be beneficial to stress test the co-culture response (i.e., monitor for more extreme acidity) and validate this sampling.

Sustainable food, resources, and livelihood

Life cycle assessment and regular collection of data on life cycle activities and inputs, particularly fuel and energy use, will support a more accurate understanding of how the uptake of dissolved carbon might positively impact greenhouse gas emissions from the broader production system, including hatchery production upstream and product processing downstream.

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Tim Henry, owner of Bay Point Oyster Company, readies an oyster cage to be placed back in the water at his farm in Little Bay in Durham, New Hampshire.

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