The Nature Conservancy

Global Principles of Restorative Aquaculture

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INTRODUCTION

The Challenge

Food production contributes significantly to global environmental challenges. As the global population swells to 9 billion people by 2050 there is a pressing need to meet the growing demand for food while staying within environmental limits.

> **Food production now accounts for nearly one quarter of global greenhouse gas emissions, and 70 and 80% of freshwater usage and habitat degradation, respectively (Poore and Nemecek, 2018).**

Aquaculture, the growing of animals and plants in the water, has also often developed at the expense of the environment. Habitat degradation, water pollution, impacts to wild fish stocks, and disease were associated with the early years of commercialized aquaculture development and continue to challenge the environmentally sustainable development of the industry today (Naylor *et al.*, 2021).

These impacts contribute to unprecedented challenges to broader marine and freshwater environments, which are the result of a wide range of ways in which human communities use and impact these ecosystems. Coastal areas have incurred a systemic loss of habitat and associated ecosystem function due to destructive fishing practices, pollution and the introduction of invasive species. Some of the most dramatic examples are oyster reefs, one of the most imperiled coastal habitats on the planet, which have experienced a staggering 85% loss in the past two centuries (Beck *et al.*, 2011), along with kelp forests (Steneck *et al.*, 2002), mangroves (Polidoro *et al.*, 2010) and seagrasses (Dunic *et al.*, 2021). The loss of these habitats contributes to a loss of ecosystem function, such as natural filtration of water and cycling of nutrients, fish production benefits, and shoreline protection.

Many coastal marine ecosystems now display the cumulative effects of lost function, especially eutrophication; nearly 1000 areas around the world have been identified as having experienced the effects of eutrophication, with approximately 600 of these showing indications of hypoxia (Diaz *et al.*, 2013). The state of global wild fisheries stocks reflects a decline in habitat and ineffective management. More than three quarters of fish stocks are currently considered to be fished from biologically sustainable stocks, but the proportion of stocks fished at unsustainable levels has increased, up from 10% in 1974 to 34.2% in 2017 (FAO 2020). Coastal ecosystems face the additional, growing threat of ocean acidification and climate change, which undermine natural recovery and restoration efforts.

Freshwater ecosystems face similar challenges. Rivers, lakes, and wetlands cover less than 1 percent of the earth's surface, but are home to 51% of all fish species (Hughes *et al.*, 2021). More than half of all freshwater ecosystems have been heavily impacted by human activities and have significantly reduced fish biodiversity due to impacts from industrialization, dams, and freshwater use for agriculture and industry (Su *et al.*, 2021).

But despite and even because of these environmental impacts, we challenge the assumption that food production and environmental health are a zero-sum game. It is possible to produce food for a growing population in a manner that is not only responsible but can contribute to the recovery of at the same time. While approaches that can support better outcomes for nature are increasingly deployed in terrestrial food production systems, such as regenerative agriculture, their use in aquatic food systems is emerging.

Given aquaculture's rapid growth over the past two decades and significant potential to expand in the future, it is a key sector in which environmental concepts need to be applied so that aquatic food systems can support sustainable development, and to ensure a brighter future for nature and people.

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The Opportunity for Restorative Aquaculture

Restorative aquaculture may be one of the best opportunities to simultaneously improve the health of aquatic environments and provide food for a growing population. Aquaculture of certain species, when farmed in the right way, can serve as a tool to help address water quality degradation, habitat loss, and climate pressures. Nearly all continents and most coastal countries have the potential for restorative aquaculture in marine environments when taking into account enabling environmental, socio-economic, and human health factors for development (Figure 1; Theuerkauf *et al.*, 2019). Additionally, in freshwater environments, agroecological approaches can support communities in achieving multiple social and economic objectives, while increasing efficiencies in the production of multiples foods with fewer inputs and impacts (Freed *et al.*, 2020).

In most countries, there is significant potential for a restorative aquaculture industry to be expanded. Oyinlola *et al.*, (2018) conclude that there is 72 million square kilometers of ocean that could be suitable for farming at least one of the 102 most farmed marine species; and Froehlich *et al.*, 2019 discuss the potential of up to 48 million square kilometers of ocean that could be suitable for the increased production of seaweeds. The potential for bivalve aquaculture to expand is similarly large, with a projected 30 times potential increase over current production (Costello *et al.*, 2020). That stated, local data, information, and stakeholder input should be used to determine industry expansion and attention should be paid to how expansion communicated to the public and stakeholders (Costa-Pierce & Chopin, 2021).

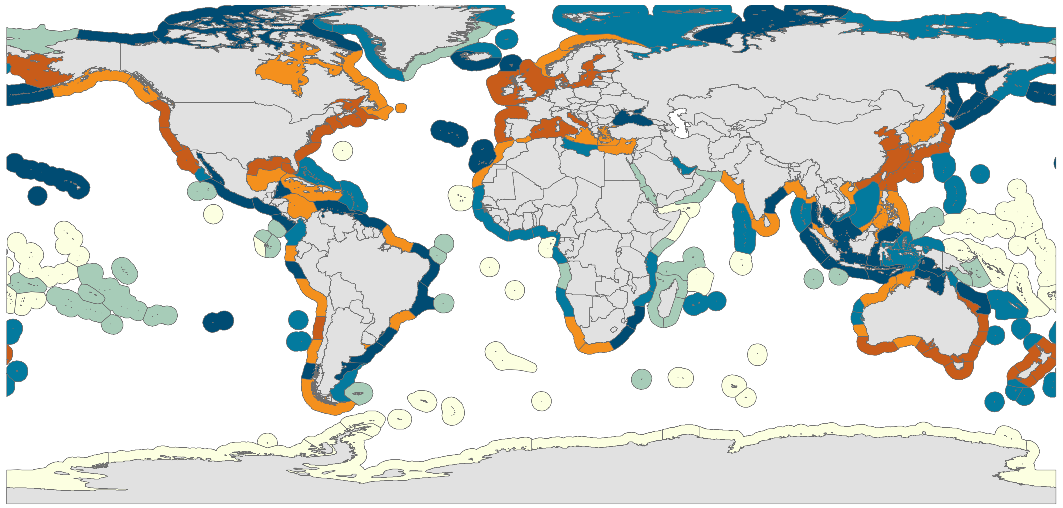
The growth of aquaculture that uses restorative practices, such as the siting of bivalve aquaculture to reduce excess anthropogenic nitrogen and phosphorous in the water or supporting wild fish production by using the habitat formed by aquaculture farms, could result in valuable opportunities to improve ocean health while generating economic returns. These outcomes could be enhanced if existing aquaculture industries implement restorative practices.

The opportunity to achieve environmental recovery at scale through restorative aquaculture is also compelling when compared to the costs associated with environmental restoration alone. While models attempting to monetize habitat, species, and environmental restoration have been developed, such projects have traditionally relied on public grant dollars or philanthropic support. For example, the cost of restoring a single acre of oyster reef may amount to hundreds of thousands of dollars when considering the full costs of the project (Bayraktarov *et al.*, 2016), limiting the ability of such projects to be developed over a substantial area, and the opportunities available to regions and countries that may not be able to afford the cost of these works.

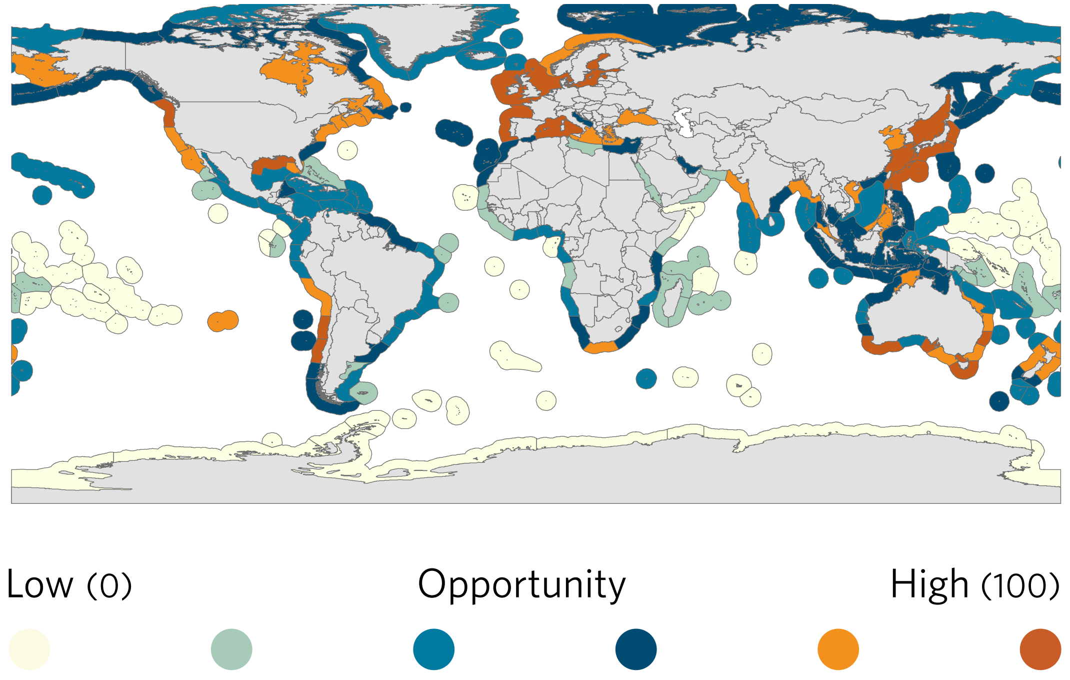
Commercial restorative aquaculture can provide similar benefits to the environment without requiring significant public investment

Figure 1. **Restorative Aquaculture Opportunity Index for Shellfish and Seaweed.***

SHELLFISH



SEAWEED



*Derived from Theuerkauf *et al.* 2019

or philanthropy and can therefore be viewed as a market-based solution to improving aquatic health. At a large enough scale, restorative aquaculture could create significant economic opportunities for coastal communities around the world, and enhance the $264 billion in revenue and employment opportunities for 20 million people that the aquaculture sector already provides (Valderrama, Hishamunda, and Zhou, 2005; FAO, 2020).

Purpose and Objectives

This document establishes a definition of restorative aquaculture and provides clarity on how this approach can be effectively implemented and fostered. Without this guidance, there is a risk of misinterpretation or inconsistent application of the concept and associated terminology. Guidance is provided in the form of a set of Global Principles of Restorative Aquaculture (hereafter referred to as the Principles) that establish the high-level intent for the effective implementation of restorative aquaculture. We consider "principles", for the purposes of this document and its use, to be a fundamental proposition, a statement that expresses a judgment or opinion, as a basis for explaining how restorative aquaculture could be best designed to deliver restorative outcomes.

By providing a definition, identifying the Principles, and establishing environmental benefit roadmaps, we hope to motivate actors to engage in restorative aquaculture and encouraging supporting policies and market-based approaches to support its further development. Greater engagement with this concept creates an opportunity to improve the health of hundreds of thousands of square kilometres of marine and freshwater ecosystems while producing food and valuable economic development opportunities at the same time.

SCOPE

This document is intended to define restorative aquaculture and describe the intent of the concept and guiding principles for its use.

The definition and guidance provided apply to large and small-scale operations, are not limited in geographic scope, and include freshwater (inland), estuarine (brackish), and marine (coastal and offshore) aquaculture. However, this document focuses heavily on opportunities especially associated with shellfish and seaweed mariculture, given the strength of scientific information supporting restorative outcomes related to these species groups and industries.

We consider this document to be a first edition based on the best available science at the timing of publication. The authors endeavor to review and update the document biennially or as necessary to incorporate new knowledge and provide new guidance (and roadmaps), as research and knowledge deepens regarding other sectors and species.

This document, and the framework it creates, through the Principles and the roadmaps do not form a certification scheme, standard, or eco-label that enables aquaculture operations to be formally classified as 'restorative'.

Indigenous and Customary Aquaculture

While this report seeks to provide clarity regarding the current definition, drivers, and implementation of restorative aquaculture, it must be noted that integrated aquaculture systems that provide ecological benefits and sustaining ecosystem outcomes are not a new invention. On the contrary, aquaculture has been practiced sustainably for millenia by many local and indigenous communities for food, trade, cultural, and environmental outcomes, with many of these systems an important precursor and parallel to this restorative aquaculture approach. Importantly, when discussing the need to "restore" our natural systems or lamenting the loss of essential marine habitats, conservationists are most often referring to pre-colonial levels of environmental connectivity and abundance, which were often the result of local and Indigenous resource management. When we seek transformation of global food systems, we must not overlook solutions that have fostered sustainability and restorative outcomes for significant periods of time, including solutions that are not based on current concepts of new technological or infrastructure-related innovation, but are rooted in place-based knowledge and traditional management.

For example, freshwater fish farming in earthen ponds has been practiced in China since 1100 BC. Additionally, across Southeast Asia production of fish has historically been coupled with the farming of rice. But with greater demand for food, monocultures for both systems have become increasingly common. In China, the co-culture of fish with rice (integrated rice-fish farming) began an estimated 2000 years ago (Lu and Li, 2006) and has since been developed in many Asian countries, including Bangladesh, Indonesia, Vietnam and Cambodia. These systems represent a unique aqua-agricultural landscape. Rice-fish systems can support natural biodiversity, through greater access for species to a range of ecosystems, though the diversity of the systems and farming approaches themselves remains key to fostering these benefits (Freed *et al.*, 2020). A range of integrated rice-fish production practices and systems exist (alternating rice-fish culture, concurrent rice-fish culture, community-based fisheries and aquaculture, and rice field fisheries; Freed *et al.*, 2020) providing the opportunity to foster approaches that best work with natural processes and the needs of local communities.

> **The integration of traditional and Indigenous knowledge of aquaculture into restorative practices will have social and cultural benefits, including greater access to ways of being, health and wellbeing, and equality, and better outcomes for the environment.**

In Hawaii, integrated aquaculture and agriculture (e.g. traditional fish ponds and taro) were also pioneered and managed historically, including at a catchment scale with inland and coastal ecosystems used to support redistribution of foods farmed in different areas through cooperation and trade across communities (Costa-Pierce, 1987). They also represent an opportunity to renew focus on integrated systems that can assist food and nutrition security, by fostering access to nutritionally valuable foods with reduced or even enhanced environmental effects. Rural and Native Hawaiian communities are actively revitalizing fish pond systems and their traditional nearshore environments, including seaweeds, corals, and wild fisheries. This place-based revitalization and restoration are rooted in Indigenous science and worldview, and includes a focus on biocultural resource abundance for the entire watershed (Asuncion *et al.*, 2020).

In the Pacific Northwest of North America, clam gardens are an Indigenous aquaculture practice dating back at least 3500 years. Indigenous people created and maintained these systems by modifying marine substrate, resulting in some systems that were at least 4x more productive than non-clam gardens (Millin, 2020). Beyond increased productivity, these clam gardens create enhanced systems that promoted biodiversity of other marine species and mammals (Duer *et al.*, 2015). Additionally, recent research on clam gardens in British Columbia show that the unique clam garden design can provide increased climate resilience by buffering temperature and carbonate fluctuations, in addition to the traditional practices of returning clam shells to the beach, which also help buffer against acidic coastal waters (Millin, 2020). The Swinomish Indian Tribal Community in Washington State, as part of their comprehensive plan to strengthen their climate resiliency and find solutions through Indigenous knowledge, are currently revitalizing their clam gardens for food, climate, cultural, and environmental benefits (Voices for Clean Water, 2020).

Aerial view of Kiholo fishpond on Hawai'i Island. © Christine Shepard.

Objectives of this Document

- Establish a definition of restorative aquaculture to provide clarity on the scope of its meaning to a range of stakeholders including: industry, governments, non-governmental organizations, and the public;
- Describe the key benefits and environmental conditions that underpin and can result from restorative aquaculture;
- Create guidance for resource managers, regulators, farming associations, farmers, and other interested parties to determine the likelihood of restorative outcomes from an aquaculture operation;
- Support implementation, measurement, valuation, and adaptive management of restorative aquaculture in practice; and
- Motivate key actors to plan for and deploy restorative aquaculture practices through integration in regional planning approaches such as zoning for aquaculture or aquatic protected areas.

AUDIENCE AND USE

We envision that the aquaculture industry, farming associations, and farmers; national, provincial, and state governments; financial institutions; NGOs; academic institutions; philanthropic donors; and eco-certification programs are all audiences for this report.

The Principles can be used by stakeholders for a wide range of settings and scales, from national planning, to regional and local seascapes, and at the scale of individual farms.

In this document, we have prioritized a process-driven approach to allows operators and other stakeholders to determine the likelihood of whether aquaculture farms are resulting in restorative environmental outcomes.

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Defining Restorative Aquaculture

DEFINITION

Restorative aquaculture occurs when commercial or subsistence aquaculture provides direct ecological benefits to the environment, with the potential to generate net positive environmental outcomes.

This definition aims to provide guidance for an industry approach that can contribute to halting, if not reversing, specific impacts from human activities on the environment, in addition to providing food or other commercial products, and livelihood opportunities. In particular, the goal of net positive – a 'net gain' target – is a central component of the definition as in order to prevent impacts and reverse significant declines, goals must be articulated and based on net outcomes (Maron *et al.*, 2021). Restorative aquaculture can help mitigate key environmental impacts such as pollution of aquatic areas, biodiversity loss, and climate change pressures.

The ability to describe environmental benefits and a net positive outcome is influenced by the available knowledge and recognition of services that can be provided by aquaculture. Additionally, the environmental benefits are context-specific and can be difficult to generalize. However, the current body of science indicates these benefits can include water quality improvements, habitat provisioning, and potentially climate mitigation.

Consequently, this document focuses on advancing Principles for restorative aquaculture given these currently 'better-known' benefits for environmental health. It is expected that additional benefits, such as support for biodiversity, coastal processes and coastal protection, or cultural ecosystem services will be better understood with continued research. These benefits should be considered in the scope of restorative aquaculture, alongside guidance for industry and managers on how to implement associated restorative practices. New knowledge and guidance will be included in future updates of the Principles.

RESTORATIVE AQUACULTURE AS DEFINED IN RECENT LITERATURE

Several definitions of restorative aquaculture have recently appeared in the scientific literature.

Theuerkauf *et al.*, (2019)
Define restorative aquaculture as "the intentional use of aquaculture to positively affect (ecosystem) services." While the definition of restorative aquaculture we provide similarly involves the provision of ecosystem services, evidence for the provision of some benefits indicates that intentionality on the part of the farmer or management body is not a key factor in determining whether a farming system is restorative.

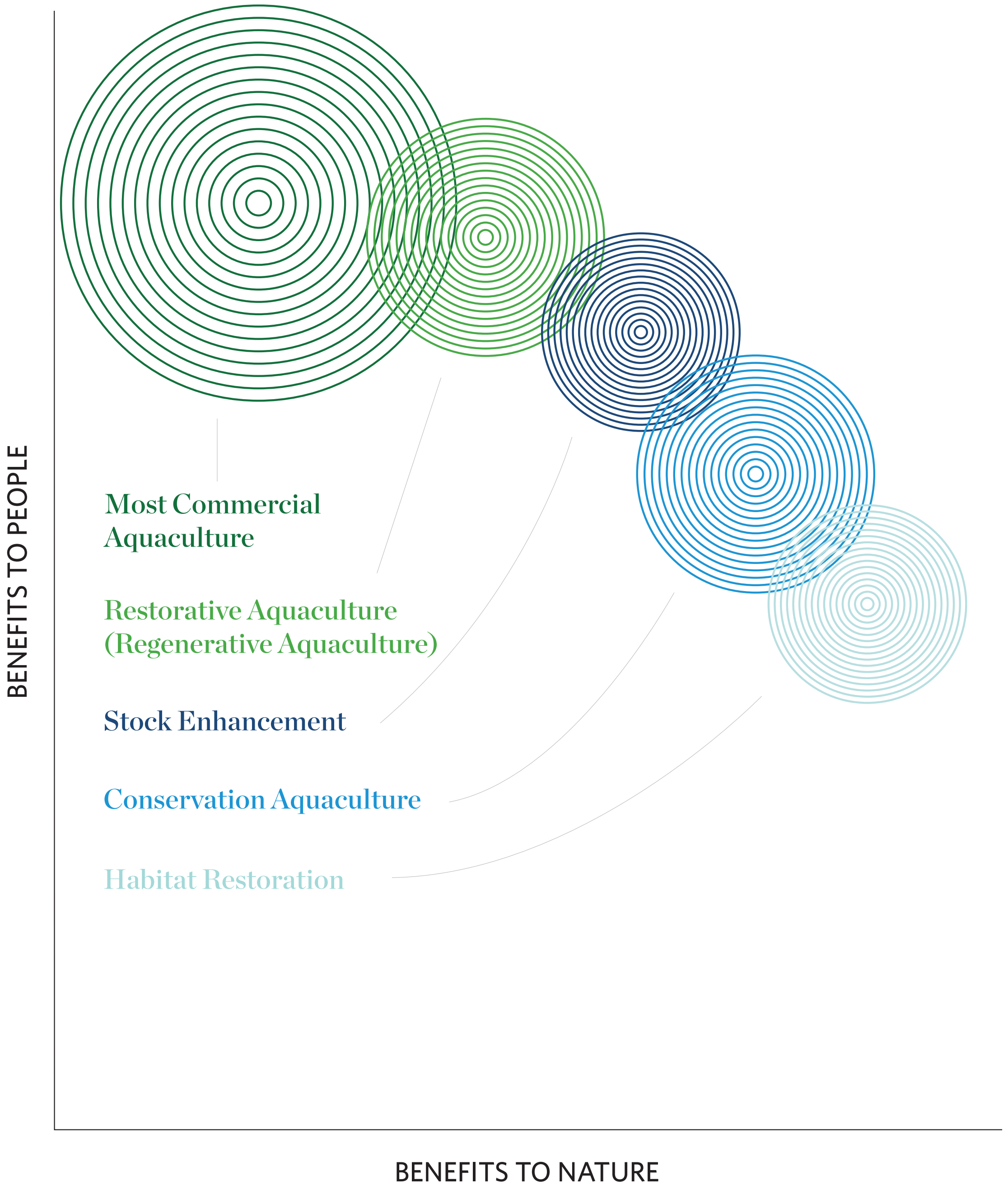
Carranza and zu Ermgassen (2020)
Define "Restorative Shellfish Mariculture" as "a multi and/or interdisciplinary approach, involving some form of human intervention during the species life cycle, aiming to address negative socio-ecological impacts derived from the unsustainable use of marine shellfish." In Carranza and zu Ermgassen's definition, the culture species must be "native and depleted or overfished, or locally, or regionally extinct or functionally extinct. This definition is largely synonymous with "habitat restoration" or "conservation aquaculture".

Maynard (2003)
Defines restorative aquaculture as "the protection and enrichment of specific marine ecosystems, such as coastal mangroves and seagrass communities, clam, oyster, and mussel beds, and coral reefs. The concept also extends to include our coastal and oceanic fishing grounds." While the definition of restorative aquaculture also reflects functions that enrich marine ecosystems, Maynard's application of the term focuses on the release of animals into the wild, which may be better defined as "conservation aquaculture."

SIMILAR CONCEPTS AND TERMS

There are a range of other terms that apply to both food production in aquatic environments supporting environmental and conservation outcomes (Figure 2). Collectively, these definitions establish a framework for sustainability and the range of ways in which aquaculture as, first and foremost, a food production industry, can evolve into a dynamic production system and practice with many social, economic, and environmental outcomes.

Figure 2. **Conceptual Diagram of the Position of Restorative Aquaculture Relative to Other Human Activities Benefiting People and Nature.**



Regenerative Food Systems, Regenerative Agriculture, and Regenerative Aquaculture

The Nature Conservancy considers regenerative foods systems to be methods of producing food "whether on land or at sea in ways that actively restore habitat and protect biodiversity in and around production areas while reducing greenhouse gas emissions" (Doane, 2020). Restorative aquaculture and regenerative agriculture can be considered regenerative food systems. Regenerative agriculture has multiple definitions in the scientific literature but can be considered, according to the Food and Land Use Coalition, as "a set of practices that regenerate soil, that reduce but do not necessarily eliminate synthetic fertilizers and pesticides, and that go beyond the reduction of negative impacts to ensure that agriculture has a positive environmental effect" (FOLU, 2019).

Restorative aquaculture attempts to apply similar environmental concepts and approaches to aquaculture. Regenerative aquaculture is also a term that has been increasingly utilized by aquaculture companies and start-ups (e.g. Greenwave, 2021) but does not have a clear definition in the scientific literature. In a recent UCSB TNC paper (Mizuta, Froehlich & Wilson, in review) that empirically reviews the literature for key aquaculture-related terms that have a conservation application, a definition for regenerative aquaculture is proposed that is based on regenerative agriculture. This definition includes a social justice component, in addition to environmental and economic benefits. For the purposes of this white paper, we generally consider regenerative aquaculture and restorative aquaculture to be synonyms.

Ecological Aquaculture

Ecological aquaculture is a "model of aquaculture development that uses ecological principles and practices as the paradigm for development of aquaculture systems" (Costa-Pierce 2002, 2010, 2021). Ecological aquaculture encourages aquaculture to be an ecological system and states that planning for environmental benefits should be incorporated from the beginning, rather than considered an afterthought. The seven principles of Ecological Aquaculture include designing farms to mimic natural systems; contributing to local society through community development; delivering economic and social profits; practicing nutrient management and not polluting; using only native species and/or strains; and modeling stewardship and innovation for local and global communities. Restorative aquaculture farms that meet these principles would be considered Ecological Aquaculture farms.

Ecosystem Approach to Aquaculture

The Ecosystem Approach to Aquaculture (EAA) is defined as "a strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems" (FAO, 2010). EAA focuses on human well-being, environmental well-being, and effective governance to be able to prioritize both while developing aquaculture. While EAA does has a focus on environmental effects, it is often described as focusing on “how” rather than “what.” EAA is a detailed process and strategy for governments and aquaculture industries to follow that has stakeholder engagement at its core. Restorative aquaculture could be incorporated into an EAA approach.

Conservation Aquaculture

Conservation aquaculture has been defined as the “use of aquaculture for conservation and recovery of endangered fish populations” (Anders, 1998). Examples of conservation aquaculture include hatchery efforts to rebuild threatened or endangered strains of Pacific salmon, endangered abalones in California, and Olympia oysters on the northwest coast of North America. There is also a related term of conservation hatchery - the rebuilding of stocks in a way that intentionally limits genetic and ecological impacts on wild stocks (Flagg & Nash, 1999). Conservation aquaculture differs from restorative aquaculture in that the primary aim of conservation aquaculture efforts is focused on recovering or rebuilding specific species. Additionally, conservation aquaculture has typically not involved the direct commercial sale of the cultured organism. Froehlich, Gentry and Halpern (2017) present an expanded, “redefined” definition of conservation aquaculture as “the use of human cultivation of aquatic organisms for the planned management and protection of a natural resource” and includes not only species-level rebuilding but also an ecosystem services view. Froelich’s et al.’s expanded definition of conservation aquaculture has some overlaps with the definition of restorative aquaculture, particularly in the context of extractive species. Conservation aquaculture and restorative aquaculture could be shared and interconnected activities within a waterbody or system—for example, in cases where commercial aquaculture of native bivalves (e.g. Olympia oysters) that is restorative to the marine environment relies upon the same hatchery infrastructure that is used for conservation aquaculture of that species; both activities could contribute to the same environmental goals of improving water quality and providing habitat.

Stock Enhancement

From a fisheries point of view, the goal of stock enhancement is “to increase stock size, and thereby fishable stock” (De Silva, and Funge-Smith, 2005). The purpose of stock enhancement is to maintain fishery productivity at a rate that supports capture activities. This is done through the supplementation of fishery stocks using cultured fish. Stock enhancement activities can be a single event or an ongoing effort. The emphasis on maintaining stocks to support capture fisheries differentiates stock enhancement from restorative aquaculture and conservation aquaculture, neither of which is explicitly, or solely intended to supply or supplement stock for capture fisheries.

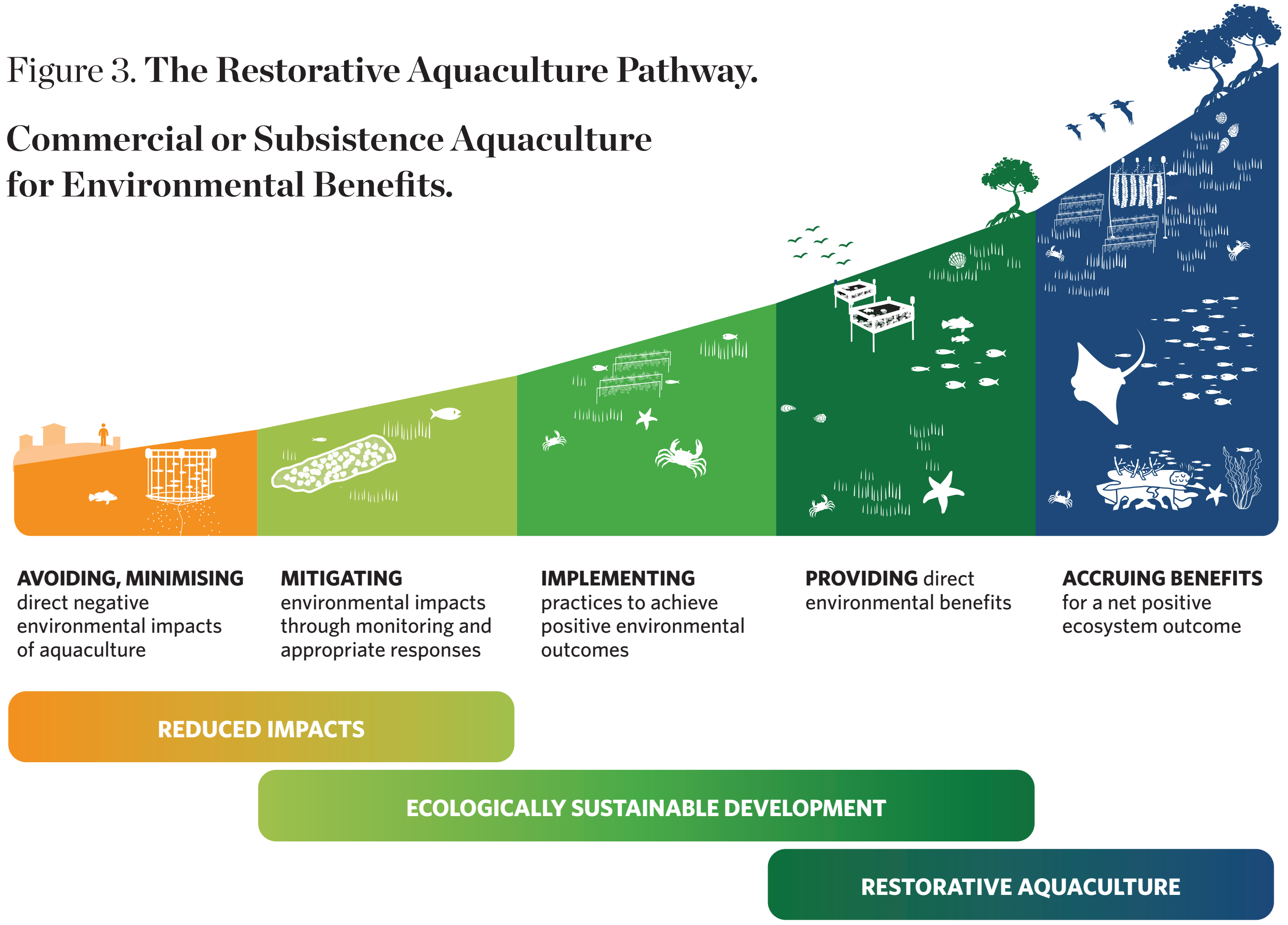
However, Lorenzen *et al.* (2010) discusses how enhancement from a biological perspective can lead not only to increased yield for capture fisheries, but aid in the conservation and rebuilding of populations and/or help mitigate habitat or other losses of fishing. Under this definition, there is an overlap with conservation aquaculture and could be an overlap with restorative aquaculture, if the stock enhancement was commercial or subsistence and provided a direct environmental benefit to the waterbody.

Aquatic Habitat Restoration

Restoration ecology has been defined as “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed” (Society for Ecological Restoration International Science & Policy Working Group, 2004). Specifically, restoration of marine and coastal habitat is defined as needing to occur “once critical habitat has been lost, or the functioning of those areas diminished” (U.S. Commission on Ocean Policy, 2004). Aquatic restoration activities are often funded through philanthropic or government support and can be implemented at a variety of scales, using any number of tools to meet the end goal. While restorative aquaculture can be one of the tools used in broader restoration initiatives, it is not necessarily used in aquatic restoration. Therefore, the outcomes from aquatic restoration and restorative aquaculture can overlap, but aquatic restoration does not always use restorative aquaculture as a tool for environmental restoration.

Figure 3. **The Restorative Aquaculture Pathway.**

Commercial or Subsistence Aquaculture for Environmental Benefits.



Nature-Based Solutions

Nature-Based Solutions is a relatively new term encompassing multiple practices in terrestrial agriculture and ecology. One of the most frequently used definitions of Nature-Based Solutions has been promoted by the IUCN as "actions to protect, manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN, 2020). While the concept of Nature-Based Solutions has been frequently applied in terrestrial agriculture, the extension of these concepts to aquatic food production has not been fully developed. Restorative aquaculture has important synergies with conservation objective and Nature-Based Solutions (Le Gouvello, Brugere and Simard, 2021). It employs similar environmental concepts and objectives and can be considered a part of the Nature-Based Solution framework (Figure 4).

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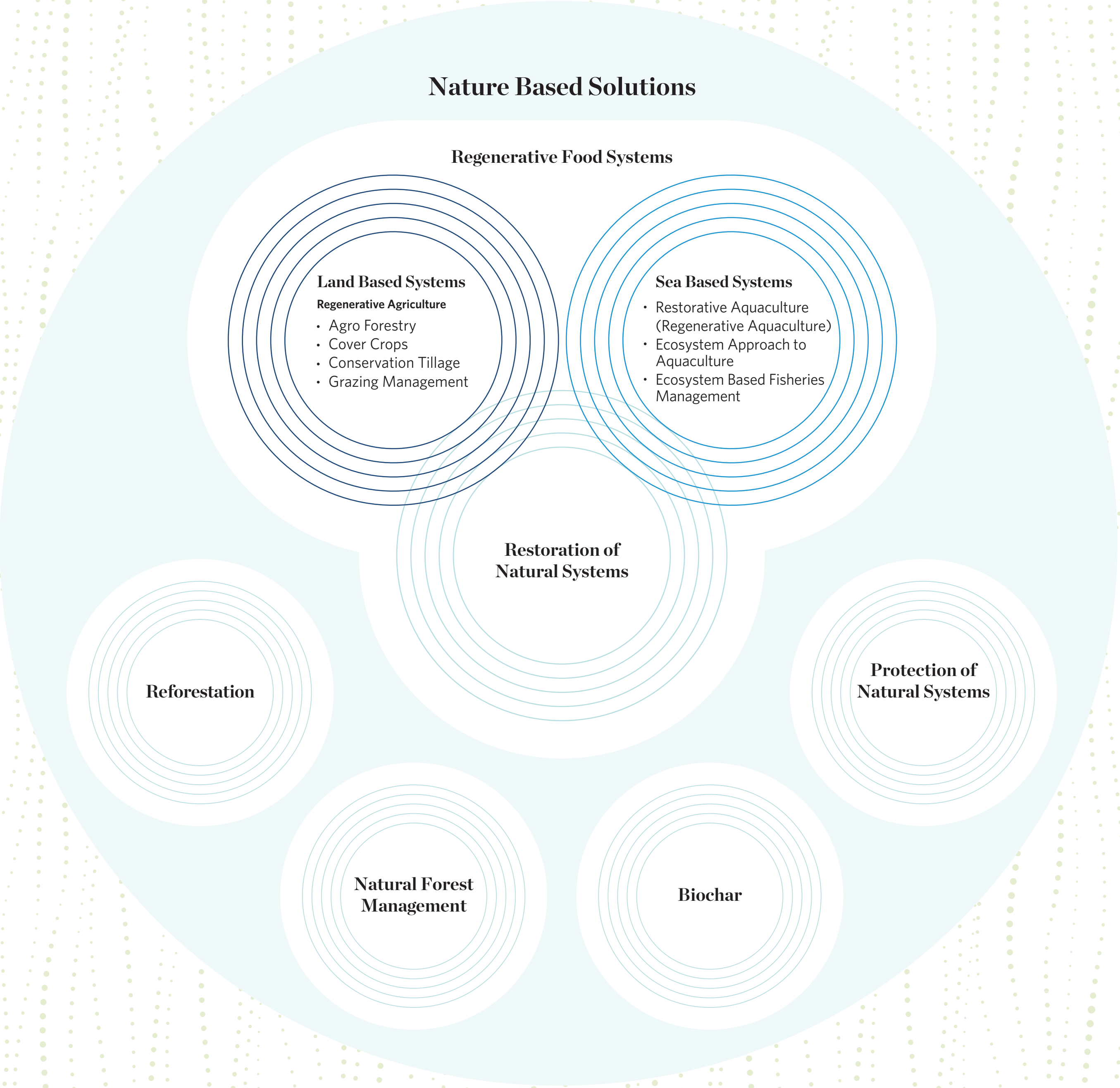
Figure 4. **Conceptual Diagram of Restorative Aquaculture as a Nature-Based Solution and Regenerative Food System.**

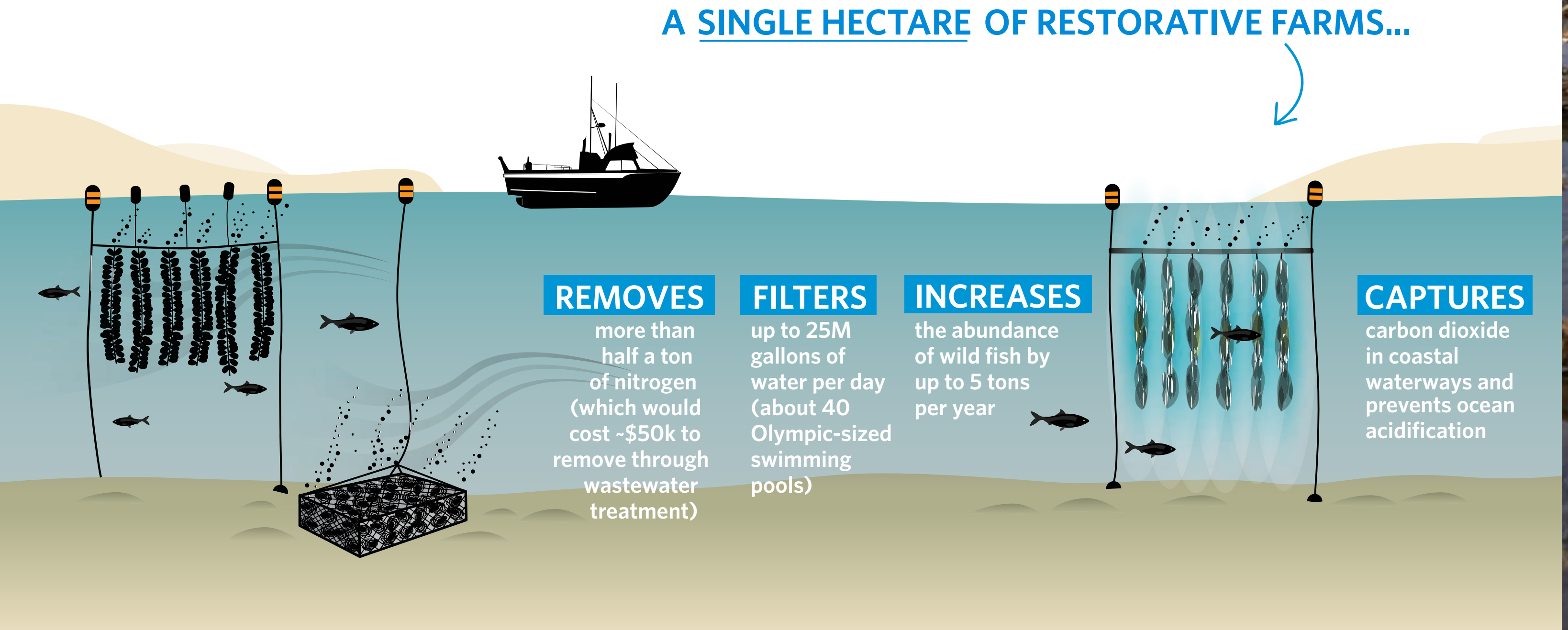


Environmental Benefits of Restorative Aquaculture

Aquaculture can provide multiple types of benefits to aquatic environments under the right conditions. Using the Economics of Ecosystems and Biodiversity Framework, Alleway *et al.* (2018) identified the potential benefits of marine aquaculture to provide ecosystem services of provisioning, regulating, habitat or supporting, and cultural. Here, a simplified framework is used to define the most likely environmental benefits from restorative aquaculture, categorizing these benefits in three distinct areas: water quality, habitat provision, and climate (Figure 5).

Water quality benefits and habitat provision are the two environmental benefit categories that are the most well supported in the scientific literature and currently have the best available knowledge associated with positive ecosystem outcomes. Carbon sequestration and ocean acidification buffering are also discussed due to the potential for restorative aquaculture to provide these climate adaption and mitigation benefits (Figure 5). That stated, the climate benefits of restorative aquaculture are currently less scientifically supported in the literature than nutrient removal or habitat provisioning (Figure 6; Gentry *et al.* 2020).

Figure 5. **Environmental Benefits of Restorative Aquaculture.**



It is expected that the environmental benefits of water quality, habitat provision, and climate and the overall benefit categories will be expanded and modified as more information becomes available. While these benefits can be accrued, aquaculture can also have adverse effects on ecosystems in these same categories. The drivers of these benefits or impacts are identified and discussed in following sections.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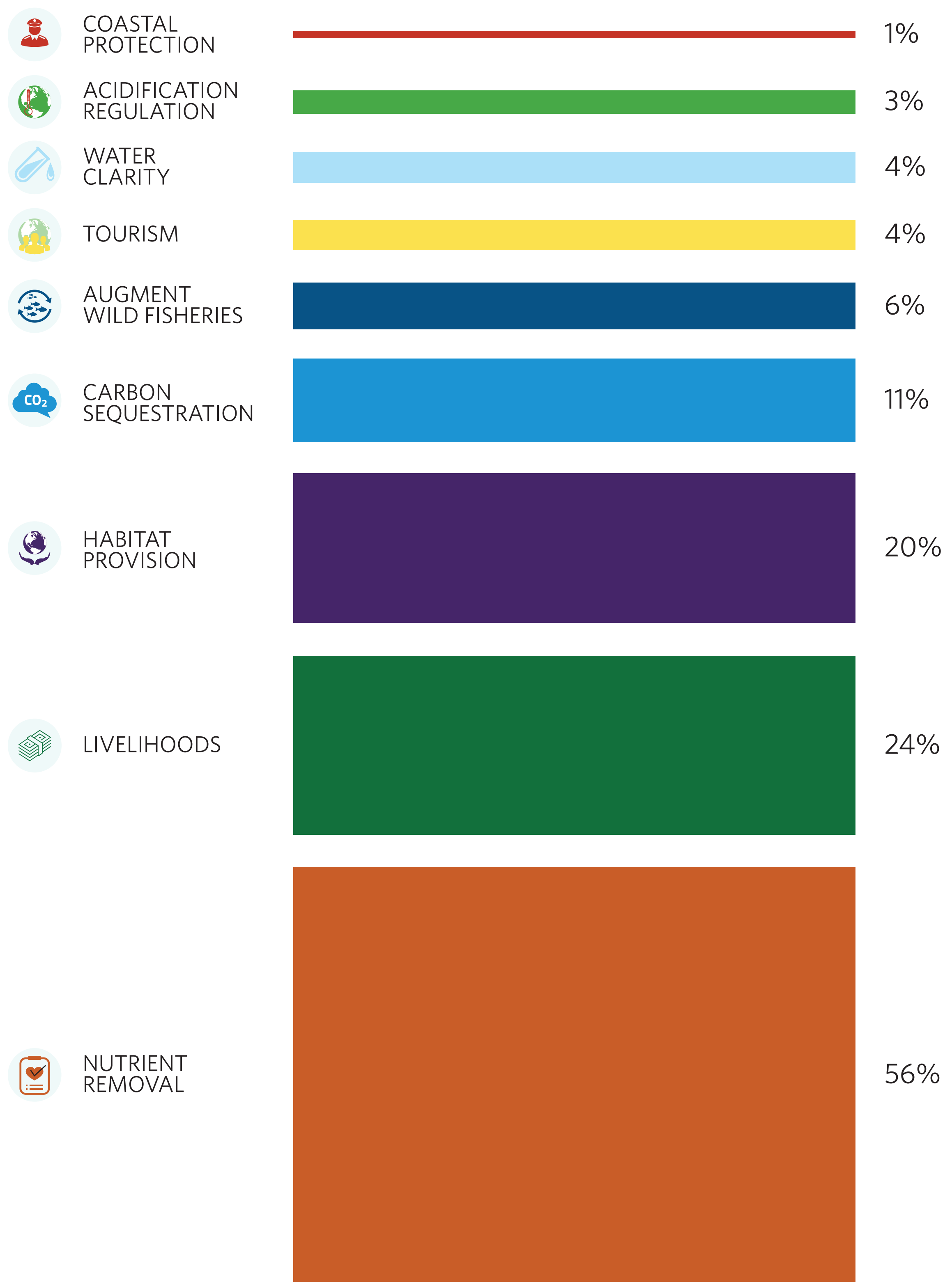

Figure 6. **Figure Derived from Gentry *et al.*, (2020); Proportion of Studies Documenting Positive Effects of Mariculture on Each Type of Ecosystem Service.**

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Water Quality

Aquaculture has the potential to improve nearshore water quality through filtration of water and suspended material, and enhanced cycling of nutrients. In particular, bivalves and seaweeds can often improve nearshore water quality at various scales, because species can remove nutrients (including nitrogen, phosphorous) via uptake in tissue and shell, which is then removed from the water body during harvest (Petersen, *et al.*, 2019, Racine, *et al.*, 2021, Xiao, *et al.*, 2017). Bivalve aquaculture may result in additional removal of nitrogen through the process of denitrification (Humphries *et al.*, 2016; Ray and Fulweiler, 2021). Additionally, bivalves contribute to water clarity, by filtering organic and particulate matter from the water column. These processes can help mitigate anthropogenic impacts on water quality and lower the likelihood of eutrophication (Bricker, Rice and Bricker, 2014; Rose *et al.*, 2014).

Eutrophication remains a primary issue for the health and productivity of many coastal and freshwater habitats. Improved water quality and clarity provides direct benefits to local water bodies and can lead to positive outcomes for natural habitats, including important nursery areas and blue carbon habitats such as seagrass. Some species can also play a role in regulating water quality through trophic interactions. For example, bivalves are used in integrated systems to reduce particulate matter from finfish waste, and herbivorous finfish species can play a role in regulating microalgae and phytoplankton that can lead to algal blooms and decreased oxygen in water bodies (e.g. Petersen *et al.*, 2016; Petersen, *et al.*, 2019).


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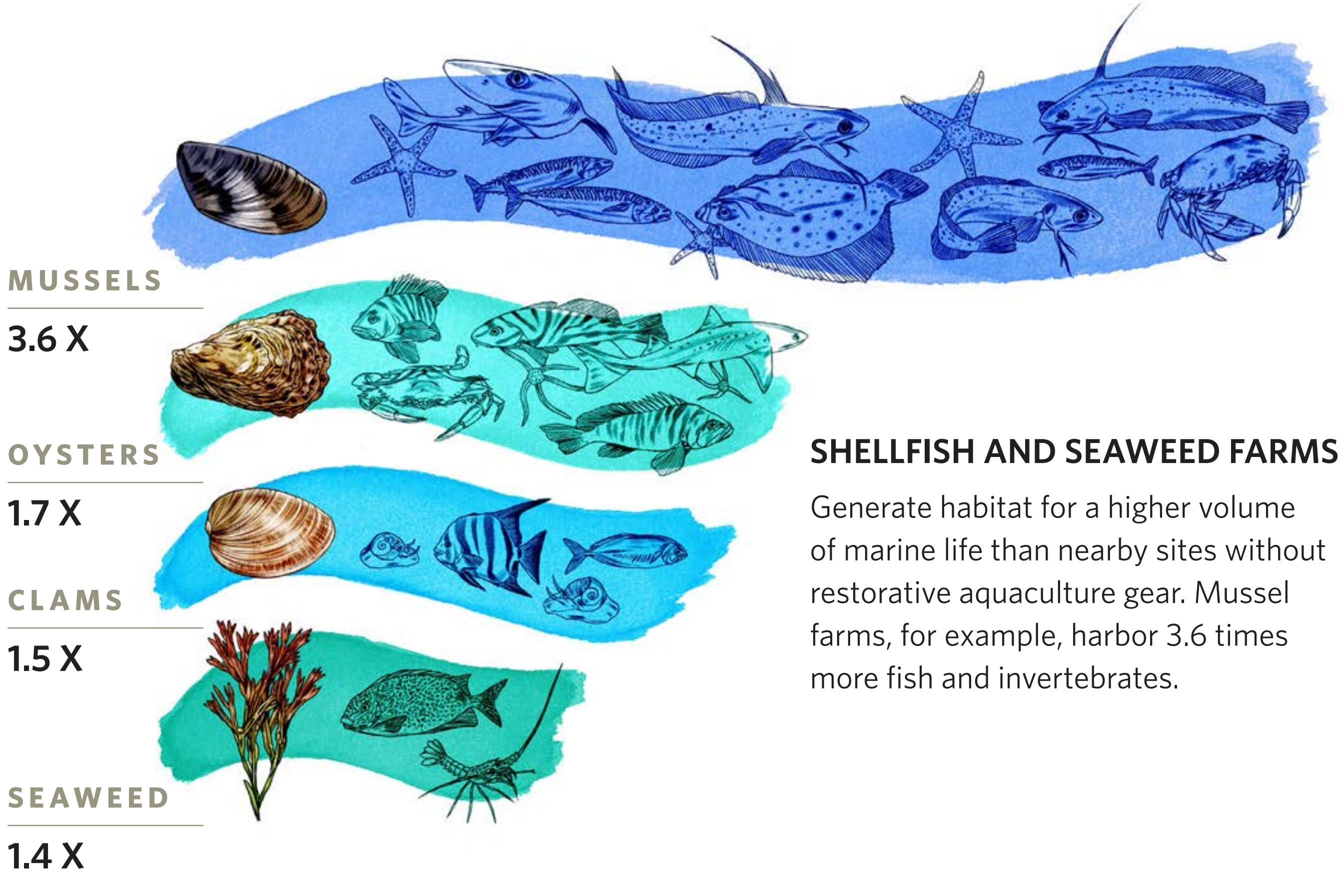
Habitat Provision

Aquaculture gear and the organisms cultivated on and within them can provide three-dimensional structured habitat that can benefit fish and invertebrates. Farms can provide refugia for juvenile fish and invertebrates, functioning in a similar way to natural nursery grounds (Costa-Pierce and Bridger, 2002; Barrett, Swearer and Dempster, 2019). In addition, aquaculture organisms and biofouling communities associated with farms can provide food resources (Kawai *et al*., 2021). In a global review of 65 studies, higher fish abundance and diversity were generally associated with bivalve and seaweed farms than nearby reference sites (Theuerkauf *et al*., 2021).

The effect on the productivity of wild marine species due to aggregation versus recruitment and subsequent enhancement of populations varies, however there is evidence of increased production due to the presence of aquaculture facilities (Tallman and Forrester, 2007). The three-dimensional structure of aquaculture can also stabilize soft sediment, helping to reduce erosion or the impacts of extreme weather events (e.g. Zhu *et al*., 2020). Spawning aquaculture stock can 'spill over' to wild populations, and while this effect has the potential to cause significant genetic diversity and/or local adaptation impacts on local populations, there is evidence that under the right circumstances, it can provide a beneficial subsidy to impacted populations, or stock enhancement for restoration efforts (Norrie *et al*., 2020). The localized effects of reduced acidification and temperature created by seaweed farms can be beneficial to the provision of effective habitat (e.g. a refuge; Xiao *et al*., 2021).

Figure 7. **Underwater Abundance.**



SHELLFISH AND SEAWEED FARMS

Generate habitat for a higher volume of marine life than nearby sites without restorative aquaculture gear. Mussel farms, for example, harbor 3.6 times more fish and invertebrates.

Climate Mitigation and Adaptation

Wild kelp forests play a key role in carbon regulation and sequestration (Queirós *et al.*, 2019). Consequently farming seaweed as a means to capture carbon and sequester CO2 has been proposed as a climate mitigation strategy (e.g. Froehlich *et al.*, 2019). Cultured seaweed requires comparatively few carbon emissions to produce and through the process of photosynthesis, captures carbon dioxide. However, the contribution of seaweed to carbon sequestration is dependent on the fate of the seaweed biomass, either through latent transport (e.g. breakage of fronds and their transfer into deep-sea sediments; (Duarte *et al.*, 2017) and to coastal blue carbon habitats (Ortega, *et al.*, 2019), or through the intentional use of harvested biomass to provide carbon benefits via end products, such as biochar and biofuels (Jones *et al.*, 2021). While climate science related to seaweed aquaculture is in a nascent stage, enhancing the potential of seaweed aquaculture to play a role in sequestering carbon could potentially be achieved through siting aquaculture operations to interact in a positive way with the transport of organic and particulate matter into near and offshore ocean sediments, where it can be sequestered long term. Carbon can be more readily traced in nearshore environments; a dynamic that should be taken considered in evaluating the potential for restorative aquaculture to provide benefits for climate mitigation.

The use of restorative aquaculture to improve water quality in nearshore areas for the purpose of supporting the preservation or recovery of blue carbon habitats (i.e.. halting the loss or supporting recovery of seagrass, mangrove and saltmarsh habitats), may be a valuable climate mitigation tool. At a local scale, seaweed aquaculture may also reduce the impacts of ocean acidification by increasing the aragonite saturation level (Mongin *et al.*, 2016), fostering biodiversity, and contributing to climate adaptation (Xiao, *et al.*, 2021).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The capacity of bivalve aquaculture to remove carbon captured in shells through harvesting has also generated interest as a carbon sequestration strategy (Filgueira, Strohmeier and Strand, 2019). However, some research shows bivalve respiration and calcification collectively release more CO2 than their shells sequester (Ray *et al.*, 2018), resulting in increased atmospheric release of CO2 from the sea (Han, *et al.*, 2017). Therefore, while there may be short mitigation outcomes in some circumstances (Thomas *et al.*, 2021) bivalves appear to be net producers of coastal CO2 (Munari, Rossetti and Mistri, 2013; Fodrie, *et al.*, 2017), and their potential to directly contribute to sequestration of carbon is therefore currently limited (Munari, Rossetti and Mistri, 2013). However, the role of bivalve aquaculture in effecting environmental processes could result in benefits that do support carbon sequestration, such as improvements in water clarity that support expansion of the health of blue carbon habitats.

Example Indicators of Environmental Benefits

Monitoring and development of targets is essential for measuring how restorative aquaculture can deliver environmental benefits. While not exhaustive, a number of indicators to measure and track environmental outcomes exist, largely applicable at a farm scale (Table 1). As the restorative aquaculture science continues to build and expand, it will be important to develop indicators at successive scales to assist farmers and government to engage with restorative aquaculture, and establish local, regional, or national targets, and measures of success.

While restorative aquaculture can provide these benefits, aquaculture can also result in negative impacts in these categories and thus these potential key indicators should be monitored for both positive and negative effects. The drivers of these benefits or impacts are identified and discussed more thoroughly in the following section.

Table 1. **Examples of Potential Key Performance Indicators at a Farm Scale Currently Available to Develop Targets and Monitoring for Environmental Benefits from Restorative Aquaculture.**

TYPE OF BENEFIT	POTENTIAL KEY INDICATORS
WATER QUALITY	• Kg of excess nitrogen and phosphorous and suspended solids removed • Liters of water filtered • Kg of excess organic material in sediments reduced
HABITAT PROVISION	• Farm area • Fish and invertebrate abundances (relative and in total quantity)
CLIMATE MITIGATION AND ADAPTATION	• Kg of CO2 and N sequestered (mitigation) • Variation in ocean acidification

Culture Environment, Models, and Species

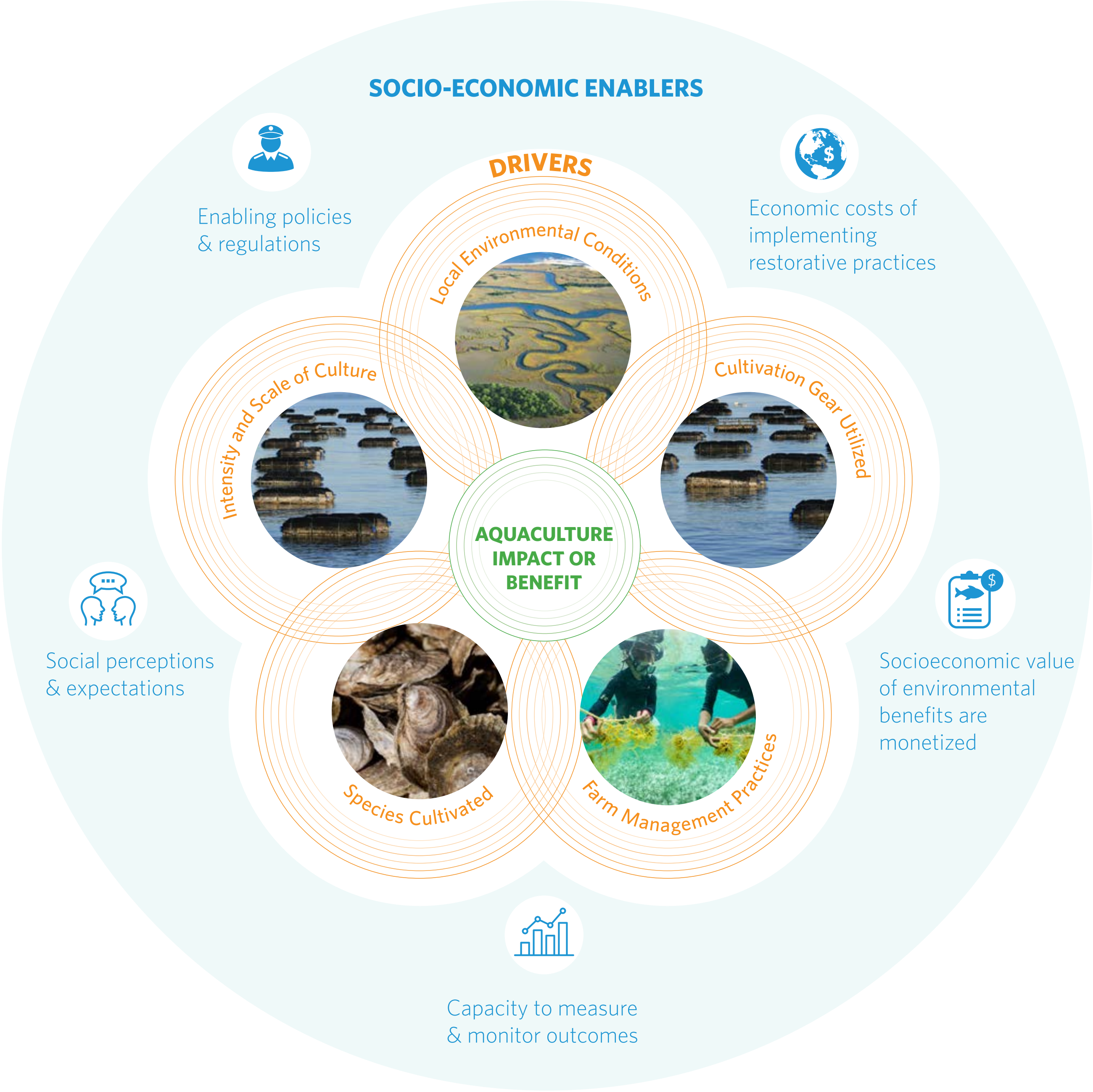
Restorative aquaculture can take place in marine, freshwater, or brackish water environments, and in a large number of aquaculture sectors.

This document largely focuses on the aquaculture sectors that require a lesser degree of inputs (e.g. no supplementary feeding) and extractive species, in particular bivalves and seaweed. However, many of the benefits and drivers discussed here are applicable to practices in all aquaculture sectors. For example, shrimp aquaculture that targets a benefit to mangrove rehabilitation may be an opportunity for restorative aquaculture in the future.

Importantly, while restorative aquaculture, by nature of the term, could be interpreted to apply only to degraded ecosystems, we do not intend for this concept to be exclusive to water bodies that display this condition. While restorative aquaculture in degraded areas could be expected to yield more significant environmental benefits, restorative practices are also applicable to undegraded areas because these practices could enhance the resilience or productivity of local environments.

The environmental benefits of restorative aquaculture are the result of several driving factors, including the intensity and scale of culture, the type of farming gear used, farm management practices, the species cultivated, and local environmental conditions. These driving factors are often interacting, and their significance may vary across time for a specific site, and across sites and geographies based on the importance of the different factors to different farming species (Figure 8).

Figure 8. **Drivers and Enablers of Restorative Aquaculture** (Derived from Theuerkauf *et al.* 2021).



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Species and Culture Models

Species

Bivalves and seaweed are two species groups with the clearest potential for restorative aquaculture, based on a growing body of supporting scientific literature, particularly as studied in eutrophic and habitat degraded systems. However, while there is currently less scientific literature available on other species, other organisms with the potential to provide direct ecological benefits will also undoubtedly be valuable to this concept and the provision of net environmental benefits. For example, sea cucumbers, sponges, snails, abalone, and sea squirts play important environmental roles in natural ecosystems and could provide restorative benefits in farmed settings. Additionally, as evidenced by Case Study 3 later in this document, the culture of extractive / non-fed finfish species that consume microalgae can mitigate algal blooms and provide positive water quality outcomes.

Culture Models

A range of modes and models of aquaculture exist that can generate restorative outcomes. These models include basic monocultures, polyculture, and solutions that adopt a circular approach. For example, a cradle-to-gate assessment of the use of marine biomass produced through mariculture can contribute to the mitigation of eutrophication and climate impacts, as they can capture excess phosphorous and recirculate this otherwise limiting nutrient for human consumption (Thomas, *et al*, 2021).

Polyculture or co-culture of seaweed and bivalves that provide environmental benefits could be considered restorative aquaculture, given the potential to generate a net positive outcome. Integrated multi-trophic aquaculture (IMTA) is an aquaculture system that most often combines fed aquaculture species (e.g. finfish), with extractive species such as seaweeds and bivalves (Troell *et al.*, 2009). The incorporation of extractive species in IMTA is primarily conducted as a way to mitigate the impacts of finfish culture, rather than to provide a net positive benefit to the environment. For this reason, while IMTA may be more ecologically desirable than a finfish monoculture in some cases, if practiced solely to reduce waste from finfish farming, it does not closely align with the intent and definition of restorative aquaculture.

Timescale of Influence

Environmental benefits might be provided by restorative practices immediately or through incremental and cumulative effects over time. How these benefits amass will be dependent on the driving factors described above (Figure 7). While some benefits may occur instantaneously (e.g. the provision of habitat for wildlife), others will take time to accrue (e.g. recruitment of wildlife and recovery of stocks from the provision of habitat). The definition of restorative aquaculture we provide acknowledges that an overall or net positive effect may take time to achieve by describing the "potential" for an outcome to be provided.

Practitioners and Intent

Restorative aquaculture places emphasis on commercial or subsistence aquaculture activities, which are led by the private sector, individuals, and communities. These activities often require permits from governing regulatory agencies, who are also typically responsible for broader aquaculture policies, industry planning, and zonal management. Regulatory agencies therefore, can play a key role in facilitating restorative aquaculture, if concepts are incorporated into regulatory policy.

In this definition of restorative aquaculture, intentionality on the part of the implementing party does not matter. A farmer or regulatory agency may have created or enabled a farm or industry that results in restorative outcomes regardless of whether they intended to or not. Restorative aquaculture refers to the effect the farm has on the environment, rather than the intent behind the design of the farm.

Spectrum of Restorative Benefits

It is acknowledged that restorative aquaculture is context-specific and is, therefore, difficult to generalize. Some farms may provide more restorative benefits than others, both in absolute terms and in their effect on ecosystem recovery. For example, a farm that produces and harvests more bivalve shellfish could be considered to have a greater restorative benefit than a smaller farm in the same water body, due to the comparative levels of nitrogen that are removed, all else being equal. Similarly, a farm sited in an area suffering from anthropogenic eutrophication could be considered having a greater restorative effect than a farm that is sited in an area where eutrophication is less severe, all else being equal. Yet, in principle, each of these farms could be considered restorative, so long as there are direct ecological benefits provided with the potential for a net positive environmental outcome to the water body.

Determining the local implications of aquaculture (both positive and negative) and what therefore constitutes a net positive outcome will be dependent on local environmental conditions, as well as shared agreements by relevant stakeholders on values for local ecosystems and the outcomes that can, and cannot, be achieved. Additional discussions on the shared benefits and potential trade-offs between different approaches will be needed as more locations and regions seek to derive benefits from regenerative food practices. These discussions will need to consider a range of local implications that are not discussed here, such as how farmers may be able to collectively contribute to benefits, or what support may be required to increase or maximize the benefits from restorative aquaculture activities without loss of revenue, including if there is a need to subsidize environmental outcomes using public funds.

As discussed, there is evidence that aquaculture can provide restorative benefits in the categories of water quality, habitat, and climate (see section Environmental Benefits of Restorative Aquaculture). However, for aquaculture to be considered restorative, all three types of benefits do not need to be "optimized" or "maximized". Benefits can occur to different degrees; one farm may provide benefits across all three categories each to a lesser degree, while another farm may provide one type of benefit to a greater degree.

Due to local environmental conditions and environmental priorities, it may be more important to prioritize one type of restorative benefit over another. For example, in a water body that suffers from eutrophication, water quality improvements may be an objective for resource managers and the community. Restorative aquaculture in this location could prioritize meeting the nutrient removal needs of the water body, i.e. choosing not to "optimize" across all types of benefits but instead focusing on providing net positive benefits for water quality.

Weighing Benefits and Impacts

All human activities have effects on natural systems, positive and/or negative. While restorative aquaculture provides benefits in some impact areas, it is also foreseeable there will be negative impacts in others. Some of the potential negative effects associated with bivalve and seaweed aquaculture, despite the positive effects they can provide, can include the potential for: impacts to submerged aquatic vegetation through shading from infrastructure or displacement and disturbance by operations, introduction of invasive species, genetic impacts on wild stocks, plastic pollution, and/or cumulative impacts to natural habitats and species if exceeding the carrying capacity of a water body (FAO, 2010; Ferreira *et al.*, 2008; Byron *et al.*, 2011). These impacts may occur on the same farms that deliver benefits for water filtration, habitat, or climate. While it is difficult to compare environmental effects against one another, steps can be taken to minimize, and if possible, avoid negative impacts entirely.

Restorative aquaculture must provide direct ecological benefits and have the potential to provide net benefits to the ecosystem. This logically requires that farmers make efforts to avoid, eliminate, or mitigate any potential negative impacts of their farming operation, such as those associated with gear, operations, and harvest. While the Principles and Roadmaps describe the concept and provide general direction on impacts to avoid and the benefits of restorative aquaculture, the benefits and impacts of restorative aquaculture in practice must be considered within the local context.

Restorative aquaculture should be considered as a component of aquaculture planning and management by government and regulatory authorities. Moving beyond the prevailing environmental framework for aquaculture that primarily focuses on reducing negative impacts and environmental risk management to a view that incorporates and promotes environmental net benefits can help improve the health of aquatic environments while also providing food for a growing population (see section Considerations for Policy and Management of Restorative Aquaculture).

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Global Principles of Restorative Aquaculture

To support effective and consistent implementation of restorative aquaculture, guidance is needed on the definition, drivers (Figure 8), and restorative practices that can provide environmental benefits. With greater attention on regenerative food systems and restorative aquaculture, there is also the risk that increased demand could lead to misuse of the term and its intent. Describing the Principles for restorative aquaculture can create parameters around expectations and support a common understanding that will assist industry, government, and public to benchmark progress.

> **The Principles established here reflect the driving factors that influence whether aquaculture is likely to provide restorative environmental benefits: the intensity and scale of culture, culture gear, farm management practices, species cultivated, and local environmental conditions.**

Inherent in each Principle is the expectation that negative impacts from aquaculture must be minimized and mitigated. While restorative aquaculture could provide considerable benefits to local and regional environments there remains a risk of negative impacts. An improved or net positive outcome cannot be achieved if environmental benefits are provided at the expense of impacts on natural habitats, species, ecosystem functions, and the cultural and economic opportunities they support for communities. Key examples include inappropriate siting of aquaculture operations or the use of non-native or invasive species that present biosecurity or genetic risk for surrounding ecosystems and wild populations.

Furthermore, because restorative aquaculture will often be linked to the production of food, farming of products that are specifically intended to provide food in areas where ecosystem water pollution occurs must be coupled with approaches to assure food safety.

Principle 1: Site farms where environmental benefits can be generated

The siting of a farm will significantly affect its ability to create net benefits for the environment. For example, siting a farm in an area where fish stocks face habitat limitations could have substantially greater environmental value than a farm sited in areas where wildlife is not limited by the availability of natural habitats. Similarly, a nutrient-extractive farm that is sited in a known eutrophic area will likely have greater water quality benefits than a farm sited in an area not experiencing nutrient pollution. To increase the opportunity for restorative aquaculture to generate the environmental outcomes intended, farms should seek to be sited in areas that can generate the services that are needed.

While it could be interpreted that restorative aquaculture is therefore only relevant to degraded ecosystems where remedial benefits can be applied, restorative practices are also relevant to undegraded areas where these practices can increase the resilience or productivity of local environments. Farms sites should be selected so as to not generate significant and/or ongoing negative impacts on natural habitats.

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Principle 2: Culture species that can provide the environmental benefits intended

The species cultivated will be a significant driver of the type of benefit that can be generated by a restorative aquaculture approach. While having a similar ecological role, different culture species are characterized by differing growth, filtration, and recycling and nutrient uptake rates (in the case of extractive species). Also, aquaculture farms can provide habitat benefits for species in the local area, but the species group, habitat preferences, morphology, life history, and other factors can influence the nature and scale of habitat benefits that are provided.

Species that will provide the greatest restorative benefits will typically be native, but it is recognized that local socio-environmental values, as well as the needs of a water body, play an important role in determining the environmental benefits that are needed, and that non-native species may play a role in providing these benefits. If non-native species are used, these species should already be present in the water body (i.e., naturalized). Alternatively, measures such as the culture of triploid organisms may be an appropriate mitigation measure to ensure new species or population introductions to the wild do not occur. Biosecurity measures are also critical to ensure culture operations do not introduce diseases or hitchhike species into waterbodies.

Principle 3: Prioritize farming equipment that enhances the delivery of environmental benefits

Cultivation methods including gear and supporting structures can increase foraging, breeding, and refuge habitat for wild fish and other species. For example, the culture of bivalves can create supplemental structure, mimic natural bivalve habitats, and facilitate the recruitment of wild seed. Cultivation gear that includes nets or other mesh material can serve as protection from predators for juvenile fish and can increase the abundance of species around the aquaculture site. Suspended culture, such as longline seaweed cultivation or mussel longline gear can provide a canopy that serves as a habitat for wild fish and invertebrate species. Gear that presents a risk of detrimental impacts on wildlife, such as gear that poses high entanglement risk, should be avoided. Further, styrofoam and other inappropriate plastics that degrade and result in known adverse effects on aquatic environments prior to being removed should be avoided.

Principle 4: Adopt farming management practices that can enhance local environmental benefits

Management of the installation, ongoing operation and maintenance, and removal of aquaculture at the end of seasons or harvest periods will influence their ability to provide benefits to the surrounding ecosystem. Timing of construction, seeding and harvesting, maintenance, and the configuration of the site will all influence the ability of an operation to result in a net benefit or negative impacts. Practices that are known to harm water quality and/or habitat include the use of chemicals or therapeutics, regular disruption of submerged aquatic vegetation or other habitats, and inappropriate maintenance that may result in breakaway gear.

Principle 5: Strive to farm at an intensity or scale that can enhance ecosystem outcomes

In order to result in a net benefit to the ecosystem, restorative aquaculture should ideally occur at a scale and intensity that takes into account the needs of the water body while avoiding seasonal or cumulative negative effects. This will require the development of an approach that balances the scale of cultivation necessary to create the desired benefit within the carrying capacity of the water body, taking into account water residence time, existing nutrient levels and loading rates, benthic composition, and predator-prey dynamics of the ecosystem. As a restorative effect is achieved, through water filtration or nutrient absorption and recovery of natural functions and habitat, the intensity and scale of culture may need to be revised. Farming of extractive species at volumes above the carrying capacity of the water body could result in negative impacts on water quality and the ecosystem and should be avoided.

Principle 6: Recognize the social and economic value of the environmental benefits provided

In addition to these five Principles, which are focused on guiding aquaculture operations within the local environmental context to deliver restorative aquaculture outcomes, and can be influenced by the activities of farmers, the broader socio-economic opportunities associated with restorative practices should be considered. Restorative aquaculture should be economically viable and feasible to implement for the benefit of operators, individually or collectively. It should also seek to also return social and economic benefits to communities, including opportunities for livelihoods. Commercial aquaculture can often be constrained by societal concerns and competition for space or resources. Where they occur, the environmental benefits of aquaculture should be supported through the development of relevant policy and regulation. Market-based mechanisms that foster socio-economic outcomes from restorative aquaculture practices, such as payment for ecosystem services, could be an important means to support widespread implementation of restorative practice and outcomes. Making the potential effects of restorative aquaculture more broadly known could also support greater impact investments into this industry, which could help support farmers in overcoming technology or operational barriers to scaling restorative practices.

Each of the Principles has differing relative effects on each type of potential restorative benefits. The table below outlines the relative potential for each combination of benefits and drivers to provide restorative benefits (Table 2).

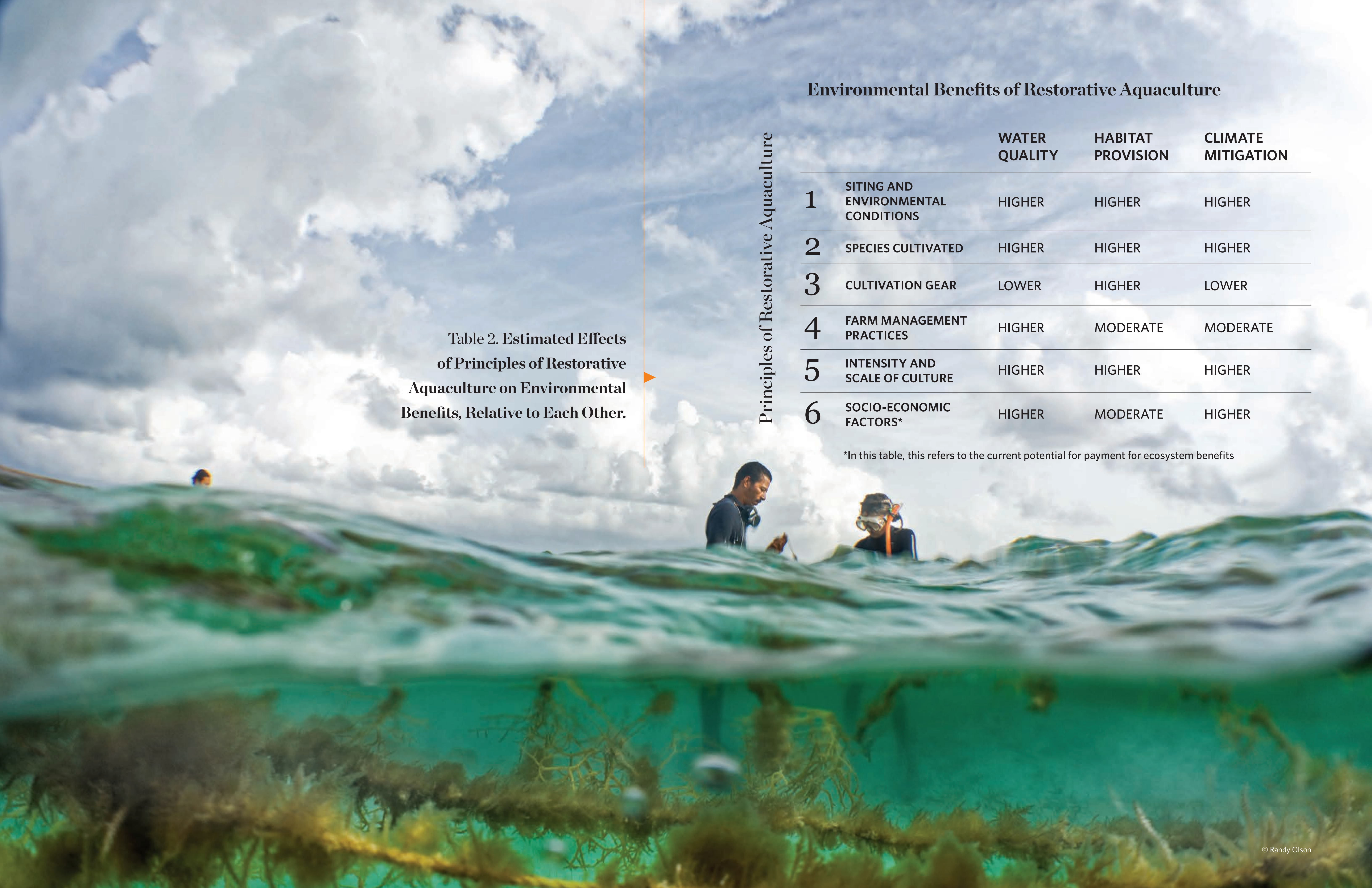

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Table 2. **Estimated Effects of Principles of Restorative Aquaculture on Environmental Benefits, Relative to Each Other.**

Environmental Benefits of Restorative Aquaculture

	Principles of Restorative Aquaculture	WATER QUALITY	HABITAT PROVISION	CLIMATE MITIGATION
1	SITING AND ENVIRONMENTAL CONDITIONS	HIGHER	HIGHER	HIGHER
2	SPECIES CULTIVATED	HIGHER	HIGHER	HIGHER
3	CULTIVATION GEAR	LOWER	HIGHER	LOWER
4	FARM MANAGEMENT PRACTICES	HIGHER	MODERATE	MODERATE
5	INTENSITY AND SCALE OF CULTURE	HIGHER	HIGHER	HIGHER
6	SOCIO-ECONOMIC FACTORS*	HIGHER	MODERATE	HIGHER

*In this table, this refers to the current potential for payment for ecosystem benefits

Roadmaps for Using Restorative Aquaculture to Meet Environmental Goals

The determination of whether an aquaculture operation results in a net benefit to the ecosystem can be an exhaustive process involving a high level of resources. The roadmaps in this document provide a tool for determining the likelihood that an aquaculture operation has specific benefits, and could be considered restorative. These tools can be applied to aquaculture operations at various scales, from the farm level to seascape and ecoregion scales.

In addition to providing a tool for farmers, coastal managers, and other potential stakeholders to determine the likelihood of benefits from an aquaculture operation, these roadmaps can provide insight into where further research will likely be needed to scientifically describe the degree of benefits.

Roadmaps are available for each type of benefit that is outlined, as a restorative aquaculture operation may not provide all types. Furthermore, resource managers in a given location may have environmental goals for a water body, sediment, and/or biosystem that relate to one, or a subset, of the types of benefits. Here, we outline four environmental benefit roadmaps for water quality, habitat, carbon sequestration, and ocean acidification buffering. However, the questions within each roadmap and the environmental benefit categories themselves are not exhaustive and, as the science continues to progress, additional questions and other environmental benefit categories and roadmaps can be developed, such as biodiversity or sediment/substrate health.

Additionally, the roadmaps are specific to the environmental benefit one is seeking and only identify the primary negative and positive impacts for that specific environmental benefit category. For example, the questions within the water quality roadmap concentrate only on water quality impacts and benefits and do not include questions and factors that are specific to habitat impacts or provisioning. However, in order to have the potential for net environmental benefit to the water body, all farming operations should make efforts to avoid, eliminate, or mitigate any potential negative impacts of their farming operation, whether those be associated with water quality, habitat, biodiversity, etc.

Each roadmap asks a series of Yes/No questions, guiding the user toward the likelihood of restorative benefits based on the responses. Users are to begin at the bottom and work their way up until the roadmap directs them to a final "Not likely restorative", "Potentially restorative/needs more research", or "Most likely restorative" outcome. Further explanation for each question in the roadmaps, as well as resources, are provided in the guidelines below.

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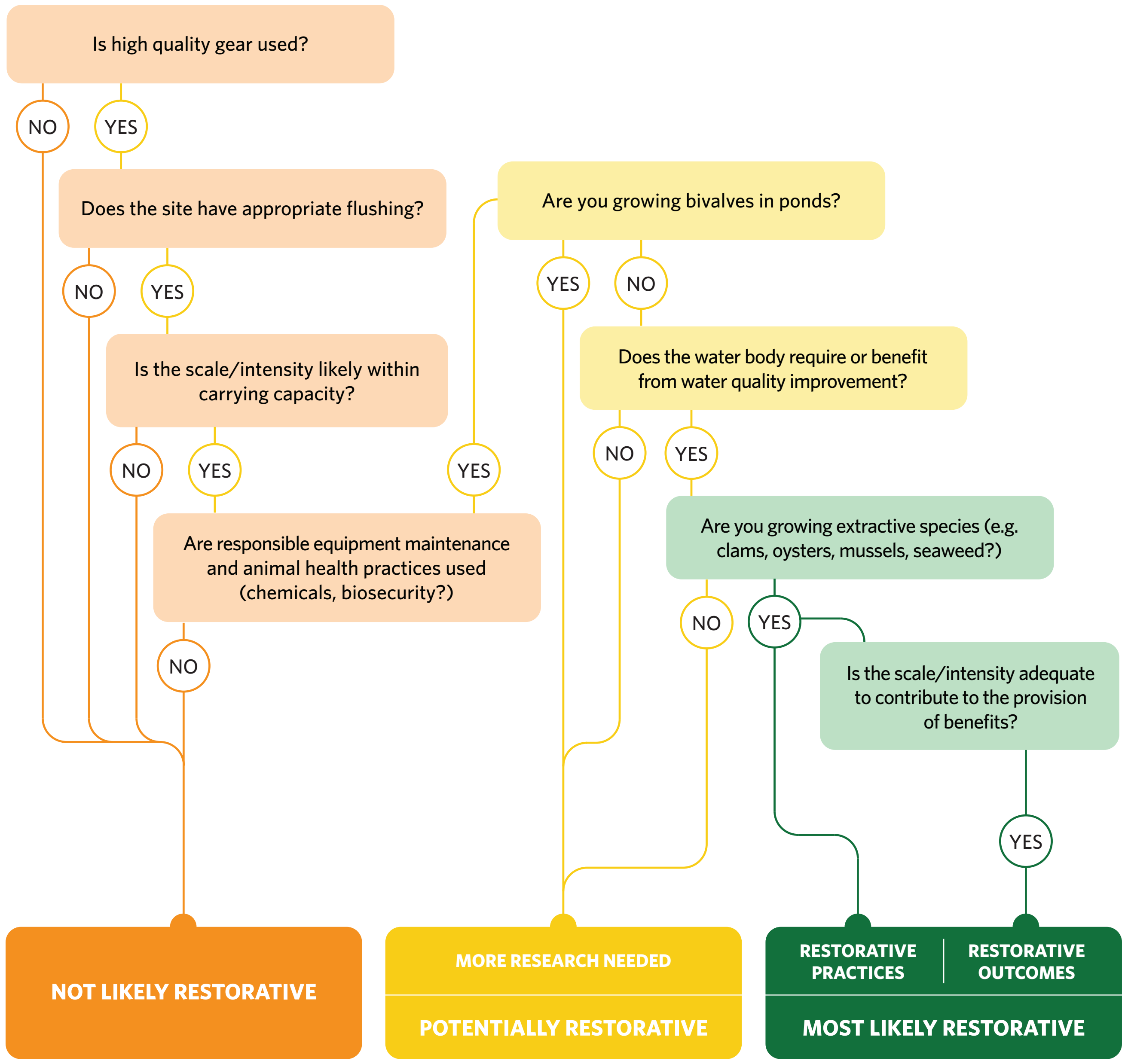
Roadmap for Water Quality Benefits

Does this Aquaculture Operation Improve Water Quality?



NOTES

High-quality gear: This refers to the ability of structures, equipment, and other materials used for production to withstand normal wear and tear without breaking apart, disintegrating, or releasing chemicals or particles into the water column. Styrofoam or low-quality plastics should be avoided.

Site has appropriate flushing: This refers to the need to consider the flow of water within the water body. Considering the flushing within the water body is necessary so that aquaculture operations do not cause excessive sedimentation or nutrient loading, which can result in adverse environmental impacts.

Scale and intensity of production is within the carrying capacity of the waterbody: The geographic scale of farming in a waterbody, as well as the intensity of production within the farming area, should not discharge nutrients at a rate that exceeds the carrying capacity of the waterbody. Generally, this is not an issue for bivalve shellfish or seaweed aquaculture, but can be at very large scales. Conversely, the potential for excessive removal of nutrients should also be taken into account, particularly in oligotrophic environments.

Responsible practices used: Farming sites and animal health should be monitored regularly, and cleaning, repair, and replacement of structures, equipment, and gear should be done according to better management practices. Operations should not release chemicals or other material into the water body at a dose or frequency that could cause a significantly negative environmental impact.

Pond systems: The culture of species within pond systems may or may not provide restorative benefits to water quality, as organisms in these systems would rely upon productivity within the pond (i.e. reduced feed inputs), and pond systems can often be disconnected from natural ecosystems. However, there are systems in which extractive species are grown within ponds and provide effective filtration services. These services may be relevant to the pond itself if it is a major water body, one that is significant to the environment and communities, and/or in some instances where water is manually transferred (e.g. pumped) from a pond to a nearby natural water body; in these situations, pond culture could be providing restorative benefits to the broader surrounding ecosystem.

Water body requires or benefits from water quality improvement: To benefit from the culture of extractive species like seaweed or bivalves, the water body should be able to benefit from improvement or increased resilience in ways that can be provided by the species being grown. The culture of these species would not be considered restorative for water quality if the water body could not benefit from water quality improvements and/or the resilience or productivity of water body could not be increased.

A standardized national or international framework can help assess the extent to which a water body suffers from eutrophication as a result of anthropogenic nitrogen and phosphorus loading. For example, the US National Estuarine Eutrophication Assessment relies upon an assessment of both primary symptoms (decreased light availability, algal dominance changes, increased organic matter decomposition) and secondary symptoms (loss of submerged aquatic vegetation, harmful algae blooms, and low dissolved oxygen).

Production of extractive species (e.g. bivalves or seaweed): Production of extractive species has a relatively high likelihood of providing an environmental benefit and, in particular, water quality benefit to the water body in which they are grown. Current research has shown that mussels and oysters, as well as seaweed, generally provide the greatest benefit to water quality.

Scale and intensity of production are adequate to provide benefits to the water body: While individual farms can provide partial and cumulative benefits, overall production should ideally occur at a scale and intensity that will result in the desired benefits to the water body. This requires a thorough understanding of the potential for the farmed species to provide the desired water quality services, as well as the degree to which the water body needs improvement. These contributions will most likely be in tandem with and constitute one component of broader restoration efforts.

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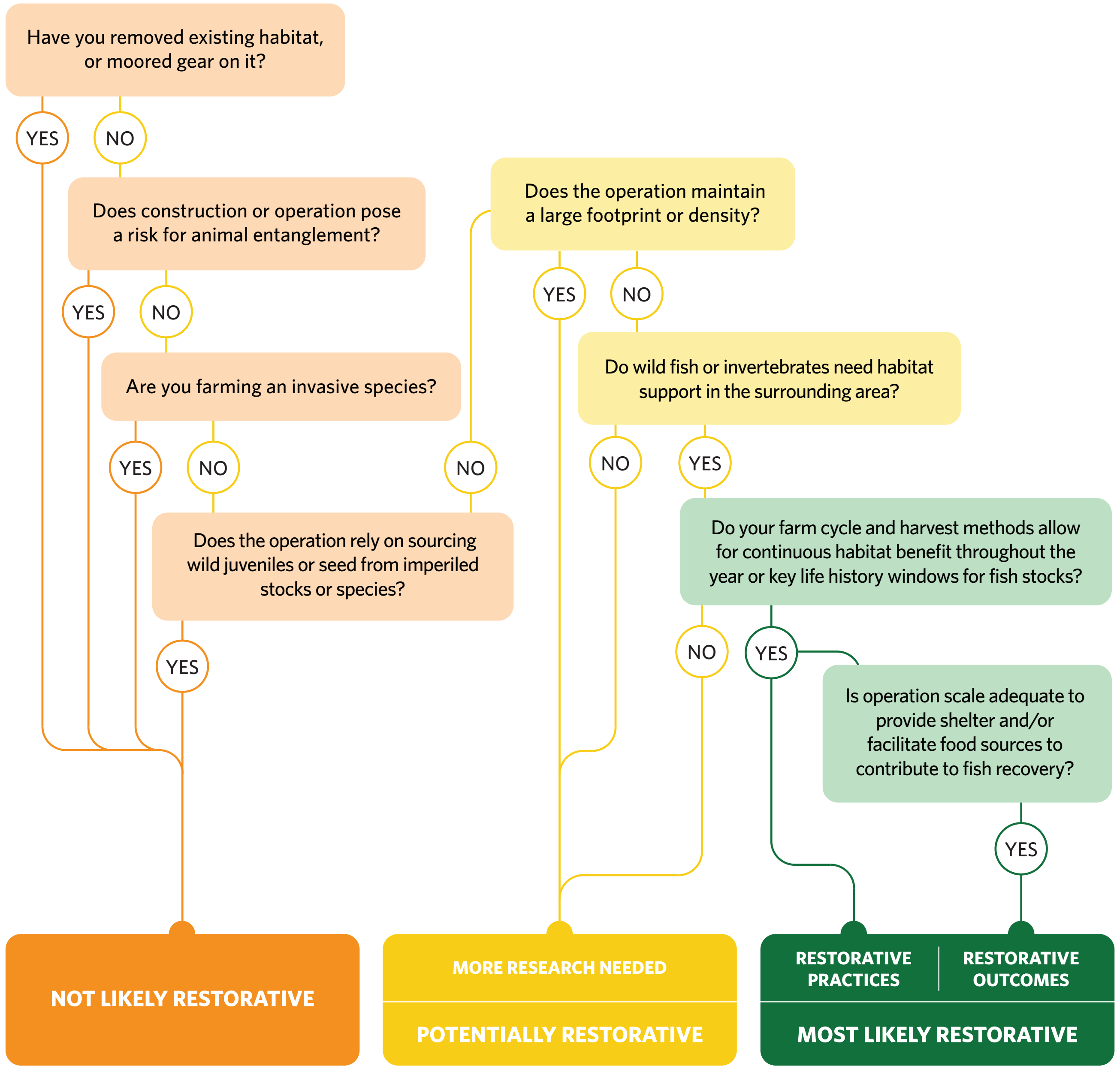
Does this Aquaculture Operation Improve Habitat and Fish Stocks?



NOTES

Existing habitat: This refers to the removal of, or damage to, existing sensitive or at-risk habitat to construct or operate an aquaculture facility. It includes the securing of structures or gear directly to sensitive or at-risk habitats. If loss of habitat functionality due to the siting of aquaculture operations generates widespread or persistent impact, this means the facility would be unlikely to produce a net benefit to the ecosystem.

Animal entanglement: While aquaculture can increase species abundance and diversity, better management practices must be used to minimize the risk of entanglement of aquatic mammals, birds, and other species potentially attracted to aquaculture facilities. While there are no current reports of marine mammal entanglement in seaweed farms and it is unknown whether mammals will avoid or be attracted to farming activities, all farm ropes must be taut and sites should be configured in ways that reduce the risk of entanglement. Additionally, as entanglement is a low probability but high impact scenario, additional farm designs (e.g. inclusion of ropes with reduced breaking strength) and monitoring controls (e.g. sensors) should continue to be tested and incorporated.

Invasive species: If a farmed species is invasive there is a high likelihood of negatively affecting the surrounding ecosystem by outcompeting wild, native species and further disrupting the natural ecosystem and resulting in overall negative impacts. Naturalized species already present within a water body under proper management measures may qualify as restorative.

Sourcing of farmed stocks: The operation should ensure that the farmed population is not contributing to the depletion of wild populations of concern to ensure that aquaculture has the potential to result in a net benefit. Seed or fry should not be collected from wild stocks that are overfished or experiencing overfishing and are not subject to a rebuilding/management plan that discourages use of wild stocks for aquaculture seed or fry.

Operation footprint and density: While individual sites may not have a significant benefit or impact on habitat, the cumulative effect of multiple sites in an area (including farm area, transportation to and from tidelands, etc.) may impact the functionality of the ecosystem. Sites and industries that operate in high densities in an area, or over a large area can provide significant benefit, but may also alter the dynamics of a habitat negatively. More research could be required at the site or at an industry-specific scale to determine the potential thresholds for cumulative positive or negative impact.

Wild stocks require support: To be of restorative benefit, wild fish stocks or invertebrates should need habitat support, rebuilding, or resilience benefit in a specific area. Aquaculture can provide fish and invertebrates refuge from larger predators, provide spawning grounds, and provide spawning forage.

Continuous habitat benefit: The duration and consistency of the presence of aquaculture will affect its ability to provide consistent benefits that align with the needs of species and fish stocks at key stages in their life history. This could be addressed through timed harvesting or restocking to provide benefit or minimize impact to wild fish or invertebrates. For example, oyster farming regulations on the West Coast of the United States prohibit the harvesting of gear when forage fish eggs are present to ensure that the gear provides reproductive benefit, rather than impact.

Scale adequate for a contribution to recovery: While individual farms can provide partial and cumulative benefits, overall production of aquaculture should strive to provide adequate shelter or facilitation of food sources to wild fish populations at a scale that helps contribute to their recovery. This requires a thorough understanding of the potential for the farmed species to provide the desired habitat services, as well as the degree to which the water body needs habitat improvement. These contributions will most likely be in tandem with and constitute one component of broader restoration efforts.

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PROVISIONAL ROADMAPS FOR CLIMATE MITIGATION AND ADAPTATION BENEFITS

Restorative aquaculture has the potential to produce multiple types of climate mitigation benefits. While the water quality and habitat benefits of seaweed and shellfish aquaculture (which may be considered climate adaptation) are relatively well-supported within the scientific literature, the climate mitigation benefits of these types of aquaculture are currently less scientifically supported.

Numerous scientific studies are currently underway investigating the potential of seaweed aquaculture to sequester carbon in sediment underneath farms and nearby marine ecosystems, such as seagrass meadows. Also, there have been initial studies that indicate that seaweed aquaculture can, at a localized level, buffer the impacts of increased sea temperatures and ocean acidification, potentially benefiting nearby calcifying organisms such as bivalves and corals.

We present the following roadmaps for climate mitigation benefit as "PROVISIONAL" roadmaps due to the highly dynamic landscape of climate research and science that is currently underway.


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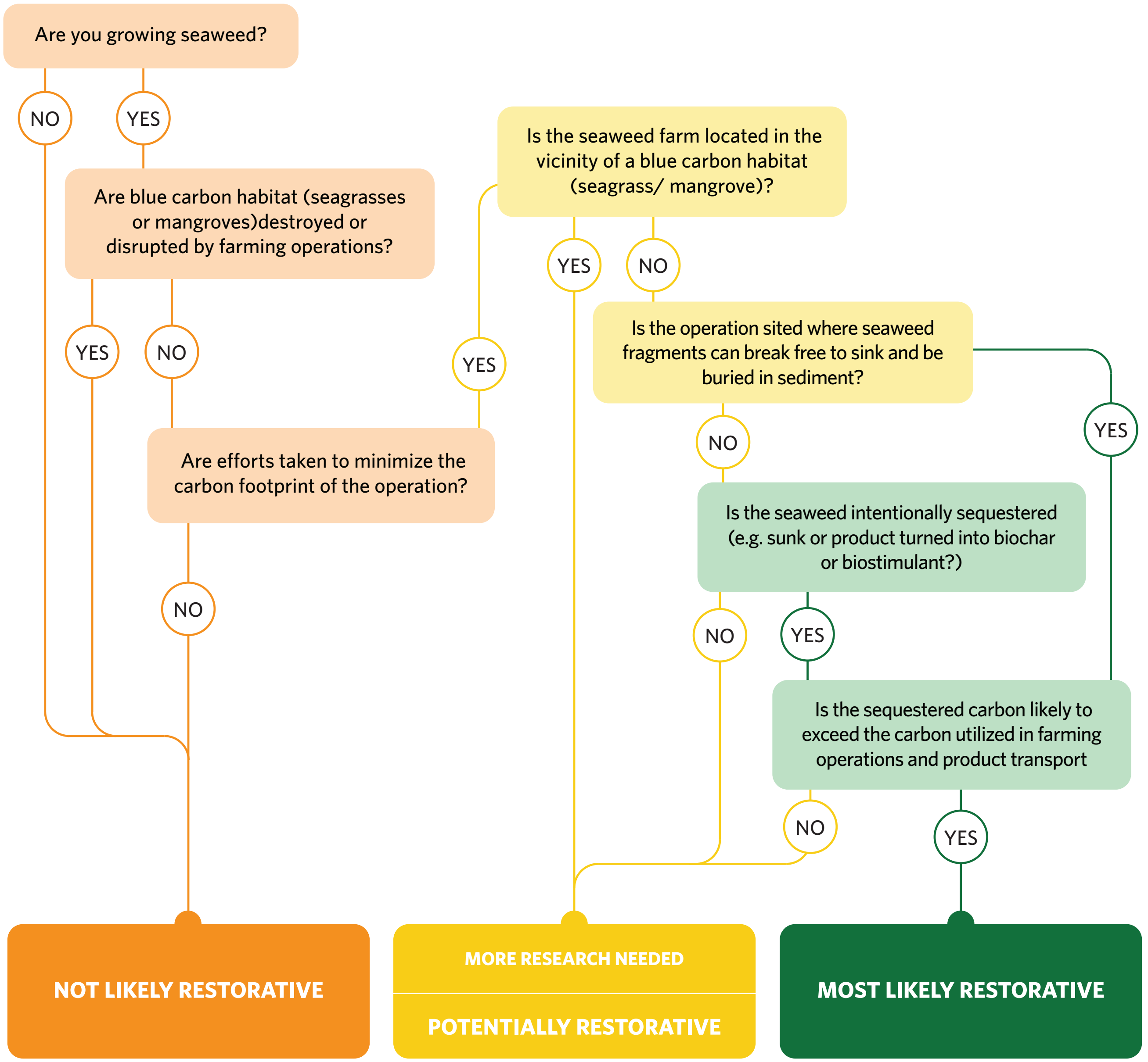
Roadmap for Carbon Sequestration

Does this Aquaculture Operation Result in Carbon Sequestration?

PROVISIONAL



NOTES

Species grown: For purposes of this document, seaweeds are considered to currently be the only aquaculture species that can provide the benefit of carbon sequestration. While calcium carbonate in shells of bivalve shellfish can be a carbon sink, carbon dioxide is emitted in the calcification process, and it remains unknown whether this results in a net benefit for carbon sequestration (Gentry *et al.*, 2020). However, it is possible that ecosystem-level benefits of improvements in water quality or clarity by different extractive species could benefit the distribution and abundance seagrasses and other blue carbon habitats, which can provide additional carbon sequestration benefits.

Impact on blue carbon habitat: This refers to marine and coastal habitats such as seagrass beds or mangroves that sequester and store carbon. Construction or operation of aquaculture sites should avoid negative impacts to these naturally occurring blue carbon habitats.

Greenhouse gas emissions: Efforts should be taken to minimize greenhouse gas emissions of the seaweed operation. While the production of seaweed may provide the benefit of carbon sequestration, construction and operation at the aquaculture site can lead to greenhouse gas emissions; this includes machinery and equipment used for construction, maintenance, planting, harvest, processing, and transportation.

Siting and oceanic conditions: Benefits of carbon sequestration from seaweed culture are realized when fragments of seaweed break off and are transported to either deep sea environments or underneath farms where they are effectively stored in the sediment. To create this benefit, seaweed aquaculture must be done at a site where the oceanic conditions are suitable for these fragments to be transported to the seafloor and convert into sediment, thereby removing the carbon dioxide from ocean circulation.

Blue carbon habitat: In the vicinity of a natural blue carbon habitat the benefits of restorative aquaculture may be relatively negligible, or may even result in a negative impact on the natural habitat. That stated, a recent paper (Ortega, et al. 2020) indicates that 33% of total marine macrophyte eDNA in blue carbon habitats is of macroalgal origin. More research will be necessary to determine whether seaweed aquaculture in this area will result in a net benefit.

Intentional carbon sequestration: In addition to potential benefits of carbon sequestration from seaweed culture, there is the potential for harvested biomass to contribute to climate mitigation through the intentional sinking of seaweed biomass to a depth where the carbon is intentionally removed from circulation (note: this may have significant negative environmental consequences which are yet to be evaluated), and/or turning the product into a biostimulant or biochar, which may be used to enhance carbon sequestration in soil. There is also the potential to use the harvested biomass to displace emissions, such as in the case of replacing fossil fuel polymers with biopolymers.

Balancing sequestered carbon and carbon footprint: While seaweed aquaculture can result in carbon sequestration, to produce a net benefit, the carbon sequestered must exceed the carbon footprint associated with cultivation.

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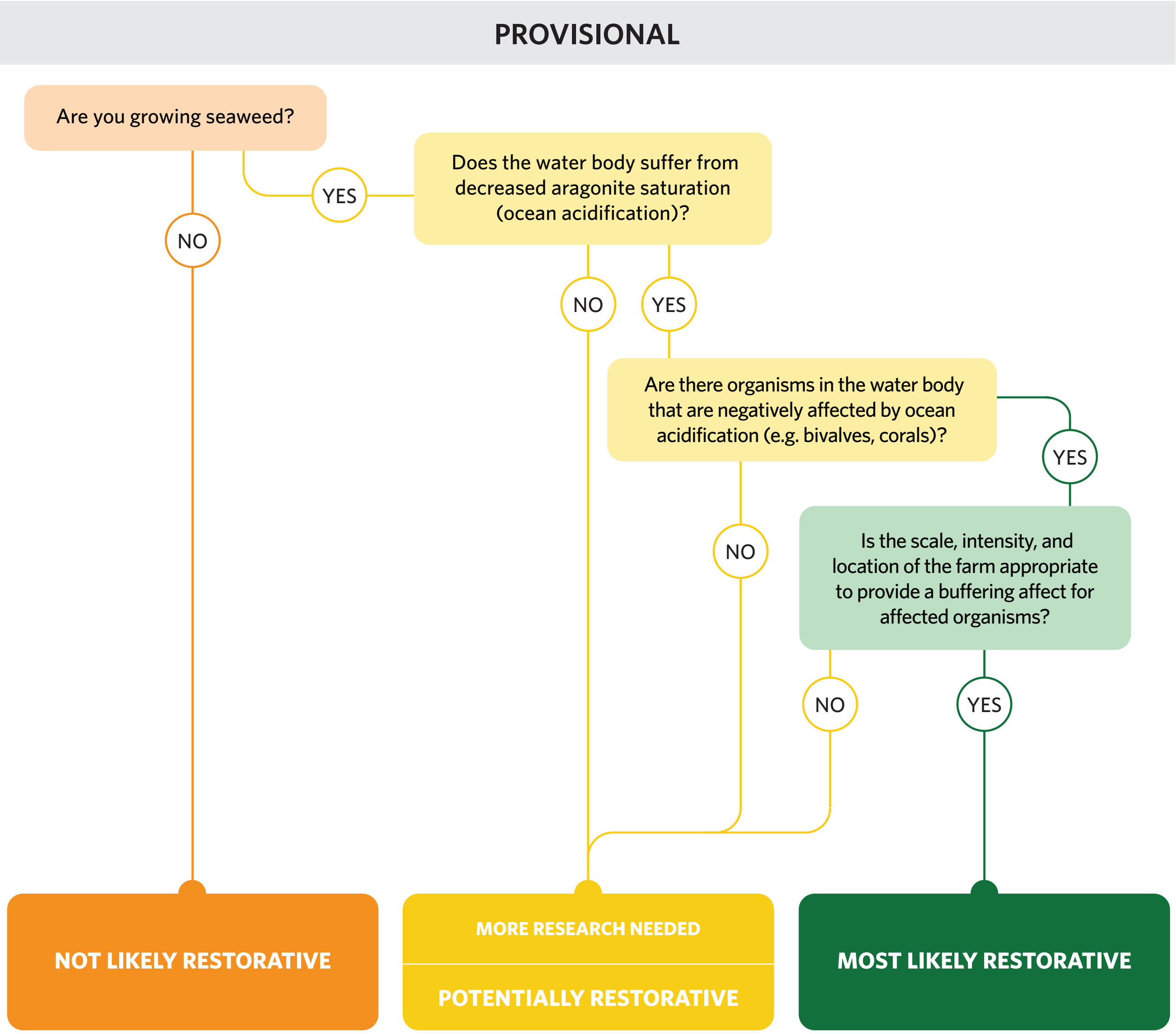
Roadmap for Ocean Acidification Buffering

Does this Aquaculture Operation Result in Ocean Acidification Buffering?



NOTES

Species grown: Seaweed is currently considered the only aquaculture species capable of providing the benefit of localized ocean acidification buffering.

Aragonite saturation: When the aragonite saturation state of a waterbody is lower than 3, calcifying organisms will become stressed. If the aragonite saturation state falls below 1, aragonite structures (including bivalve shells) begin to dissolve. If a water body is suffering from decreased aragonite saturation, it may be a good candidate for restorative seaweed aquaculture to provide localized buffering benefits.

Presence of calcifying organisms: The benefits of restorative seaweed aquaculture will be the most significant if there are calcifying organisms (e.g., bivalve shellfish, corals) present within the water body that are in need of and can have improved calcification due to the farmed seaweed's presence.

Scale, intensity, and location of seaweed production: Production must occur at a scale and intensity that will result in the desired benefits to calcifying species. Additionally, the farm needs to be sited close enough to the calcifying organisms to benefit from the localized "halo" effect. This requires a thorough understanding of the potential for the farmed seaweed species to provide the desired buffering service, as well as the degree to which ocean acidification impacts need to be mitigated in the local area.

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Considerations for Policy and Management of Restorative Aquaculture

Aquaculture systems are both social and ecological systems (Johnson et al., 2019), and as such socio-economic factors play an important role in determining whether nations engage with aquaculture, and the scale of production (Gentry, Ruff and Lester, 2019; Ruff, Gentry and Lester, 2020) . There are a number of existing analyses and policy approaches that have been established to support sustainable development of aquaculture that can be further built upon to facilitate restorative aquaculture, including: integrated social, economic, and ecological analyses (Johnson et al., 2019); approaches to forecast aquaculture outcomes (Couture et al., 2021); and an evidence-base that describes the ways in which inclusion of people in decision-making can enable equitable aquaculture outcomes (Krause et al., 2015). Also, recent work by the High-Level Panel for a Sustainable Ocean Economy explores what is needed to ensure a sustainable, prosperous future for food from the sea. It highlights that while some interventions can result in win-win situations, many solutions or policy interventions will come with trade-offs, the nature of which will vary depending on the needs of each country, and the constraints each jurisdiction faces (Costello, Cao, and Gelcich, 2019).

Overlying these regional and local considerations there are, however, common challenges that need to be addressed. The High-Level Panel describes three key opportunities for action for mariculture. These opportunities for action are still valid when "mariculture" is generalized to include freshwater (and marine) aquaculture, and are highly relevant for restorative aquaculture. Sector or species-specific requirements could guide opportunities to embed restorative aquaculture within a broader operating model. For example, barriers to the effective development of sectors critical to the opportunity for restorative aquaculture are increasingly understood, such as those that constrain seaweed farming, including fragmentation of the sector outside of Asia and complex regulatory requirements that deter trialing of farming in different environments (Lloyd's Register Foundation, 2020; Cai, *et al.* 2021).

As a policy instrument in itself, this white paper provides a tool for industry, government, and the public to engage in more detailed, context-specific discussions about what is needed to ensure restorative aquaculture can be practiced in their jurisdiction. Drawing on the recommendations of the High-Level Panel we recommend the development of several approaches that could support aquaculture operators in deriving additional benefits from restorative aquaculture. Addressing regulatory barriers, issues with the perception of aquaculture activities, and market failures will help restorative aquaculture farmers realize greater economic returns at the same time as achieving positive environmental outcomes at a greater scale.

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POLICY DEVELOPMENTS TO SUPPORT RESTORATIVE AQUACULTURE

1. Addressing uncertainty and barriers in regulatory frameworks:
   - Foster policies that appreciate and prioritize addressing water quality pollution, habitat degradation, and climate mitigation.
   - Incorporate the potential ecological contributions of aquaculture into national and subnational policies and regulatory processes.
   - Create efficient or streamlined regulatory mechanisms that better facilitate restorative aquaculture (e.g. streamlining of assessment and permitting for restorative practices, recognition for the duration of consent/ licenses granted for restorative aquaculture farmers).
   - Develop spatial planning tools that can identify areas and approaches that will maximize restorative outcomes at subnational and local levels, including facilitating spatial planning and zoning for aquaculture development and fostering equitable access.
   - Adequately resource regulatory agencies to effectively monitor, manage and value risks and benefits.
2. Support informed perceptions about aquaculture and emerging restorative aquaculture technology and practices:
   - Uplift and support Indigenous people in continuing or revitalizing traditional aquaculture practices and/or engaging in new aquaculture activities and interests, including broader purposes for engaging in aquaculture (e.g. continuing cultural traditions, subsistence, resource-based employment, engagement with export markets, aquatic gardening).
   - Foster clear, effective communication from a range of stakeholders, including environmental NGOs and environmental government agencies on the broader value of restorative aquaculture to people and nature.
   - Develop and implement coordinated communication materials that accurately describe environmental benefits of restorative aquaculture and operations to support increased "social license".
   - Develop the science, monitoring approaches, and tools specifically oriented to measuring environmental benefits from aquaculture.
   - Invest in the technology and tools that can automate data collection needs and decrease regulatory costs for aquaculture sectors including 'real time' monitoring of activities, environmental benefits, and impacts.
3. Consider policy interventions to address market failures and impediments to innovation:
   - Develop the science, tools, and regulatory systems needed to economically value and credit nutrient, biodiversity, and carbon offsets from restorative aquaculture; a "restorer earns" approach.
   - Foster innovation by supporting accelerator programs, business incubators, and other similar programs that can advance technology development and business models that can enhance restorative benefits.
   - Invest in research, development, and infrastructure needed to overcome sector specific barriers (e.g. new biorefinery technologies to expand opportunities and cost effectiveness of seaweed processing, hatchery capacity, selective breeding programs, evolution of more sustainable feed types and their availability).


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Case Studies

The following case studies provide illustrative examples of restorative aquaculture in practice. These examples are intended to demonstrate the process of applying the roadmaps to determine the likelihood an aquaculture industry or operation is providing restorative benefits. The case studies explore how specific aquaculture practices may or may not be considered restorative. We explore application of the roadmaps in freshwater environments in the world's largest aquaculture producing country, by examining the impact of filter-feeding carp on lake water quality in China. In a second case study, we investigate how farm-scale practices could be considered in view of regulated or shared ecosystem-scale goals by exploring the oyster aquaculture's contribution to water quality in the Chesapeake Bay. In a third example, we reflect on the emergent seaweed industry in Belize and how habitat benefits could shape farm and sector-wide approaches to continued industry growth and development. These case studies were selected to understand the potential for restorative aquaculture across a range of sectors, growing environments, and species. They also differ in terms of the status of the aquaculture sector (large or small), its trajectory of development (well developed and occurring over a significant period or relatively nascent), and the geographies and ecosystems in which they occur.

CASE STUDY 1

Lake Aquaculture of Filter-Feeding Fish (Silver carp, *Hypophthalmichtyhys molitrix*, and Bighead carp, *Aristichthys nobilis*) in China for Water Quality Benefits

ENVIRONMENTAL CONTEXT AND GOALS

China is the world's major fish producer. Since 1991, aquaculture in China has accounted for more farmed aquatic food than the rest of the world combined, and in 2018 aquaculture of fish represented nearly 58% of total global production (FAO, 2020). A significant majority of this production occurs through inland aquaculture, especially the culture of carp and tilapia in freshwater environments. Aquaculture in ponds is a primary method for culture in China. Production from these systems has increased markedly in the past 40 years, from 719,000 tons in 1981 to 22,300,000 tons in 2019, with the area of these ponds increasing from 8.48 km2 to 26,400 km2 over the same period (Hu *et al.*, 2021). At a larger scale, artificial lakes are also being stocked with fish as a basis for aquaculture and culture-based fisheries.


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▲ **QIANDAO LAKE**

Located in Chun'an County, Hangzhou City, Zhejiang Province (one of the leading provinces for pond aquaculture, Hu *et al.* 2021), Qiandao Lake, which was created in 1959 to support hydroelectric power generation, is the largest artificial lake in China to date. Covering a water area of about 580 km2 the lake has 1,078 islands, a shoreline 2,500 kilometers long, and reaches an average depth of 30 meters. The total storage capacity of the lake as a reservoir is 17.8 billion cubic meters. The water residence time of the lake is about 2 years, with an average annual inflow of 9.41 billion cubic meters and an average annual outflow of 9 billion cubic meters (Han *et al.*, 2013). Today, Qiandao Lake has become a "National Eco-model Area" featuring coordinated development of tourism, aquaculture and multiple industries.

Yet, the environment of Qiandao Lake once suffered serious degradation. Since 1995, eutrophication accelerated due to nearby pollutant discharge and intensive fed, cage aquaculture. As a result, Qiandao Lake started to experience large-scale blue-green algae (cyanobacteria) blooms on a frequent basis. The overall phytoplankton density in the lake jumped from 0.45 million cells/L in 1992 to 1.08 million cells/L in 1998 (Wu and Lan, 2012). The subsequent deterioration of water quality had a substantial impact on local aquaculture production. For instance, the annual average production of bighead carp and silver carp dropped from an annual total 1,600 tons between 1991-1997 to 400 tons in 1999; a decrease of around 75% (Liu *et al.*, 2007). Also, because Qiandao Lake is an important drinking water source for Hangzhou, Jiaxing, and other areas, frequent algal blooms seriously affected the safety of water for surrounding communities. As a result, the main goal shared by all stakeholders, became restoration of water quality in the lake back to its original level, by tackling algal blooms.

The restoration of water quality in Qiandao Lake can be roughly divided into two parts. First, more stringent measures have been taken to restrict pollution inputs. For example, the discharge of upstream industrial pollutants has been reduced, and nearly 4 km2 of fed aquaculture (such as catfish, bass and Mandarin fish) has been eliminated. Such measures have greatly relieved the pressure of pollution on the lake. Second, managers have released silver carp (Hypophthalmichtyhys molitrix) and bighead carp (Aristichthys nobilis) into Qiandao Lake, species that are native to the lake and region, and directly or indirectly consume microalgae, thereby mitigating algal blooms and improving water quality. In 2020, according to relevant monitoring, the water quality in Qiandao Lake reached a high standard (Chun'an County Branch of Hangzhou Ecology and Environment Bureau, 2020). As a result, centered around silver carp and bighead carp aquaculture, re-stocking and rational harvesting have been implemented at a larger scale, bringing economic benefits while supporting water quality, and preserving the stability of the ecological structure and functions in the lake.

In order to ensure the survival of the stocked silver carp and bighead carp, managers have targeted removal of some predatory fish species from the lake, though it must be noted this could be detrimental to the status of these species if they constitute vulnerable populations. Some studies show that it's necessary to maintain a certain number of predatory fish species for the stable operation of the entire ecosystem, since the absence of predatory fishes may change the plankton community structure through inter-species interactions, thus impacting the effectiveness of counter-measures for algal blooms.

CURRENT STATE OF THE INDUSTRY

Since 2010, more than 660 tons (about 6 million individual fishes) of juvenile silver carp and bighead carp have been released into Qiandao Lake annually, approximately 50% each across almost the entire lake (580 km2). Annual production of carp from the lake is close to 5,000 tons, bringing a direct economic benefit of about 500 million RMB (Song, 2020).

Studies have shown that 1kg of weight growth in silver carp or bighead carp can consume about 40kg of microalgae (Song, 2020). Based on the annual production of 5,000 tons of carp in Qiandao Lake, at least 200,000 tons of microalgae per year can be removed. In addition, provided that fish is composed of 10% nitrogen and 3.5% phosphorus (Li, 2012), carp in the lake can also remove about 500 tons of nitrogen and 175 tons of phosphorus per year.

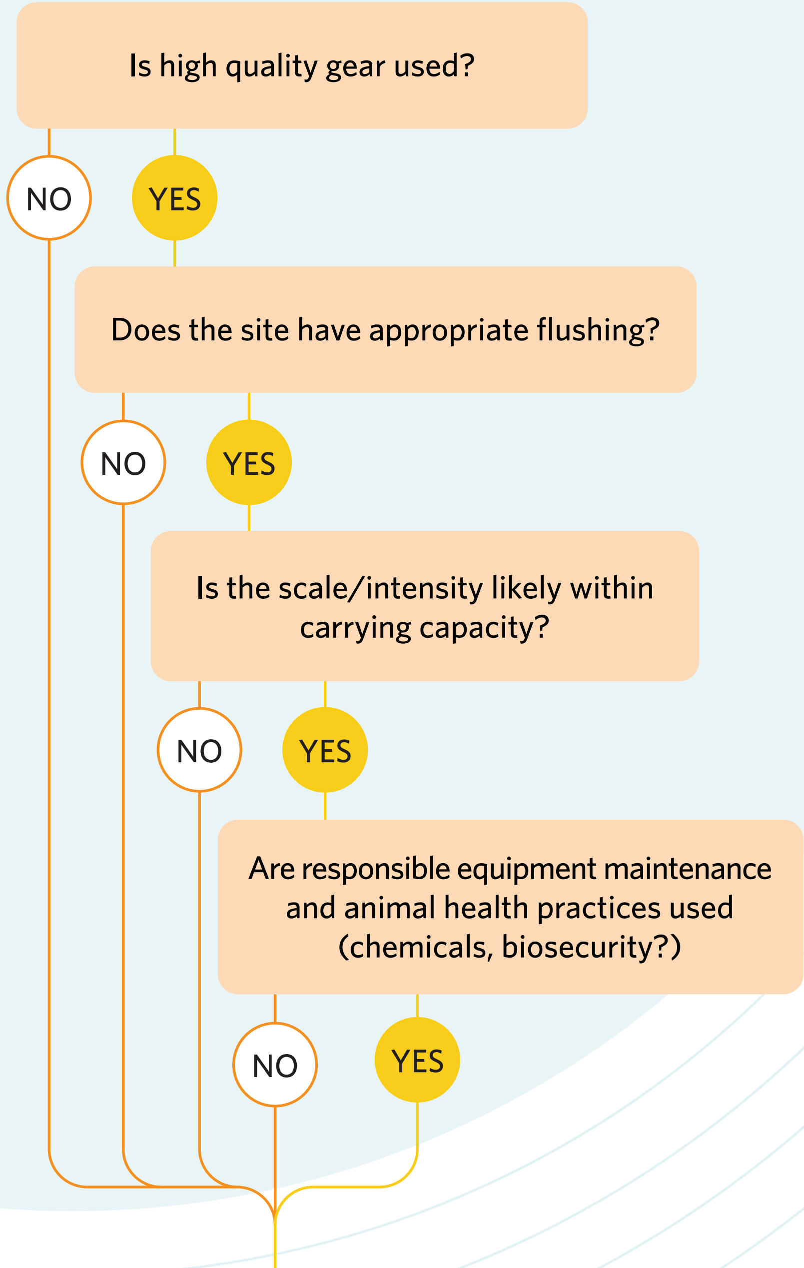
At present, the ratio of bighead carp to silver carp in Qiandao Lake is mainly 1:1, but it is also thought that this ratio could be adjusted to achieve the most optimal yield. In addition, once pollution inputs areas better controlled other predacious fishes with higher economic value might also be released, on top of such filter feeding fishes as sliver carp and big head carp.

▼ **LOCALS HARVESTING CULTURED BIGHEAD CARPS IN QIANDAO LAKE**

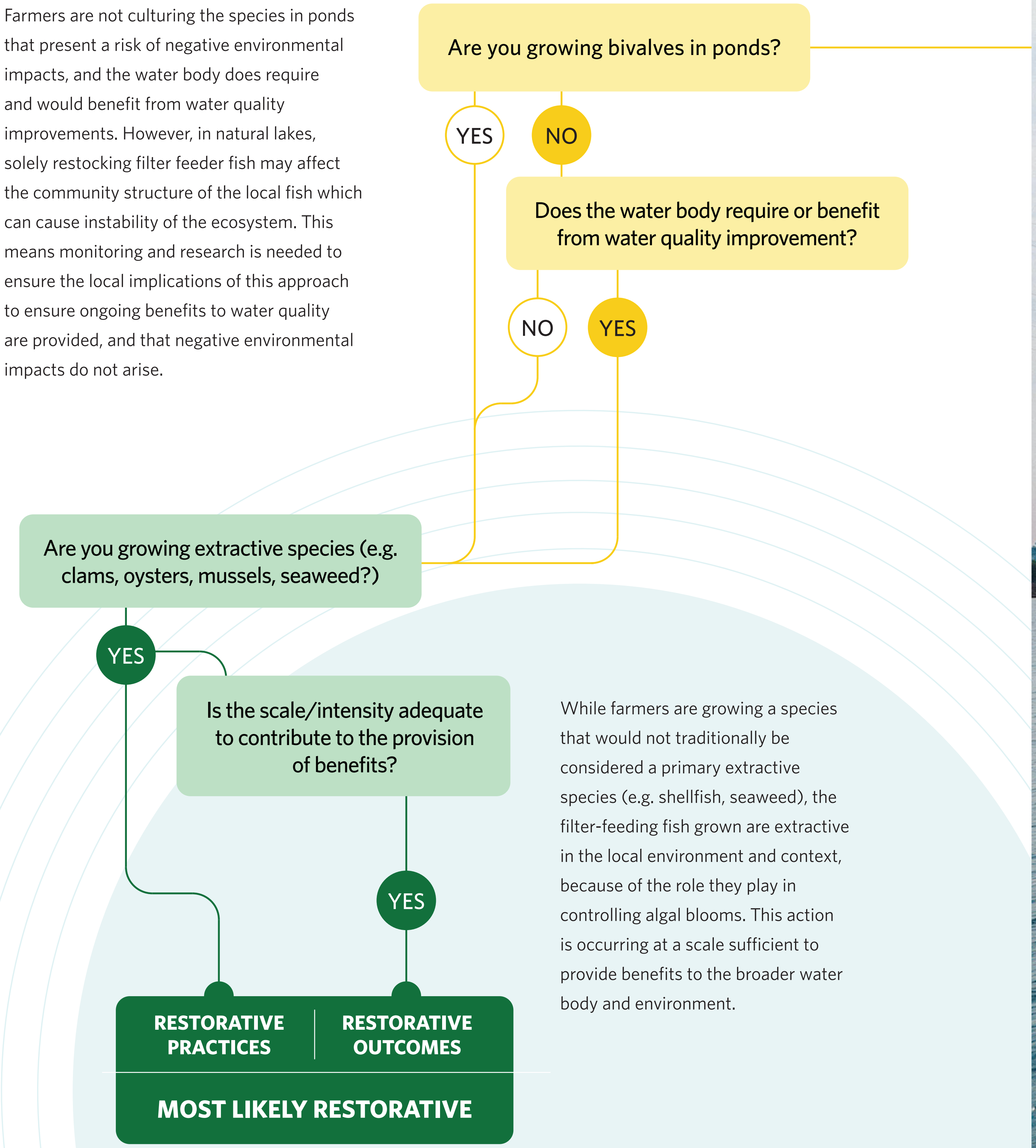
© Songlin Wang

Application of Roadmap: Does the Aquaculture Operation Improve Water Quality?

Bighead carp are released and cultured in the artificial lake without the requirement for supporting gear, feed or chemical inputs. Water flow in the lake is appropriate for culturing these species, and the number and proportion of carp released each year are considered to be within the carrying capacity of the water body. The species cultured are native to China with juvenile fish sourced from local hatcheries. The quantity harvested is also limited, and consistent with a strategy of catching large fish and retaining smaller sized individuals for further growth.



Farmers are not culturing the species in ponds that present a risk of negative environmental impacts, and the water body does require and would benefit from water quality improvements. However, in natural lakes, solely restocking filter feeder fish may affect the community structure of the local fish which can cause instability of the ecosystem. This means monitoring and research is needed to ensure the local implications of this approach to ensure ongoing benefits to water quality are provided, and that negative environmental impacts do not arise.



While farmers are growing a species that would not traditionally be considered a primary extractive species (e.g. shellfish, seaweed), the filter-feeding fish grown are extractive in the local environment and context, because of the role they play in controlling algal blooms. This action is occurring at a scale sufficient to provide benefits to the broader water body and environment.

SUMMARY

In Qiandao Lake, the culture of bighead carp and silver carp has effectively controlled algal blooms, thus helping regulate water quality. Furthermore, the quality of the water environment enables the cultured silver carp and bighead carp to attract a higher price at market and provides support for tourism, generating further significant economic benefits. The region has achieved coordinated development across social, economic, and ecological needs. However, several studies have shown that the ecosystem of Qiandao Lake remains in an early stage of development, with lower ecosystem stability and more simple food webs. Excessive stocking of silver carp and bighead carp may therefore affect the biological community structure of the lake as a whole, increasing potential ecological risks (Li *et al.*, 2011). As such, continued attention should be given to the carrying capacity of bighead carp and silver carp in the lake, as well as the potential harvest of predatory fishes, from the perspective of biodiversity, to ensure the stable operation of the environment and the influence of this form of aquaculture on other species.

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CASE STUDY 2

Oyster Aquaculture's Contribution to Water Quality Goals in the Chesapeake Bay

ENVIRONMENTAL CONTEXT AND GOALS

The Chesapeake Bay is the largest of more than 100 estuary systems in the United States and is the third largest in the world. The Bay and its tributaries span more than 11,600 km2, its watershed encompassing seven U.S. states and more than 165,000 km2 of a range of terrestrial systems and land uses. The Bay is an important breeding ground and home for more than 350 species of marine fishes, which benefit from the presence of critical coastal habitats including seagrass beds and oyster reefs.

Oyster populations in the Chesapeake Bay, formed largely by Crassostrea virginica, were historically abundant and were utilized as a food source by Native Americans. After the arrival of European colonists' oysters were lightly exploited for commercial purposes until the early 1800s but harvests drastically increased in the post-Civil War era, reaching a peak in harvesting later that century. By 1960, the wild oyster fishery had plummeted, with annual harvests less than 10% of historical landings (Schulte, 2017). By the 2000s, oyster abundance in the bay had declined to 99.7% of that estimated to be present in the early 1800s (Wilberg *et al.*, 2011). With that decline, the Bay has lost the oysters' natural capacity to filter sediment and algae and remove nitrogen and phosphorus from the water.

© Jason Houston

▲ **KCB OYSTERS IN LOTTSBURG, VIRGINIA.**

Water quality issues paralleled the decline in oyster populations throughout the 1900s. In addition to the loss of oyster reefs, primary factors contributing to water quality declines included increased agriculture production in the watershed, population growth, and coastal development, all of which accelerated the input of pollutants from terrestrial sources. Excess nitrogen and phosphorous from agriculture, stormwater runoff, wastewater facilities and air pollution, are the primary causes of eutrophication in Chesapeake Bay. In 2004, a national assessment by the National Oceanic and Atmospheric Administration identified the mainstream of the Chesapeake and 4 of 8 tributary rivers as experiencing high nutrient loading (Bricker, 2007). Algae blooms, prompted by high levels of nutrients, have created seasonal "dead zones" in the Bay where oxygen is limited and fish and shellfish cannot survive, blocking sunlight needed for seagrasses, and smothering aquatic life on the estuary floor. Despite efforts to reduce pollution at their source progress has been insufficient in meeting agreed water quality goals for the Chesapeake Bay and its tributaries.

In 2009, then President, Barack Obama, signed Executive Order 13508, Chesapeake Bay Protection and Restoration, directing federal agencies to develop strategies to protect and restore the Chesapeake Bay's water qualities and habitats. The Order declared the Bay a "national treasure" and "one of the largest and most productive estuaries in the world." The Executive Order was developed in furtherance of the U.S. Environmental Protection Agencies' existing authorities to ensure Fishable and Swimmable waterways under the Clean Water Act. Strategies developed by federal agencies resulted in long term commitments to recover oyster populations in key tributaries in the bay.

In 2010, the U.S. Environmental Protection Agency, established for the Bay a Total Maximum Daily Load (TMDL), setting nitrogen, phosphorus, and sediment limits for six states in the Chesapeake Watershed and the District of Columbia. According to the EPA, "more than 40,000 TMDL's have been completed across the United States, but the Chesapeake Bay TMDL [is] the largest and most complex thus far," due to its geographic expansiveness and multi-jurisdictional scope (US EPA, 2010). Under the TMDL processes, nutrient loads are controlled, in part, through the formal identification and application of Best Management Practices by industries or activities.

CURRENT STATE OF THE INDUSTRY

Aquaculture of Crassostrea virginica is managed through a combination of state and federal regulations. State agencies play a primary role in permitting oyster aquaculture activities. Shellfish aquaculture in Virginia is one of the US's most established aquaculture industries, and accounts for the second highest oyster production out of any state. Oyster aquaculture in Maryland, however, is a relatively new industry, beginning only in 2009, following the revision of the State's laws enabling areas of the sea to be leased for farming (Hood *et al.*, 2020).

Historically, farmers in Virginia deployed spat (juvenile oysters) settled onto shell for further culture on the seafloor across relatively large lease areas, with large farms up to several hundred acres in size. But in the last two decades farming of oysters in containers or baskets to supply a fresh, "half-shell" product has become increasingly prevalent. In both Maryland and Virginia, suspended culture through floating longline cages (e.g. Oyster-Grow cages) or suspended "Australian" longline and basket systems have been increasingly favored by growers, compared to on-bottom culture.

In 2018, Maryland's shellfish aquaculture industry consisted of 17 on-bottom farms with 2014 acres under production, alongside an additional 15 off bottom farms. In the same year, Virginia's industry consisted of 109 on-bottom farms with 60 km2 under production, and an additional 68 off-bottom farms (USDA, 2019). In both states, the number of marketed oysters produced and sold has expanded rapidly in recent years. In Virginia, single oyster production increased from less than one million oysters in 2005 to over 30 million oysters in 2018 (Hudson and Virginia Sea Grant Marine Advisory Program, 2019). In Maryland, the first harvests occurred in 2012 and have since grown to over 10 million oysters (70,000 bushels) in 2017 (University of Maryland Extension, 2019).

EFFORTS TO INCORPORATE OYSTER AQUACULTURE UNDER THE CHESAPEAKE BAY EPA TMDL

Following the TMDL BMP protocol, a 13-member expert panel coordinated by the Oyster Recovery Partnership was convened to make recommendations to the EPA on whether existing science could support nitrogen and phosphorous reduction for various oyster practices occurring in the Bay, inclusive of restoration of oyster reef habitat and aquaculture. This group aimed to identify whether nutrient cycling and reduction rates could be adequately quantified given variability in oyster survival and growth rates in both settings.

In 2016, The BMP panel recommended Oyster-Associated Reduction Protocols for TMDL use. These protocols quantified the amount of nitrogen and phosphorus stored in oyster tissue, as a result of oysters filtering and consuming organic matter, mostly algae, from the water column. Based on seven studies, all drawing on research specifically in the Bay, the expert panel concluded that tissue content averaged 8.2% nitrogen. Phosphorous tissue content averaged 0.9%, based on three studies. The BMP panel placed conditions on the applicability of these protocols, including, that the protocols only apply to aquaculture in tidal waters, and only include oysters that are removed from the time at which the BMP is approved and implemented. Oysters also must have been grown from an initial size of less than 2 inches (shell height), to be alive when removed (to ensure nutrients are retained with the tissue at the anticipated rate). State authorities must report the number of oysters harvested or pounds reduced annually. As tissue and shell weights can vary significantly oyster to oyster, the BMP requires random sampling of a growers product to create an average dry weight to enable calculation of nitrogen and phosphorus removal utilizing the percentage figures identified by the panel (Cornwell and Reichert-Nguyen, 2016).

Both Virginia and Maryland have begun to operationalize the BMP through state-based nutrient trading programs. The Maryland trading program is a voluntary program, and "intended to create a public market for nitrogen and phosphorus and sediment reduction" to enhance the restoration and recovery of the bay (Maryland Department of the Environment, 2020). In 2020, The State of Maryland issued its first trading guidance related to oyster aquaculture to enable growers to accumulate credits. One company, Blue Oyster Environmental, is attempting to aggregate credits and serve as a credit broker (Miller, 2020). Blue Oyster Environmental made the first oyster aquaculture nutrient trade in Maryland by selling nutrient credits to the Baltimore Convention Center to offset the impact of their events (Viviano, 2020).

Ongoing research is continuing to analyze the effect oyster aquaculture has on water quality and the ecology of the Bay. From 2016-2018, The Nature Conservancy worked with the Virginia Institute of Marine Science and four Virginia oyster growers attempted to measure the in-situ water quality effects of farms. After studying several aquaculture farms that varied in scale and the type of gear used, no evidence of significant negative impacts on benthic macrofauna, sediment quality or water quality was found. In the few instances in which significant differences in water quality were observed (improvements between areas inside and outside the farm) only small differences in average values were recorded (Kellogg, Turner and Massey, 2018).

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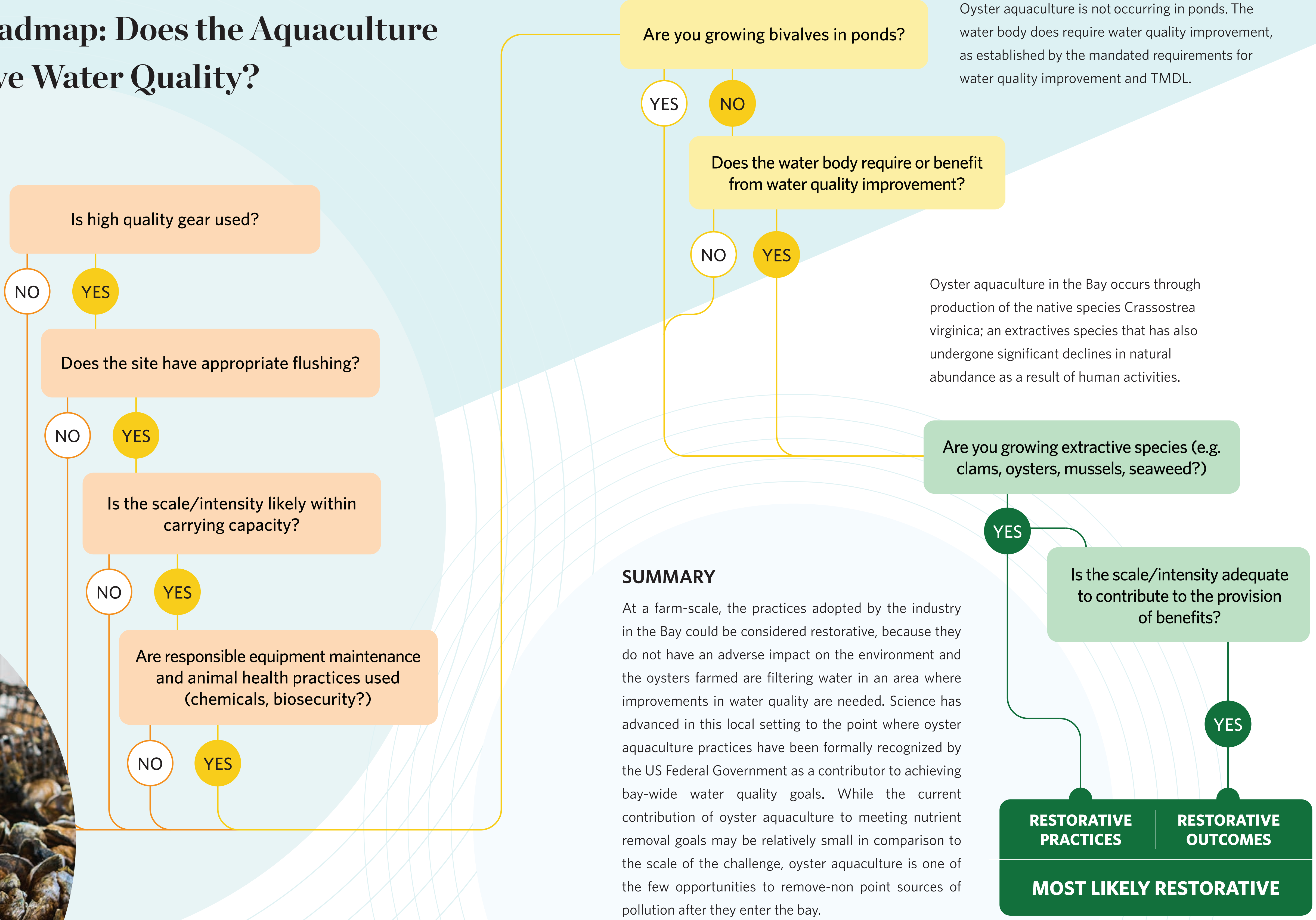
Application of Roadmap: Does the Aquaculture Operation Improve Water Quality?

Oyster aquaculture in Chesapeake Bay is managed via regulations that require quality gear to be used and regularly maintained. Farms also must be sited in areas that have an appropriate degree of water movement to support farm-scale flushing. Research has established that the current density of farms and scale of production is conducted within the carrying capacity of the ecosystem, and that no negative environmental impacts on the benthos, sediment or water quality can be detected from the aquaculture activity.



Is high quality gear used?

NO YES

Does the site have appropriate flushing?

NO YES

Is the scale/intensity likely within carrying capacity?

NO YES

Are responsible equipment maintenance and animal health practices used (chemicals, biosecurity?)

NO YES

Are you growing bivalves in ponds?

YES NO

Does the water body require or benefit from water quality improvement?

NO YES

Are you growing extractive species (e.g. clams, oysters, mussels, seaweed?)

YES

Is the scale/intensity adequate to contribute to the provision of benefits?

YES

RESTORATIVE PRACTICES

RESTORATIVE OUTCOMES

MOST LIKELY RESTORATIVE

Oyster aquaculture is not occurring in ponds. The water body does require water quality improvement, as established by the mandated requirements for water quality improvement and TMDL.

Oyster aquaculture in the Bay occurs through production of the native species Crassostrea virginica; an extractives species that has also undergone significant declines in natural abundance as a result of human activities.

SUMMARY

At a farm-scale, the practices adopted by the industry in the Bay could be considered restorative, because they do not have an adverse impact on the environment and the oysters farmed are filtering water in an area where improvements in water quality are needed. Science has advanced in this local setting to the point where oyster aquaculture practices have been formally recognized by the US Federal Government as a contributor to achieving bay-wide water quality goals. While the current contribution of oyster aquaculture to meeting nutrient removal goals may be relatively small in comparison to the scale of the challenge, oyster aquaculture is one of the few opportunities to remove-non point sources of pollution after they enter the bay.

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CASE STUDY 3

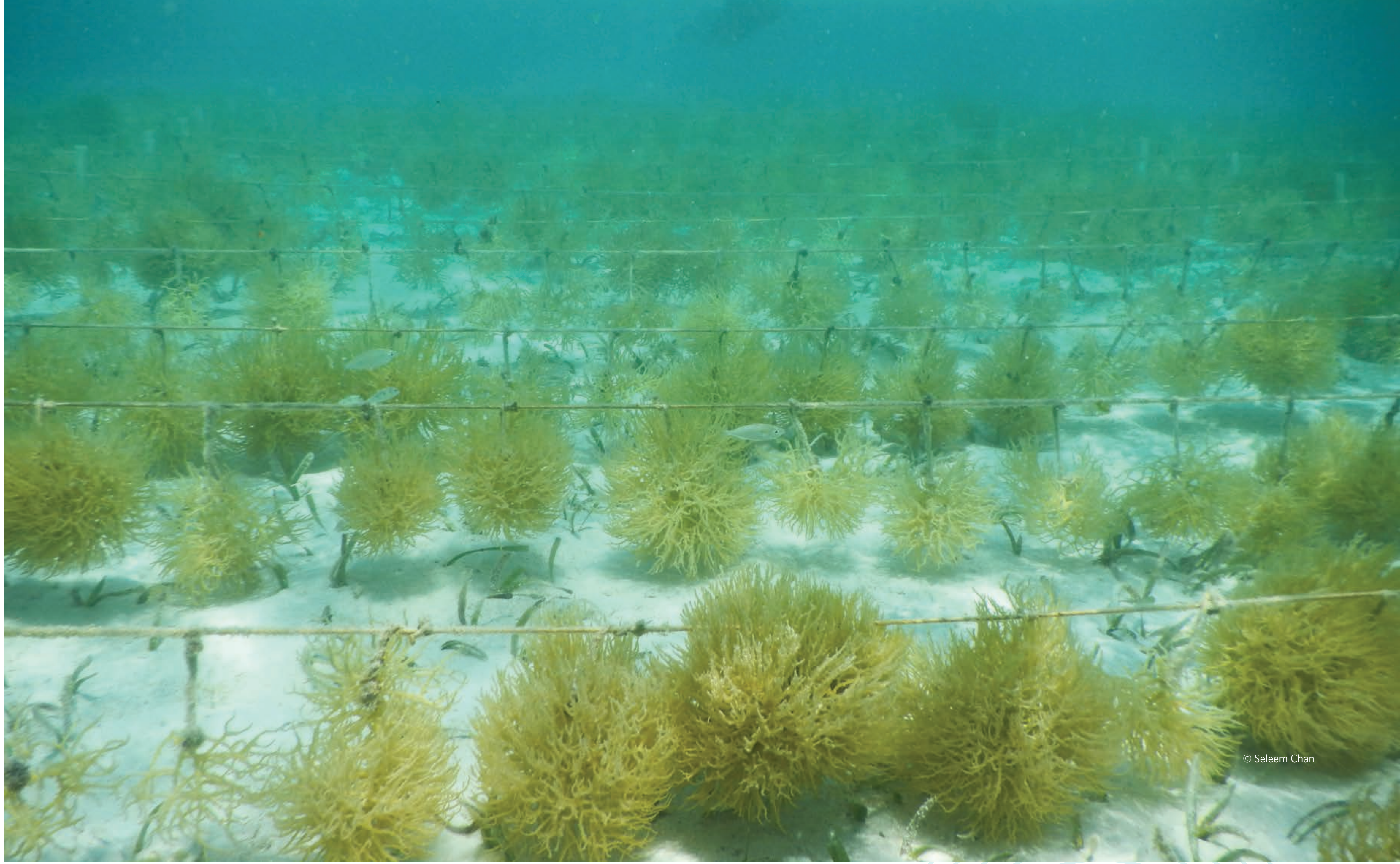
Seaweed Aquaculture in Belize for Habitat Benefits

BELIZE

ENVIRONMENTAL CONTEXT AND GOALS

As a part of fishery reform efforts at a national level, investment into the development of a seaweed aquaculture industry is being made in Belize, with a focus on finding a solution for both people and nature. Efforts to develop a seaweed industry began in 2010 due to decreasing opportunities in fisheries associated with diminishing catches of wild lobster, conch, and reef fish. The seaweed industry has been welcomed by the community as an opportunity to increase their economic resilience and conserve the wild fish they rely on, while still making a living on the ocean. The culture of the native seaweed Eucheuma isiforme is being developed with the intent of supplementing and diversifying income for fishermen, and to relieve pressure on wild stocks of fishery resources (PSF, 2020). E. isiforme remains the most extensive species for cultivation alongside a small domestic market for Graciliaria, though it remains uncertain which species in this genus is being used for cultivation.

Ecological monitoring at two pilot seaweed farming sites in Placencia by TNC has identified an overall minimal impact and measurable ecological benefits from seaweed farming activities. Impacts on benthic composition, seagrass health, and fish and macrofaunal species richness and abundance, as well as ecosystem parameters such as nitrates, light intensity, temperature, and dissolved oxygen were assessed during 2017 and 2018 (Foley, 2019).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An "Ecological Score Card" was used to evaluate the effects of seaweed farming at these trial sites across 16 variables. At Hatchet Caye, the control site averaged a score of 3.0/5 (3 considered equivalent to normal conditions found prior to establishment of a farm), while areas adjacent to rafts averaged 3.56/5 and inside rafts averaged 3.64/5. This assessment indicated that overall ecological health was enhanced above normal conditions, both within and immediately surrounding farms.

At both sites, fish biodiversity was either higher or increased more over time around seaweed culture rafts than at control sites. At Hatchet Caye, ecologically important reef grazing fish species were found to be present around the rafts absent at the control sites, and general macrofaunal abundance was also found to be higher. While monitoring of nutrient concentrations has been limited, no significant phosphate concentrations were detected at the single site tested. Nitrate levels were found to be


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higher at the farm site than at the control site, though these were not significantly different. The reason for this difference is unknown and requires further assessment (Foley, 2019).

Some seaweed farming takes place within mixed-use Marine Protected Areas under research permits. Farm sites are also currently 30-40km offshore from mainland Belize, far away from inhabited areas. Hatchet Caye/ Little Water Caye and Turneffe Atoll are approximately 17 and 23 nautical miles from locations that the farmers live in; Placencia and Belize City respectively. Identifying sites closer to the mainland is a future consideration. But, while this would have economic benefits for the industry it is expected that climate change will be a challenge (Tucker and Jones, 2021). In 2019 water temperatures increased substantially in Turneffe, and is suspected to have resulted in die-off of pilot farms at that time. This has led to experimentation with new farm designs. The industry was previously using floating raft systems, however these resulted in seaweed staying close to the surface of the water, usually hanging 1-2 feet below the surface where the temperature fluctuates the most. The new system being tested has seaweed submerged closer to the seafloor, where temperatures are known (from monitoring surveys conducted by TNC) to remain more consistent, and infrastructure less vulnerable to extreme weather events.

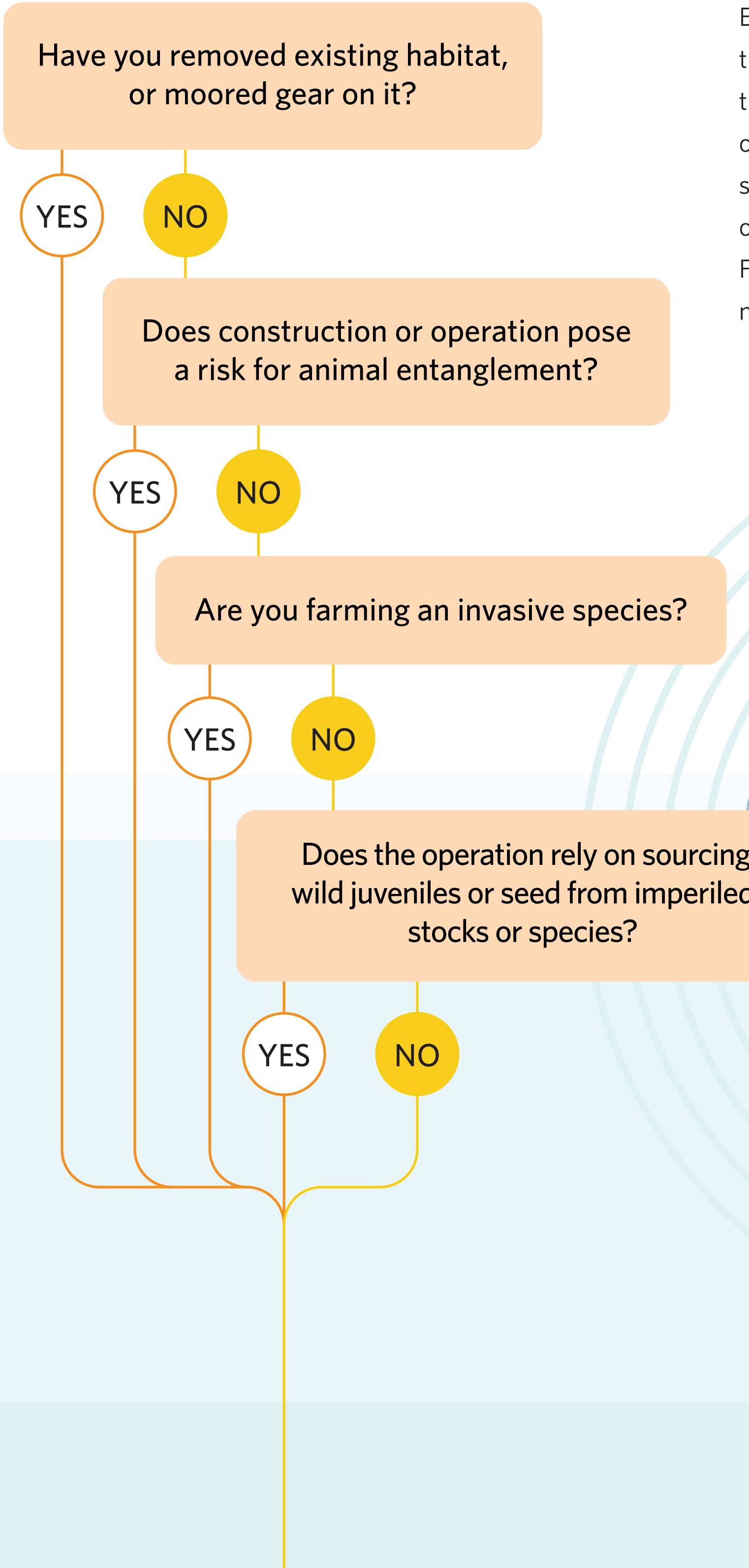
CURRENT STATE OF THE INDUSTRY

Annual production volumes of E. isiforme in Placencia and Turneffe Atoll vary, with production to date from the largest farm in the Placencia Seaweed Farmers (PSF) division totaling 590 kg. Nearly all production is sold locally with many local shops using seaweed in smoothies and milkshakes with purchase of seaweed for USD 15 per pound (USD 7 per kg); two times the global average price. Seaweed is also used in health care products sold in local markets. The intent of the industry to scale up and sell to those who have expressed interest internationally, potentially into a cosmetics market that would value the relatively pristine waters in which the seaweed is farmed.

The Placencia Producers Cooperative Society, formerly a fishermen's cooperative, has played a lead role in the seaweed development effort and shifted its focus entirely toward seaweed production through its PSF division. More recently, with support from TNC, the Belize Women Seaweed Farmer's Association was founded in 2019. Both groups are based out of Placencia and farming sites for both groups are based in Little Water Caye and Hatchet Caye respectively, and further effort is being made in Turneffe Atoll to expand the industry. These groups currently support the operation of a handful of pilot farms and one commercial farm.

The development of a seaweed industry in Belize has also been supported by the Belize Fisheries Department. While there is currently no industry-wide governance in place to guide this development, the Belize Fisheries Department, The Nature Conservancy, and the Seaweed Working Group are collaborating to develop an effective approach and supporting policies and are in the process of creating an industry-wide plan for socio-economic and ecological sustainability.

Application of Roadmap: Does the Aquaculture Operation Improve Habitat and Fish Stocks?



Existing habitat has not been removed to develop the activity. Farming infrastructure is used that should minimize the risk of entanglement of other species, though this impact has not specifically been assessed because of the low occurrence of marine mammals in the area. Farming activities are being development for native seaweed species only.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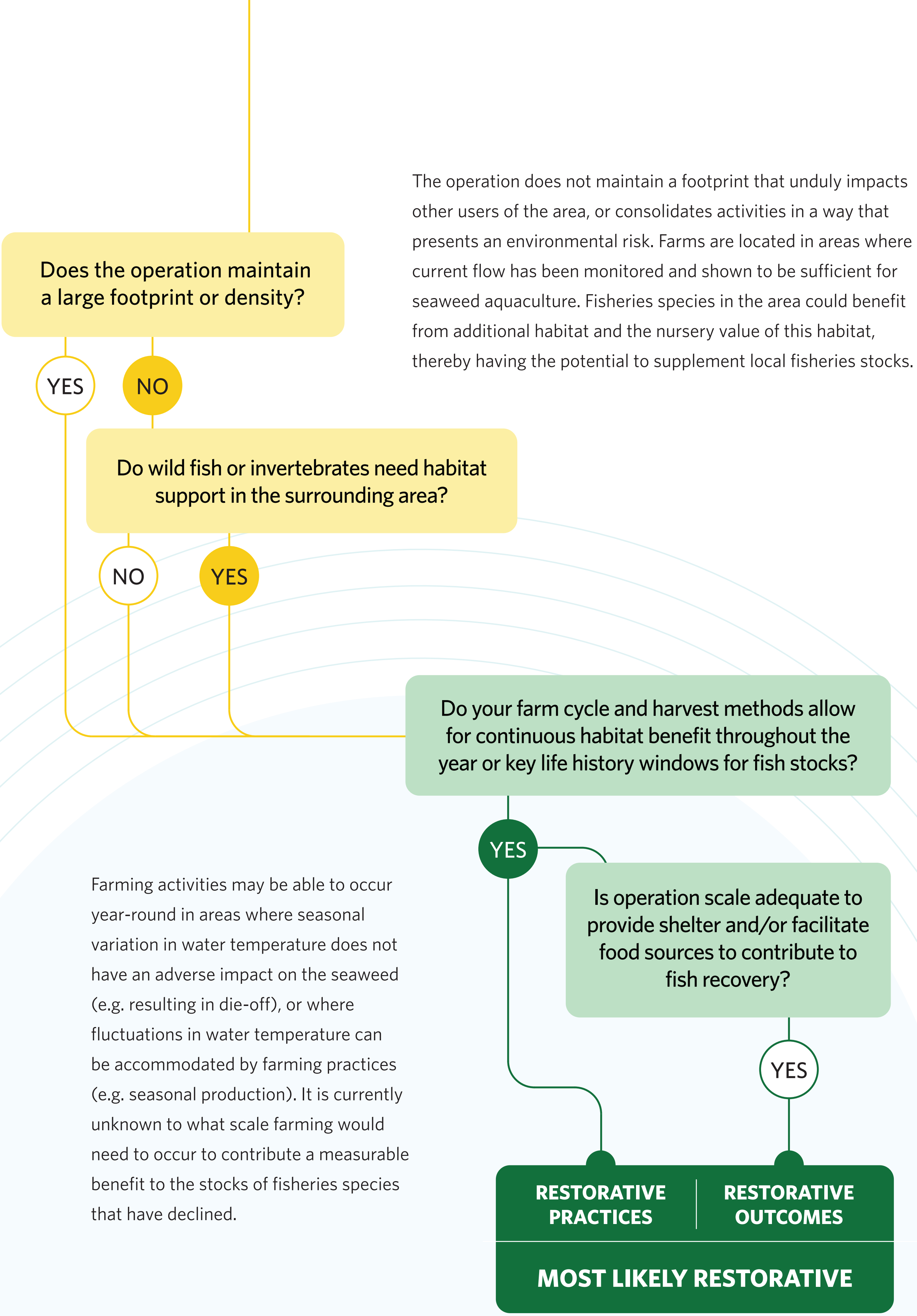
The operation does not maintain a footprint that unduly impacts other users of the area, or consolidates activities in a way that presents an environmental risk. Farms are located in areas where current flow has been monitored and shown to be sufficient for seaweed aquaculture. Fisheries species in the area could benefit from additional habitat and the nursery value of this habitat, thereby having the potential to supplement local fisheries stocks.



Farming activities may be able to occur year-round in areas where seasonal variation in water temperature does not have an adverse impact on the seaweed (e.g. resulting in die-off), or where fluctuations in water temperature can be accommodated by farming practices (e.g. seasonal production). It is currently unknown to what scale farming would need to occur to contribute a measurable benefit to the stocks of fisheries species that have declined.

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SUMMARY

Monitoring of initial seaweed farming activities in Belize indicates that measurable habitat benefits are being provided, and that the environmental benefits provided by these sites are greater the negative impacts. There is the potential for these sites to provide a nursery function, to replenish declining wild stocks of ecologically and commercially important reef-associated species of fish and invertebrates. Based on this habitat benefit the seaweed farming activities being developed could be considered restorative aquaculture. However, research and monitoring should be continued to more comprehensively understand the scale at which farming needs to occur to provide a consistent habitat benefit, at the farm-scale and beyond the farm to effectively enhance fisheries stocks. Positive effects such as these could be considered in planning for development and growth of a seaweed aquaculture industry (e.g. spatial planning for siting to gain from this environmental benefit) to maximize ecological but also social and economic outcomes.

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