SUSTAINABILITY CONSIDERATIONS FOR THE EXPANSION OF US OPEN OCEAN AQUACULTURE

Unleashing Advances in Science, Technology, and Artificial Intelligence to Support Sustainable Open Ocean Aquaculture in the US

Environmental Defense Fund

About Environmental Defense Fund

Guided by science and economics, Environmental Defense Fund (EDF) tackles our most urgent environmental challenges with practical solutions. EDF is one of the world's largest environmental organizations, with more than 2.5 million members and a staff of 700 scientists, economists, policy experts, and other professionals around the world.

About the Project

EDF and partners are pursuing a science-based, inclusive approach to the development of aquaculture in the federal waters of the United States. EDF advocates for federally directed research to better understand potential offshore aquaculture impacts and steps needed to ensure aquaculture operations throughout the supply chain are sustainably designed and use best practices, which minimize risk. Well-regulated, responsible, and sustainable open-ocean aquaculture operations can drive new investment and jobs, support community resilience, increase U.S. food security, and address issues associated with climate crisis disruptions. EDF is working to build support among ocean, coastal, and seafood stakeholders and policy makers to establish a rigorous, science-based environmental and social regulatory framework that provides a predictable environment for business investment, protects ocean health, and supports equitable outcomes for coastal communities and individuals working throughout the seafood industry.

To learn more about EDF's U.S. aquaculture portfolio, contact Maddie Voorhees, EDF's Climate Resilient Fisheries and Oceans program at *mvoorhees@edf.org* or visit *www.edf.org*.

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Sustainability Considerations for the Expansion of US Open Ocean Aquaculture: Unleashing Advances in Science, Technology, and Artificial Intelligence to Support Sustainable Open Ocean Aquaculture in the US

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Environmental Defense Fund (EDF) enlisted Council Fire, PBLLC to collate research on the current landscape associated with the containment of native finfish species relevant to developing a U.S. open ocean aquaculture industry. This paper was developed in collaboration with EDF staff, who seek to identify ways to optimize opportunities and minimize risks to people and nature while supporting a sustainable seafood system domestically.

Contents

Sustainability Considerations for the Expansion of US Open Ocean Aquaculture: Unleashing Advances in Science, Technology, and Artificial Intelligence to Support Sustainable Open Ocean Aquaculture in the US

Introduction

This White Paper explores developments in science and technology that could support a sustainable, competitive open ocean aquaculture industry in the United States Exclusive Economic Zone (EEZ). It then highlights examples where U.S. research and development could progress technology, enabling the country to engage in sustainable domestic open ocean aquatic food production.

"Open ocean aquaculture" refers in this paper to aquaculture carried out in waters 3-200 nautical miles from the U.S. coastline – i.e., in the U.S. EEZ, also known as federal waters, outside states' legal jurisdiction. The focus is on the *physical conditions associated with the open ocean* rather than all waters that happen to fit the legal definition of falling within the EEZ, namely the challenging conditions associated with deeper water, stronger currents, higher winds, and exposure to the generally harsh, high-energy and high-risk conditions of the open ocean.

Commercial farming of plants and animals in the open ocean in the U.S. will be a challenging enterprise. To protect the ecosystem and gain the needed public support, open ocean aquaculture must affordably solve the ecological risks it poses. The key risks are depletion of wild fish stocks to feed carnivorous cultured fish, escapements of cultivated fish that could carry either diseases or genetic risks to wild fish, harm to the ocean habitat from animal enclosures, or (to a lesser extent in open waters) pollution from feces and feed. Growing and scaling the U.S. aquaculture industry requires identifying technological and scientific solutions to reduce these risks at an economically reasonable cost.

Regulatory and permitting challenges also stand in the way of widespread open ocean aquaculture today. Only one permitted finfish farm operates in deep water, in conditions similar to federal waters, Blue Ocean Mariculture, which operates in Hawai'i ("There's Only One Offshore Fish Farm in the U.S. Why?", 2024). In 2022, marine aquaculture (finfish, mollusks, and seaweed), including all offshore marine waters (open ocean and more protected), represented 35.3% of global aquaculture production however, only a tiny fraction of that production was in North American waters (The State of World Fisheries and Aquaculture, 2024; Zajicek et al., 2021).

Yet, industries with decades of relevant expertise – among them marine transport, offshore oil and gas, terrestrial agriculture, genetics and related fields, modeling and data mining, pharmaceutical development, satellites, and artificial intelligence – have been innovating, adapting, and evolving new technologies and scientific and engineering approaches in the U.S. that are making it possible for the ocean sector to develop and evolve.

This paper identifies several current and emergent technologies and innovations in science, engineering, artificial intelligence (AI), and other fields that could help make open ocean aquaculture economically viable and sustainable in U.S. federal waters, especially if remaining knowledge gaps and permitting challenges are addressed.

Innovations in Nutrition: Reducing Impacts, Improving Results

Globally, deep water finfish aquaculture is dominated by finfish whose nutritional requirements are met with aquaculture feed. Aquaculture feed is traditionally mainly derived from forage fish, also known as bait fish, and has represented the biggest portion of ongoing operating costs[1] and a significant ecological and reputational challenge for the aquaculture industry.[2] Over the decades, the aquaculture industry has lessened reliance on wild-caught fish mixing terrestrial crops like soybeans into aquaculture feed (Naylor et al., 2021; ("Soy Helped Build Aquaculture"), 2021). To ensure the farmed fish still receive their nutritional needs, aquaculture feed producers have tackled the animal nutrition challenge from numerous angles, including by

[1] Feed is typically the highest input cost for a finfish farmer ("ASC Feed Standard", n.d.).
[2] Today as much as a quarter of captured fish are used for feed, although primarily for terrestrial animals (Siddik et al., 2024). In the ongoing global debates about food security and equity, as well as biodiversity, the pressure to prioritize utilization of captured fish for direct human consumption over animal feed is likely to continue to increase ("West Africa", 2024).

(1) developing novel fish feed ingredients, such as algae and insect larvae, (2) pioneering new technologies to use byproducts from wild-caught fish industries, (3) developed precision case-specific feed formulations to optimize feed for animal health, growth, and to minimize metabolic waste, and (4) employing precision genetics to breed improvements that optimize animals' ability to convert feed to muscle. Overall, the trend continues toward reducing reliance on wild fish and improving the efficiency of converting feed to fish mass (feed conversion ratio) (Zajicek et al., 2021).

Other feed-related innovations related to waste reduction, circularity, and AI are discussed below.

Novel Fish Feed Ingredients

Fish need proteins and omega-3's in their feed to thrive and to pass such nutrition to humans as consumers. Innovations in aquaculture feed aim to replace environmentally and economically costly wild-caught, fish-derived proteins and omega-3s with effective and lower-cost options that will increase the sustainability of aquaculture production. **Microalgae**, single-celled organisms found in fresh and saltwater, is one such example. Microalgae have been used successfully as feed supplements, improving growth, gut health, immunity, and disease resistance in aquaculture production (Siddik et al., 2024). More research is needed to lower production costs, pair fish with the best algae species, advance this product from the supplement to the bulk product stage and create precision formulations containing optimal quantities of omega-3's and proteins to support the growth and health of the fish species being fed, hence optimizing the production process. This area represents a critical topic for further research and investment because algae rely solely on the sun for food production through photosynthesis, without the need for fertilizer or fossil fuels. Researchers of one in-depth assessment concluded that "[a] number of complex research challenges lie ahead to find the best production measures to produce, harvest, and process this potential feed source at scale, but there is great promise for future expansion" (Siddik et al., 2024; Pers. Comm. Mathiesen, 2024).

Likewise, **insect-derived feeds** such as Black Soldier Fly Larvae (BSFL), rich in protein and able to be raised rapidly on-site, using far less land than soybeans or corn, have recently secured the necessary permits to be used as fish feed in the U.S. and EU.[3] This novel aquaculture feed source has not only been shown to improve immunity and growth in aquatic animals, but the BSFL can themselves be fed with, for example, residential food waste (as in a system in Singapore) or aquaculture food waste, as in an example in Chile to convert otherwise-unwanted waste into a valuable resource (Mohan et al., 2022; “Insect Farming Projects”, n.d.).[4]

In the feed innovation category, **single-cell organisms** are a rapidly developing field for aquaculture, as yeast and bacteria are used in feed formulations. “In a process similar to beer brewing, single-cell ingredients are produced by aerobic fermentation, pasteurized, dried, and then added to other dry ingredients during feed manufacturing. These products provide nutrients that replace less sustainable ingredients. Their high protein content and essential amino acids make them ideal for fish growth and development” (“Innovations in Sustainable Aquaculture Feed”, n.d.). Methane and carbon dioxide gasses, or liquid agricultural wastes or methanol, can be used as feedstock in fermentation, minimizing land conversion needed to increase terrestrial crops for aquaculture feed, such as corn or soy. Id. A pilot plant launched in Lisbon in late 2023 by MicroHarvest is an example of bacterial aquaculture feed innovation. The plant will produce an aquaculture feed called HILIX, made from extracted bacterial cells containing a mix of amino acids, proteins, free nucleotides, vitamins, and minerals, according to the company (Negrete, 2023).

Precision Genetics: A ‘New Breed’ of Aquatic Animals

Breeding genetic improvements to optimize aquatic animal feed conversion efficiency is not new. In Finland, for example, a long-term selective breeding program for rainbow trout (*Oncorhynchus mykiss*) improved their feed conversion ratio (i.e., higher efficiency to turn the nutrients in feed into fish mass) dramatically: compared to the 1980s, today, only half the amount of feed is needed to raise the same kilograms of fish. Better conversion efficiency reduces the environmental impact of waste from effluent and uneaten feed (similar to runoff

[3] The EU recently changed its rules to allow insects in fish feed (“Is the Time Ripe for Using Insect Meal in Aquafeeds?”, 2022).

[4] Because heat energy is needed to sustain BSFL production, siting and climate will naturally set geographic limits on locations where this innovation is practical (Pers. Comm. Mathiesen, 2024). Since the nutritional value of BSFL changes in quality and quantity based on the nutrient source on which it breeds, using food waste for BSFL’s food source must be carefully controlled to ensure that the diet for aquatic animals being cultivated stays balanced.

from excess fertilizer). Production costs have dropped, and profits have increased commensurately (Kause et al., 2022).

Using genetic sequencing and gene editing, conventional breeding techniques could be vastly enhanced and sped up to select for desired characteristics—including disease resistance, speedy growth, feed conversion rates, reproductive success, etc. (Yue and Shen, 2022; "Tools and Techniques", 2024). Aquaculture has only just begun to reap the potential benefits in this realm.

Precision Nutrition: Crafting Case-Specific Nutrition Formulas

Crafting species-specific nutrition formulations is another area in aquaculture that offers opportunities for better performance: improved feed conversion ratios, reducing the discharge of excess nutrients. For example, researchers have found that protein needs vary highly from species to species – ranging from 24% to 70% of the diet, depending on species and life stages, among other factors (Teles et al., 2020). For example, the feed giant Skretting announced in 2024 the availability of AmiNova. This fish feed formulation was specifically calibrated to the amino acid profile of Chilean salmonids. It contains the 'ideal amount of digestible 'amino acids to carry out their function in fish nutrition for this species. The precision diet removes what would otherwise be excess amounts of protein from the feedstock, which, as noted above, reduces risks of nutrient pollution and associated eutrophication risks. Skretting called this the 'next step 'in evolving their fish feed away from removing marine 'raw ingredients '(i.e., capture fisheries species targeted for feed) from their aquatic feed ("Salmofood Gets RTRS Chain of Custody Certification for Soy", 2024).

Innovations in Open Ocean Facility Siting, Infrastructure Design, Materials and Servicing

It is critical for open ocean operations to be located in sites that reduce conflicts with other ocean uses, conserve ocean ecosystems, and provide optimal conditions for the profitable and safe farming of aquatic species. Rapid advancements have been made in addressing the challenges of open ocean conditions, notably high-energy wave action, extreme weather conditions, and predation attempts such as by sharks and other charismatic megafauna. The need to identify optimal locations for mooring facilities and reduce the impacts of enclosures on the surrounding ecosystem while controlling the costs of monitoring, servicing, and maintaining facilities located further from shore has inspired innovations in modeling, facility design, and several related fields.

Placement Considerations

Open ocean sites are generally more exposed to the intensity of ocean conditions and have deeper waters, wave action, and current movements than enclosed fjords or shallow coastal waters. This may alleviate common challenges in enclosed environments, such as reducing fish waste accumulation. However, appropriately siting aquaculture facilities in open ocean areas of the U.S., particularly considering complex factors such as increased water temperatures caused by climate change (and resulting changes in the location of various fisheries), toxic algae blooms, and increasing demand for marine energy and extractive uses, is still crucial to project acceptance and success.

Location Siting Tools

Major efforts to improve the modeling of relevant ocean and climate features and conduct siting for aquaculture in multi-sectoral ocean planning have changed the landscape for aquaculture location proposals over the last decade. **Sophisticated modeling systems** and ocean floor maps can predict seafloor impacts, currents, and metabolic waste flushing patterns to make siting decisions and avoid water quality impacts ("New Technology Provides Tools to Protect Water Quality", n.d.).

In two key U.S. EEZ areas, the Gulf of Mexico and Southern California, the National Oceanic and Atmospheric Administration (NOAA) has produced Aquaculture Opportunity Area (AOA) Atlases to identify siting options. The Atlases employ data sources that have fixed information and continuous sources (fishing, vessel traffic, and climate). They overlay 200 data layers to consider ocean tide, temperature, habitat conditions, national security, underwater cables, commercial navigation, fishing practices and gear use, cultural and heritage resources, current and future extractive uses, and other potential ocean uses. This comprehensive approach identifies and ranks the best siting options for open ocean aquaculture that minimize resource use conflicts. NOAA calls it the "most comprehensive regional marine spatial planning ever conducted for U.S. federal waters." These regional AOA mapping exercises are not a prepermitting product but could facilitate permitting efficiency. Four additional coastal areas are teed up for consideration in round two of this exercise (NOAA Fisheries, 2021).[5]

Infrastructure Design Innovations

The physical design of marine fish farms takes various forms, and infrastructure placed in the open ocean waters will have to be sturdy enough to withstand the rigors of waves, wind, predators, interactions with servicing vessels, and corrosion and fouling. Nearshore, fish farms began as floating nets, then evolved to surface cages–effectively containment nets with human walkways around them to perform farm operations like feeding, observation, and extracting market-sized fish.

Figure 1: Submersible cage. Source: Ocean Era

As enclosures have moved into deeper waters farther from shore, enclosure designs evolved rapidly to avoid conflicts with other users, reduce pollution associated with shallower waters, and lower flushing rates in more enclosed coastal bays and fjords. Ocean conditions necessitate different designs, including the ease of servicing cages from stable platforms in calm waters and species' biological needs. For example, benthic species like cod (*Gadus morhua*) and sea bream (*Sparus aurata*) will not do well in a surface pen. In addition, surface enclosures increase the risks of sea lice infestations and escapements. Innovations in submerged cages, submersible, and semi-submersible designs have emerged and continued to advance, resulting in stronger, lighter, and more cost-efficient infrastructure for ocean-based fish farming worldwide. Submersible cages are designed to do the following, according to their manufacturers:

- Avoid oxygen-depleting algal blooms that can be deadly to fish.
- Find optimal currents to keep fish active and healthy.
- Locate ideal water temperatures to optimize growth and avoid thermal stress.

[5] The next locations that are planned for AOA mapping consideration are: Western Pacific/Guam; USVI and Puerto Rico; Florida, and Alaska for shellfish and seaweed aquaculture (state and federal waters) (NOAA Fisheries, 2021).

- Avoid parasites that concentrate near the surface.

Submersible cages take several forms today. In Hawai'i, Ocean Era is trialing a submersible cage that floats below the surface in ocean eddies, raising kampachi (*Seriola rivoliana*); cobia (*Rachycentron canadum*), too, can thrive while remaining submerged. Figure 1 (above) is of submerged cobia cages designed by Innovasea. These enclosures can be raised to the surface for servicing and lowered completely underwater during stormy weather to protect from waves and wind (see this video).

Using submersible cages and focusing on species that can be reared in such enclosures, the U.S. industry could leapfrog over the challenges presented by widespread sea lice or other infestations (skin flukes, parasites) associated with surface cage systems, where the animals are more exposed to various disease vectors ("Soy Helped Build Aquaculture", 2021).

Figure 2: Semi-Submersible Aquaculture Platform. Source: "Intelligent Semi-Submersible, 2023"

Submersible designs operate routinely at depths of around 10 meters and are brought to the surface only for harvesting or servicing. In contrast, **semi-submersible**, rigid designs are normally operated at the surface, but they have ballast tanks that can be filled to lower them during adverse sea conditions, such as high winds and waves during storms. These semi-submersible pens are generally moored – or secured, to the ocean floor.

These rigid designs are also less susceptible to fish escapes caused by larger predators being attracted to the fish inside the enclosures or to breakage. Figure 2 is a semi-submersible aquaculture platform measuring 86x32 meters and 16.5 meters high in Liusha Bay, South China Province, raising golden pomfret (*Trachinotus ovatus)*. It is also equipped with solar panels, making it self-sufficient in energy production. It can be monitored and operated remotely ("Intelligent Semi-Submersible", 2023).

In places where bottom habitat impacts are a concern, **advanced mooring systems** that minimize interactions with the seafloor can offer alternatives. For example, Ocean Era, which grows finfish and seaweed in the Gulf of Mexico, is trialing a single-point swivel mooring design to reduce contact with the seafloor and associated impacts on habitat (Fujita et al., 2023).

Designs for open ocean systems that are entirely **unmoored** or free-floating – in effect, ocean-going barges with fish pens on board that can readily exchange water supplies – represent another design option. China has at least one large-scale pilot vessel of this kind on the water. The Guoxin 1, quoted as a ship twice the size of the Titanic, contains 15 breeding tanks in which they grow out fry (baby fish) that are first hatched on land and stock the tanks at a density 4-6 times greater than typical of traditional net pens. They can do this by using a system of continuous seawater exchange, using natural seawater, as the vessel cruises in deep ocean waters while avoiding bad weather and red tides ("China Delivers Guoxin 1", 2022).

Figure 3: China's Guoxin 1 aquaculture vessel. Source: The Maritime Executive, 2023

While some experts have pointed out that unmoored barges are not inherently bad (large numbers of fish naturally excrete in the ocean, and a floating system has no ocean floor impacts), this approach risks spreading diseases or invasive species in the ocean to wild populations. Unmoored vessels also present monitoring challenges if they travel in high seas waters outside the country of origin's EEZ (Pers. Comm. Smiley, 2024). Incidents, like discharging effluent or unobservable microscopic exotic species, could occur without regulation and enforcement.

Hybrid system designs combine terrestrial and open ocean elements. In Norway, it is common practice to rear salmon on land up to the large smolt stage (up to 12-15 months old) and then place them in open ocean cages, combining the land-rearing phase with the farming[6] of vegetables and utilizing the recaptured and recycled smolt wastes in fertilizer for the terrestrial crops. Keeping the fragile (and much smaller) juveniles in tanks on land can minimize the risks of exposure to disease and predation. The fish and cages are sturdier when the larger smolts are

[6] The practice of growing more than one crop species in one place ("Polycultures", n.d.).

placed in the submersible or semi-submersible cages in the open ocean. They are less susceptible to damage from predation or breakage due to severe weather or wave action than coastal surface cages. Icelandic aquaculture leaders hope to extend the polyculture approach to recycling fish wastes collected from deep water pens with enclosed designs and reuse them in farming polyculture on land (Pers. Comm. Mathiesen, 2024).

Net improvements decrease operational risks of escapes, predation, and biofouling. Open ocean pens are susceptible to predator attacks, unpredictable weather, and waves. Designers have developed stronger and more effective netting and cabling materials in response to these risks. In reviewing recent advances, one net manufacturer opined, "[t]he breakthroughs in predator-proof aquaculture netting technologies have been a significant step forward for aquaculture. With these advancements, fish farmers and seafood producers can protect their stock from predation with much greater ease than ever before" (Howard, 2023). For example, Dyneema mesh (self-proclaimed as "the world's strongest fiber"), which one major U.S. producer found was "shark-proof when taut."

Another example is the crocodile-proof polyethylene terephthalate, made by KikkoNet, which is used to improve the safe farming conditions for barramundi (*Lates calcarifer*) aquaculture in Australian waters. Blue Ocean Mariculture in Hawai'i combines copper alloy mesh and KikkoNet polyethylene. Copper alloy, while expensive, is not only predator-proof, but it is also resistant to the buildup of barnacles, algae, and other unwanted plants and animals, also called "biofouling"; thus, it saves net cleaning labor and materials costs (Sims, 2024). Copper alloy mesh netting can also be recycled, and it has a relatively long lifespan of seven to ten years (Fujita et al., 2023).

Future net design advances will likely focus on remote sensing, monitoring, and robotics, as well as creating "smart nets" to alert producers to threats and use alarms and deterrents to keep predators away (Howard, 2023).

Innovations in Maintaining Animal Health

Methods to prevent or mitigate transmission of pathogens or hereditary impacts between (and among) wild and cultivated aquatic animals are advancing in the aquaculture field. Valuable tools have been created but applied in only a few species thus far.

Genome Sequencing and Editing

While breeding and hybridization in plants and animals is as old as domesticated agriculture, and the science of genetics dates back to Gregor Mendel in 1865, the highly advanced tools of gene sequencing and editing[7] are game changers that create opportunities to speed up progress in breeding animals suitable for sustainable open ocean aquaculture at an entirely different rate. Advances in gene sequencing, for example, have made it far faster and less expensive to perform selective breeding for fish broodstock and raise fish with a very good feed conversion ratio or other highly desirable traits like disease resistance or resilience to warmer water temperatures.

The aquaculture sector has not seen adequate investment in genome sequencing, resulting in only a few species being studied in depth. Today, whole genome sequences are either wholly or partially available for only a handful of major aquaculture species groups, mostly freshwater (Siddik et al., 2024). However the industry is rapidly advancing with genetic sequencing techniques, which will eventually enable producers to enhance the performance and resiliency of more fish stocks, to enhance their overall health and performance on a faster timetable that builds on accumulated knowledge.

More than one U.S. expert recommended that the U.S. industry focus its open ocean sector development on diversification: to consider investing in valuable whitefish species rather than salmon (Smiley, 2024; Sims, 2024). That might mean selecting promising species (e.g., marketable, farmable, scaleable) and investing in their gene sequencing to incentivize progress and encourage movement in the direction of those species.

Gene editing is an emerging technology that can enable fish farmers to further enhance a valuable species' **disease or heat resistance, speed of maturity to harvest, or growth potential** (Siddik et al., 2024). Identifying and enhancing such characteristics could be the focus of advanced breeding efforts.[8] The Food and Agriculture Organization (FAO) Guidelines for Sustainable Aquaculture recommend that any gene editing efforts for aquaculture adhere to

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[7] This paper omits genetically modified organisms (GMOs), in which the genetic traits of one species are transferred into another, given the immense cost of market introduction due to difficulty of fully assessing risk, and public resistance to their production. In contrast, gene editing, which does not involve the introduction of another species ' DNA, is regulated less restrictively; genome-edited fish are approved for sale in at least three countries (Argentina, Brazil, and Japan; Fletcher, 2024).

[8] The latest in gene editing is being applied to try to save coral from extinction: CRISPR-CAS9 technology is being used to specifically pinpoint the heat-resistance gene from one coral and insert it into other coral species to create super corals - rapidly giving an assist to the evolution of the species ahead of the climate change heat wave that is likely to arrive (Holtzman, 2023).

the FAO Global Plan of Action for the Conservation, Sustainable Use, and Development of Aquatic Genetic Resources for Food and Agriculture.

Gene editing to achieve 100% **sterility** in farmed fish is another technique being pursued to support the commercialization of species for open ocean aquaculture; this can help mitigate impacts of aquaculture escapements on wild populations. In addition to posing a lower risk of cross-breeding with wild fish, sterile fish have shown faster growth due to devoting less energy to preparing for reproduction.

Disease Prevention & Mitigation

The industry has used various techniques to **vaccinate live fish**, including oral vaccines delivered via feed, injection, and vaccine baths. Yet disease outbreaks have continued to occur, resulting in the loss of affected animals (and attendant financial losses) and the need to cull other potentially affected animals. This is due to the evolution of viruses rendering vaccines less effective and the limited number of diseases for which vaccines are available (Siddik et al., 2024).

The latest in available disease response is the development of **autogenous vaccines** – i.e., vaccines that are rapidly developed for a specific disease outbreak at a particular facility, when no commercial vaccine exists, or when the pathogen has evolved such that a licensed vaccine is no longer effective. These more targeted and flexible disease responses can only be used by special authorization today and, thus far, have only been used in a few species, but their potential is huge. “Future autogenous vaccines could be developed in response to pathogen adaptation or modified to provide protection in different species. Effective and adaptable vaccines are paramount to ensuring that fish in aquaculture are protected from current and future pathogens” (Wright et al., 2023).

Antibiotics are used in aquaculture to (1) prevent diseases before they occur (by giving them at low, “sub-therapeutic” concentrations); (2) to treat sick animals; (3) to prevent or minimize an anticipated spread/ outbreak of disease, or (4) to improve the growth or food conversion rate of the animals. Antibiotics are usually administered as feed additives or in immersions (like vaccines). The use of antibiotics in aquaculture results in the presence of these substances in the water column and sediments and ultimately is linked to an increase in antibiotic-resistant bacteria spreading in the aquatic environment and posing the risk of human exposure to antibiotic-resistant bacterial infection. For this reason, minimizing the routine use of antibiotics whenever possible is desirable.

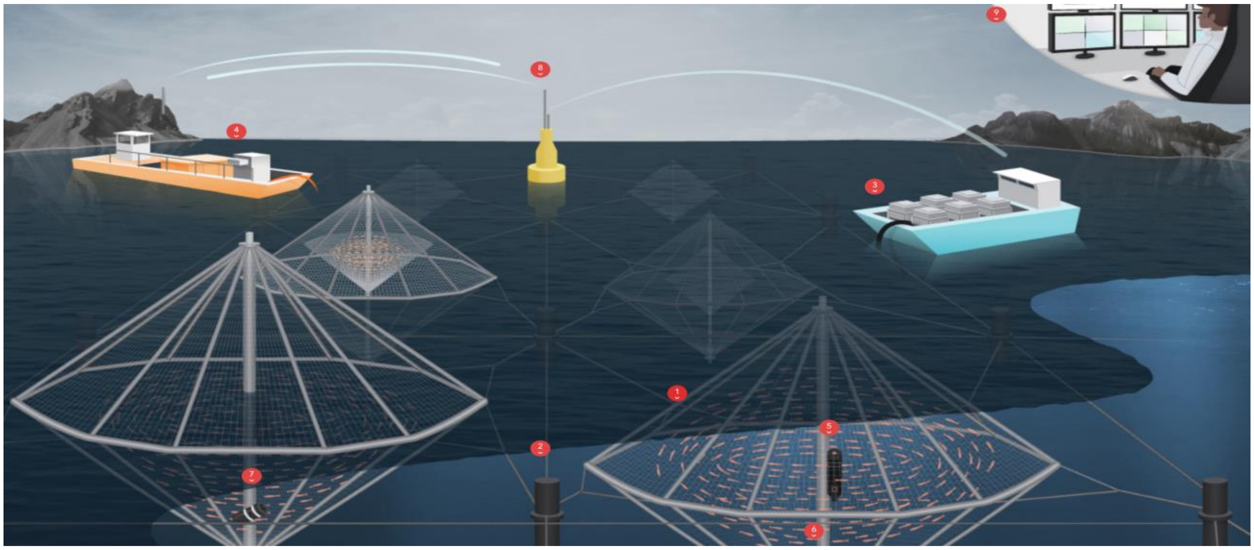
One area under development in aquaculture – outside the use of routine antimicrobial use, should bacterial infection occur – would forgo routine reliance on antimicrobials but instead turn to **bacteriophages to prevent infections**. Bacteriophages, viruses that infect and kill bacteria, are the focus of an upcoming research collaboration with aquafeed mega-producer Skretting and a pharmaceutical company; they noted the need to employ "a blend of technologies, like genomics, biotechnological engineering, bioinformatics, and artificial intelligence" in pursuit of methods to reduce dependency on antibiotics ("Salmofood Gets RTRS Chain of Custody Certification for Soy", 2024). However, this approach has disadvantages if the bacteriophages cause discoloration or scarring, lowering the value of the otherwise healthy fish (Mathiesen, 2024).

Antimicrobial peptides, compounds naturally produced in fish immune systems, are another new class of pharmaceuticals that can quickly eliminate harmful bacteria. They have other advantages over traditional antibiotics, such as rapid biodegradation and the ability to stimulate an animal's immune response. Thus far, antimicrobial peptides are not available for fish. Still, this area is ripe for further research investment to determine how best to administer them in fish and avoid the development of resistance (Wright et al., 2023).

Artificial Intelligence and Machine Learning Advances

AI and machine learning developments combine new capabilities in cameras, remote sensors, drones, the Internet of Things, data analytics, and robotics with AI, helping the industry tackle many of the challenges posed by open ocean operations.

AI and remote monitoring advances – the combination of continuous video imaging, collection and analysis of data, and machine learning – have been used to develop algorithms for optimizing feeding for different fish species, estimating biomass, detecting disease, and rapidly spotting escapes, among other things. These advances can save time and money and trips to the open ocean pens and thereby reduce emissions – they can also save stress on the fish and prevent escapes (which can occur during fish sampling grabs conducted the 'old-fashioned way') when divers have to open cages and grab fish for, e.g., counting lice or measuring (Innovasea Data Science, n.d.). Pairing other technology advancements like pen or enclosure design and precision feeding (described above) with AI and remote monitoring can make farm operations more efficient and effective (Figure 4).



(1) Submersible Pen System: Stays below the surface to avoid pounding waves and keep fish at healthier depths	**(6) Biomass Estimation**: Groundbreaking technology and advanced algorithms accurately assess each pen's volume of fish.
(2) Mooring System: A heavy-duty grid-based mooring system tethers pens to the ocean floor and keeps them secure during typhoons and hurricanes.	**(7) Feed Optimization**: Monitor environmental conditions, satiation levels, and pellet consumption to make data-driven decisions on the spot.
(3) Submerged Pen Feeding: A unique underwater feeding system feeds fish in each pen from a single surface point with minimal feed loss	**(8) Cloud Communications**: Data is delivered to operators in real-time and offloaded securely to the cloud to access anywhere using a smartphone, laptop, or tablet.
(4) Harvesting: Raising the pens gathers the fish in a smaller area to make harvesting easier.	**(9) Cloud-Based Software**: Combines real-time data with powerful analytics tools to give instant insights into farm operations.
(5) Environmental Sensors: Strategically positioned throughout the site, these monitor everything from water temperature and tilt to dissolved oxygen and turbidity to keep fish safe and healthy.	

Figure 4: Integrated AI and cloud-based technology to optimize farm operations. Source: Innovasea Open Ocean, n.d.

A recently announced plan by Innovasea to produce northern red snapper (*Lutjanus campechanus*) in the open ocean off the coast of Aruba (with an adjacent land-based hatchery) illustrates how electronic and AI innovations are combined. The company describes how they will "deploy various sensors that measure salinity, oxygen level, currents and other environmental aspects of the water. Other sensors will take measurements of the fish, aided by AI software. Stereoscopic cameras, for instance, will capture a left and right viewpoint, allowing 3D imaging. Feeding this information into AI helps it determine when a fish is in profile, making it possible to use that image to measure the dimensions of a fish and thereby track average size and growth. Other software will look at the behavior of the fish, using this data to determine if the fish are hungry or full. Associated AI software will employ machine vision to spot food pellets as they fall out of the cage. Together, these measurements can help [the company] adjust how much food should be dispersed and when it should be delivered, with the goal of optimizing feeding. The sensors and software serve two purposes, both tied to not having food do anything but make fish grow" ("How Offshore Oil Rigs Could Offer a New Platform for Aquaculture", 2021).

Disease Detection Through Imaging and Analysis

Rapid detection of disease or infestation in fish pens is critical for preventing disease spread within or beyond the enclosure. For example, Norway has recently authorized a camera system for automating the assessment of sea lice in farmed fish as an alternative to the time-consuming and stressing direct manual removal of fish from pens to check individual animals. This system combines high-resolution images with analyses of fish behavior to determine the presence and density of the parasites with a degree of certainty that was deemed adequate by regulators (Innovasea Data Science, n.d.).

In practice, disease detection technology can also look like the U.S.-based company Manolin, using machine learning models and predictive analytics technology to forecast the early onset of pancreas disease and infectious salmon anemia in farmed salmon, claiming an accuracy of over 93% (Mayer, 2021).[9]

Feed Optimization Through Cameras, Analytics, and Remote Feeding Options

The manual method to optimize feed usage involves experienced operators observing fish behavior on-site–including divers in the water– or via remote camera observation to determine when to start and stop feeding. Relying on experience, subjective knowledge, and judgment

[9] Manolin's disease forecasting tool was reported to be the only one for sale in 2021 when it became available.

about when the fish have been satiated based on their behavior is commonplace; however, detecting feed pellets in the water is difficult in sometimes turbid or stormy conditions in the open ocean.

Using machine learning models and analytics, **cameras** can capture enough images during a sampling period to provide statistically valid samples that can then be used to develop models about the biomass and behavior inside a net pen, which are needed for decisions about feeding and harvesting to optimize fish health, water quality, and profits. The adoption of such systems under the challenging conditions of the open ocean is still in its early stages, and trials are underway by industry leaders in open water production in Norway and Iceland's waters (Innovasea Data Science, n.d.).

Biofouling: Servicing & Cleaning Through Drones, Sensors, Cameras and Remote Operations

Drones and other unmanned vehicle systems make routine monitoring of open ocean farms safer and more affordable. There are currently three types of unmanned vehicle systems used in deep water ocean aquaculture that could be used in U.S. open oceans: (1) unmanned aerial vehicles (UAVs), (2) autonomous underwater vehicles (AUVs), and (3) unmanned surface vehicles (USVs). A recent overview of emerging technologies in the sector concluded that '[d]rones have become invaluable tools in aquaculture, serving various purposes beyond farm monitoring. Their versatility extends to tasks such as assessing and quantifying algal blooms, diagnosing diseases in aquatic populations, gathering sensor data, and facilitating water sampling" (Bohara et al., 2023).

Sensors and cameras mounted on drones have been used to transmit real-time data to trigger operator maintenance and servicing decisions in remote facilities. For example, dissolved oxygen sensors integrated with a remote device controller have been utilized to maintain the proper oxygen level in whiteleg shrimp culture, and machine learning has been used to distinguish dead embryos from live ones in a rainbow trout production system (Bohara et al., 2023).

Remote operation of an underwater drone equipped with a gripper arm enables an aquaculture facility to inspect nets and address maintenance issues such as attaching a hook or removing an unwanted object from the enclosure ("Underwater ROVs for Fish Pen Inspections", n.d.). This can speed up response to a problem, reduce risks to divers, and reduce fuel and vessel maintenance costs.

Automated robots, too, have been used underwater to inspect the status of and clean nets in the salmon industry, reducing the need for human operations in underwater enclosures (Yue and Shen, 2022).

Traceability for Inputs, Products, and Food Safety

Figure 5: This IBM infographic details the supply chain points that can be tracked and secured with blockchain technology. Source: Global Seafood Alliance, 2021.

Traceability is increasingly necessary to meet rising consumer expectations and regulatory standards for seafood products. The traceability tools that first took hold in capture fisheries 'fight against illegal fishing, such as satellite monitoring to trace a bluefin tuna from net to plate, also give aquaculture producers methods to show consumers responsible sourcing practices, gaining traction in the marketplace.

Blockchain, a method of securely storing data that enables the creation of a record or ledger so that one can trace a tagged object or transaction (whether a ton of fish feed or an individual fish) from its origin to its final destination, is one tool in the battle against mislabeled, illegal, or unsanitary seafood.

Thai Union, one of the largest seafood companies in the world, uses a trademarked blockchain transparency program called Sea Change to facilitate the traceability of its product supply chain to consumers and other stakeholders.

Nova Sea, one of Norway's largest salmon farmers, began implementing IBM blockchain technology to create a permanent digitized record of each transaction as its salmon products moved through the supply chain so that each party could download and use an app to scan each salmon lot at each point along the value chain ("Blockchain Expands Its Aquaculture Presence with Shrimp and Salmon", 2021). Radio Frequency Identification (RFID) tags are used for the individual fish, with a unique identifier that contains information about its origin, farming practices, and transportation history. However, an industry rep has noted that "[t]he absence of standardized traceability practices across the industry can pose challenges in data exchange and interoperability" ("Advanced Traceability System in Aquaculture Supply Chain", 2023).

Other Innovations for Open Ocean Aquaculture

Several promising sustainability innovations in open ocean aquaculture are visible on the near-term horizon, already at the pilot or commercial scale of operation or nearly ready to be taken up. Given the U.S.'s significant advantages in available open ocean area for placement of facilities,[10] and its vast industrial and technical capacity in science and agriculture, focusing on emerging and early-stage innovations provides opportunities to develop a cutting-edge, sustainable aquaculture program. While some of the below examples come from fisheries or nearshore aquaculture, they could be readily applied to open ocean aquaculture. The status of these innovations (whether commercialized, pilot scale or still in development) is noted in each case.

Commercialized: Integration of Open Ocean Aquaculture Facilities with Tourism

While it may not be suitable at every site, several diverse locations have combined ecotourism (and even recreational fishing) with open ocean aquaculture. For example, tourists in Greece can visit offshore sea bream (*Sparus aurata*) pens and go scuba diving to see the operation ("Aquaculture Tourism", 2023). China also facilitates tourism at a deepwater pufferfish (*Takifugu* spp.) production site in the Yellow Sea near Rongcheng ("Tourism Lure for Chinese Offshore Aquaculture", 2019).

[10] The U.S. has one of the largest EEZs in the world.

Waste Reduction and Circularity

There are multiple components to the need for innovation in waste reduction and enhancing the circularity of production for open ocean aquaculture: (1) reducing reliance on wild fish for feed, (2) reducing all waste in food production and use, and (3) making effective use of byproducts from all food production sectors. The first of these is central for high-value species likely to be grown in open ocean systems since they are often carnivorous finfish: their long-term sustainability (and ability to retain certification) will likely hinge on sourcing feeds that do not deprive humans or the aquatic ecosystem of critical food resources.

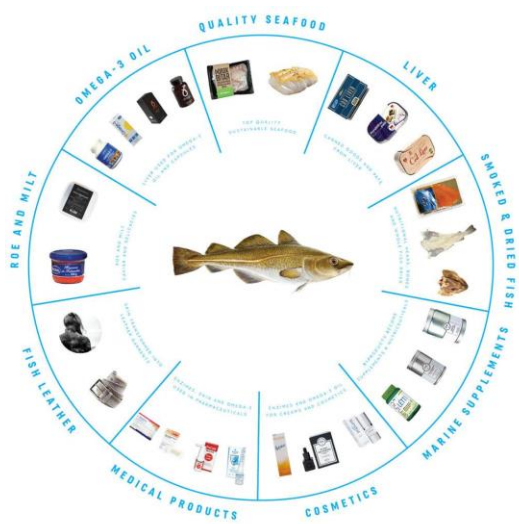


Figure 7: 100% Fish presents the range of products made out of fish in Iceland. Source: "100% Fish", n.d.

Commercialized: Using 100 percent of every fish

The Iceland Ocean Cluster, an economics and technology incubator, runs 100% Fish, a project whose mission is "to inspire the seafood industry and seafood communities to utilize more of each fish, increase the value of each fish landed, support new business opportunities, increase employment and decrease waste." After gleaning the most from each filet (caught or cultivated) with highly mechanized, laser-operated processing equipment, the Cluster's participants have identified and created new uses for every part of the animal – including fish leather, nutriceuticals, burn-healing bandages, and even a soft drink that mixes fish collagen with cola called 'Collab' (see Figure 7). A recent report states they have" unlocked uses for almost 95% of a cod (*Gadus morhua*)—a pretty recent jump forward. In 2003, people only knew what to do with about 40% of the fish" ("Iceland's Quest to Use 100 Percent of Its Fish Waste", 2023). The project groups wild caught and aquacultured seafood together with their goal of using 100% of each fish – and shellfish – consumed, tackling not only fish bones and mollusk shells but also the tubs and containers used in the processing of these products ("100% Fish", n.d.; Sigfusson et al., n.d.).

Figure 6: COLLAB RED - Raspberry & Apricot. Source: Nammi, n.d.

Under Development: Turning byproducts of fish processing into fish food

Food processing – including fish processing, is a significant source of waste if not properly managed. A Norwegian company, Berggylta, plans to help Norway address the challenge of wastewater treatment posed by the blood generated in processing millions of tons of fish each year while also producing a salable and nutritious fish feed. The company reports that they have submitted five patent applications to process fish blood into a feed source, intending to remove the fish blood from water and then process it into a feed ingredient for salmon – taking advantage of its high protein, iron, and omega-3 contents. They estimate the end product can make up 15 to 20% of a fish feed formula ("Norway Protein Source from Fish Blood", 2024). Any large-scale aquatic animal processing facility could evaluate this technology for its multiple potential benefits for water quality and reduced demand for other protein and omega-3 sources.

Pilot Stage: Integrated Multi-Trophic Aquaculture (IMTA) systems for triple-bottom-line benefits, standardized metrics

Three pilot studies, with various combinations of salmon (*Salmo salar*), seaweeds (various species), oysters (*Ostrea edulis*), sea urchins (*Paracentrotus lividus; Tripneustes gratilla*), white shrimp (*Litopenaeus vannamei*), tilapia (*Oreochromis niloticus*), and abalone (*Haliotis midae*), were conducted, some in ocean settings and some in laboratories on land, to determine whether these integrated systems of cultivation can contribute to meeting circularity goals. Since there are no standardized industry metrics today, the team fashioned several logical ones for the sector: water recirculation and bioremediation. The results showed very high levels of water recirculation by the bivalves, as well as bioremediation, which was improved by 80% to 90%, providing evidence that such multi-trophic systems could be useful for food production, nutrient removal, waste minimization, and water quality improvement simultaneously (Checa et al., 2024). While IMTA is not a new technology, the systematic documentation of its ability to meet multiple sustainability targets while producing multiple high value food products, including finfish, is a positive step; the recommendation that standard metrics be agreed to may deserve discussion.

Integration of Wind Energy & Aquaculture

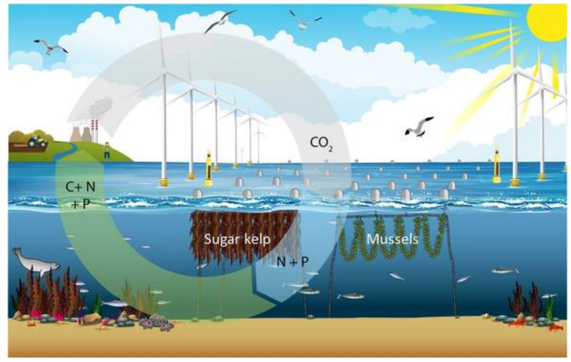


Figure 8: Conceptual figure of multi-use combining offshore wind farms with low trophic aquaculture. Source: Maar et al., 2023

Looking ahead to the potential of aquaculture to contribute to carbon drawdown - The integration of aquaculture with offshore energy (still speculative) combines offshore wind farms with farming of blue mussels and sugar kelp (Maar et al., 2023). While this design is not yet in place, it has been proposed to co-locate offshore wind farms with low-trophic aquaculture (mussels and seaweed) as an efficient, multi-use strategy that could provide emission-free energy, nutritious seafood, and restorative ecosystem services through capture and utilization of emissions (carbon dioxide (CO2) and nutrients), with carbon being built into the mussel shells via bio-calcification and nutrients and carbon into mussel tissue via other biological processes. The seaweed would remove nitrogen and potassium from the water column, mitigating localized ocean acidification and eutrophication. Improvements in local diets would be another benefit (Maar et al., 2023).

Sweden Proposal: Although the wind farm-seaweed carbon drawdown proposal above remains speculative, a co-located wind farm and salmon farm project has moved from being purely speculative to being publicly announced in the last few months. Freja Offshore, a Swedish company, reported that it would launch a joint venture with a Norwegian aquaculture company to establish aquaculture fish farms within its floating offshore wind farm in the North Sea, aiming to maximize the use of the space. According to the report, the cages will be submersible to 50-70 meters and independently anchored, not attached to the turbines ("Co-Location Pilot: Wind Farms and Aquaculture Set to Share Marine Space", 2024).

U.S. Proposal: In U.S. waters, Innovasea has proposed to repurpose a decommissioned oil and gas rig in the Gulf of Mexico that stands in 150 feet of water for aquaculture, perhaps combined with wind turbines but has said that it could be economically viable with cobia (*Rachycentron canadum*) aquaculture alone ("How Offshore Oil Rigs Could Offer a New Platform for Aquaculture", 2021).

Barriers to Progress & Recommendations

Despite the promise of open ocean aquaculture, the U.S. is not playing a leading role in open ocean production and remains heavily reliant on imported seafood today. For the U.S. to move forward with open ocean farming, barriers to investment and permitting will need to be addressed, as well as remaining questions on sustainability challenges.

The U.S. could take action to accelerate progress in developing a sustainable domestic open ocean aquaculture industry that meets more of the country's appetite for healthy seafood by opening the doors wider to innovation and operationalization. The next sections are specific recommendations.

Governance Recommendations

A recommendation to designate a lead agency for permitting and to establish a management and decision-making process for permit issuance stems from several studies of the state of progress in aquaculture in U.S. federal waters. These studies consistently found that the U.S.'s ability to move forward with open ocean aquaculture has been extremely slow, with the multi-layered review process and permitting being key factors ("A National Strategic Plan for Aquaculture Research", 2022; Love et al., 2017;" U.S. GAO Offshore Marine Aquaculture", 2008; Marshak, 2019).

Designating a lead agency could create enabling conditions for industry to use its ingenuity to address ecological and economic challenges, especially in the early phases, while many new designs and technologies are in the pilot stages.

In addition to permitting delays, another issue that affects the ability to attract financing for a pilot or new technology is the length of permitted time associated with farming sites. This is an area in which the lead agency could provide incentives for high performance and good choices and assist companies in gaining access to capital financing (Marshak, 2019).[11]

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[11] The FAO Draft Guidelines for Sustainable Aquaculture makes recommendations for all countries to establish a lead agency. The EU just issued similar recommendations in an effort to jump start its own open water aquaculture sector (Strategic Guidelines for EU Aquaculture, 2024). Far from being unique to the U.S., the problem of overlapping agency jurisdiction is inherent in a sector that operates in waters that are subject to shared public uses.

Looking at Norway, which is the global leader in open ocean aquaculture technology use, as an example, it is reasonable to predict that U.S. innovators will be able to design and innovate successfully for the specific performance requirements permitters establish to operate sustainably in challenging ocean environments once the permitting process begins. To kick-start necessary innovations, industry leaders have suggested an experimental permitting process. There is precedent in the U.S. fishing sector, with which NOAA has extensive experience. The Norwegian aquaculture sector discussed earlier in this report, offers an example of how this has stimulated innovation in aquaculture design.

One way to think of the progress gap is that the aquaculture sector in U.S. federal waters needs a management system, just as the nation has for the U.S. fishery management system. One study compiled and analyzed trends in both wild seafood and aquaculture, evaluating most nations that are members of the International Council for Exploration of the Seas (ICES)[12] and have extensive fishery management plans in place. The study found that "the majority of ICES nations lack long-term strategies for aquaculture growth, with an increasing gap between future domestic production and consumption" (Zajicek et al., 2021; Froehlich et al., 2018). The authors noted, "While great strides were made to support best fisheries practices—including governance, funding, and research support—to recover many wild stocks, much less effort has been given in most of the ICES nations to usher in aquaculture practices in a similar, but more anticipatory manner" (Zajicek et al., 2021). Like the U.S., these countries in Figure 9 also have major aquatic food production deficits.

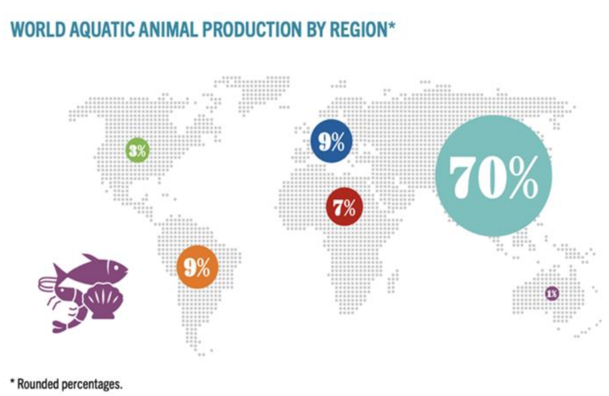

Figure 9: World Aquatic Animal Production by Region. Source: The State of World Fisheries and Aquaculture, 2024

Further evaluation is needed to determine whether **underwater and airborne drone operational rules** can be adapted to allow functional aquaculture facility operations to

[12] Belgium, Canada, Denmark, Estonia, Finland, France, Germany, Iceland, Ireland, Latvia, Lithuania, Netherlands, Norway, Poland, Portugal, Russia, Spain, Sweden, United Kingdom and United States were the ICES states analyzed.

proceed without imposing unnecessary burdens if drones operate only within facility boundaries or below delineated altitudes. This may be another area ripe for targeted investment in research and development.

The FAO Guidelines for Sustainable Aquaculture recommend industry-wide traceability standards and guidelines established via a process initiated by governments and inclusive of all parties ("Guidelines for Sustainable Aquaculture", 2024). Traceability made more practicable with new blockchain and remote transmission tools, is important for open ocean aquaculture and could benefit the entire industry.

Regulation and Innovation: Regulatory Guardrails Could Speed Progress While Protecting Ecosystems

As this report outlines, producers are researching and resolving key challenges in open ocean aquaculture, and production quantities are rising—although aquaculture progress has been slower in the U.S. and Europe compared to China. Many trends in technology and science are positive: for example, improvements in feed conversion ratios, ingredient usage, precision diets, and AI-and automation-assisted feeding systems have yielded major benefits.

However, innovative advancements still require enabling conditions for testing, piloting, and scaling within an environmentally responsible framework. Such a framework would include regulations that set science-based industry performance standards, ensure that operations are adequately monitored, and enforce sustainability requirements.

The Guidelines for Sustainable Aquaculture adopted by the U.N. Food and Agriculture (FAO) Committee on Fisheries in July 2024, balance the need to make space for innovation in an actively evolving area of materials, science, and technology by recommending precaution in most areas and by specifically identifying a small number of areas for formal regulation. The Aquaculture Guidelines recommend the following to "States and relevant stakeholders":

> *"Protecting the health and welfare of aquatic organisms requires the adoption of regulations and standards on health of aquatic organisms and on antimicrobial use, at all steps in the production cycle. The implementation of biosecurity protocols requires a national aquatic organism health strategy and associated action plans, enforced by enhanced national capacities with cost-effective management of the risks posed by infectious agents. Furthermore, regulations and standards and their enforcement should be based on international instruments in order to meet technical requirements concerning biosecurity, health management and animal welfare."* ("Guidelines for Sustainable Aquaculture" 17).

Financial and Research Gap Recommendations

Significantly increase federal support for both basic and targeted research, with the condition that federally funded research results must be shared in their entirety and data must be accessible broadly.

Aquaculture is the fastest-growing food production sector, yet current Federal research and applications investment remains very modest compared to investment in terrestrial agriculture. One study found that, from 1990 to 2015, the U.S. government spent $1.04B, including matching funds on aquaculture research and development (R&D). The U.S. Department of Agriculture's R&D spending over that time frame totaled $41B (Love et al., 2017). The same study calculated that $1 invested in aquaculture R&D had a 37-fold rate of return.[13] The U.S. is a leader in financing baseline research, such as the fundamentals of gene sequencing – but when it comes to aquaculture, there has been a failure to capitalize on the potential benefits of this knowledge in the aquaculture sector beyond a very narrow set of domestically important species (e.g., catfish, trout hatcheries). The U.S. oil and gas industry also has great expertise in offshore construction and operation, which can be repurposed for aquaculture. This is being explored in detail by the Gulf Offshore Research Institute, which was created to evaluate how to use decommissioned oil and gas platforms and infrastructure and the skill sets associated with them in the Gulf of Mexico.

The U.S. Department of Energy financed a study of how the federal. government and aquaculture industry could encourage the associated ocean sectors, whose skills and equipment have relevance for open ocean construction, observation, and servicing, to work together to make use of their shared skills and also to take advantage of the decommissioned energy infrastructure in the open ocean waters in the Gulf of Mexico for 'blue development 'in aquaculture. The study found numerous opportunities that merit a closer look, noting that both the platforms and the network of vessels and infrastructure that already exists could facilitate open ocean aquaculture production that would help to close the U.S. 'seafood import deficit and repurpose the infrastructure in a way that makes sense. "What we do have, that most other

[13] Notably, philanthropy is also underinvesting: a more recent study found that, from 2016-2021, global grantmaking for aquaculture was less than one tenth that of grantmaking for fisheries despite the fact that aquaculture now accounts for over half of aquatic food supplies worldwide (Summary of Funding to Aquaculture & Fisheries, 2024).

countries don't, are 600 unused offshore structures, any one of which can become a center supporting aquaculture," the authors noted (Robinson, 2021).

Technology: Consider novel financing approaches that generate innovation-sparking programs. For example, Norway incentivized sustainability innovation by offering fee-free open ocean aquaculture licenses for companies developing technologies to solve environmental challenges, foregoing millions of dollars of permitting fees. The competition (21 projects were awarded out over 100 applicants) led to a massive flowering of engineering creativity in offshore net pen designs, to which the public has had access. As a result, net pen design has benefited worldwide. Although the program meant forgoing millions of dollars in permitting fees, the estimated market value of those 21 projects was over 1 billion USD as of 2021 (Moe Føre et al. 2022). Other such competition could offer rewards for an innovative solution to an identified problem or challenge with an acceptable risk level. The key challenges for future competitions can be agreed upon via an inclusive process including academic, industry, community, tribal, and other interested parties; the permitting authorities can assess submissions with input from independent experts knowledgeable about the relevant innovations but not working directly for industry. Making winning designs or innovations public would not prevent patenting innovative designs.

Science: Expand genetic sequencing for promising species. Through a consultative process, identify priority native, popular, commercially promising marine species for genetic sequencing to enable focused research that can amplify key positive traits. Such traits may include climate resilience, feed conversion rates, or disease resistance. Because salmon has been so well studied in numerous locations worldwide, investments will likely find more value by emphasizing and addressing remaining questions about other native and marketable fish. Public concerns about risks from open ocean enclosures could be reduced if the species proposed for production are native and do not pose the special challenges of species, such as salmon, that have endangered wild stocks sharing the same waters (and competing for the same grocery shelves) with any escaped and genetically altered kin.

Support government research and joint public-private investment to identify, prevent, and treat aquatic animal diseases. This includes using various disease diagnostics that use cameras, sensors, and water DNA testing that can be employed at sea. Low-cost rapid diagnostics, especially ones that can be used in the field and do not require bringing samples back to the lab, are of particular value to open ocean facilities.

When determining research priorities, diversification and other priorities may shift focus onto species native to U.S. ocean waters other than the ones already heavily studied by the private sector.

Feed: Research into sustainable and nutritious alternatives to wild fish feed could benefit aquaculture. There are multi-layered benefits to the circularity-based advances noted in this paper: feeds that re-use byproducts such as fish blood or food waste and other food or plant processing byproducts to make feed, thus reducing waste and emissions as well as generating feed, are of particular importance if carnivorous fish are to be cultivated. Additional investment in consistently formulating precision feeds with byproducts of food production is a key area to build public support for raising potentially costly carnivorous fish in a climate-sensitive world.

Similarly, investment is needed to make microalgae a scalable and affordable feed ingredient and to cultivate native macroalgae as profitable products in solo or polyculture settings. Experiments in polyculture and determining which aquaculture products work best co-located in different regions ’AOAs deserve regional attention.

Sector Partnerships

The U.S. AOAs represent a remarkable milestone in multi-sectoral marine spatial planning: not only do they encompass a vast number of different users and time scales, but they also fully consider aquaculture and fisheries as part of the planning process. Until now, this has not been done, and NOAA can be credited with launching a next-generation process.[14]

In addition, the work of the Gulf Offshore Research Institute, which was initiated to focus on how offshore oil and gas platforms could be repurposed once they are no longer producing oil and gas, could serve as the starting point for a collaborative effort between the U.S. Department of Energy, NOAA, and the Bureau of Ocean Energy Management. This collaboration could establish a joint office for exploring and supporting research on the co-location of aquaculture facilities with offshore energy platforms in U.S. open ocean areas, including but not limited to the Gulf. The initiative also calls on industry experts to contribute their expertise and ideas to this endeavor.

[14] One additional note about the AOA Atlases: The data layers assembled in the development of this atlas will help the U.S. live up to its international commitment, as a member of the High Level Panel for a Sustainable Ocean Economy, an 18-country alliance of leaders committed to sustainable seas, sustainably manage 100% of the ocean under national jurisdiction by 2025.

Conclusions

The U.S. has an immediate and immense opportunity to move forward strategically with science-based open ocean aquaculture to make it a safe and sustainable ocean industry. Risks and challenges posed in fish farming in deep waters like disease and escapes, could be minimized through investment and novel incentives, such as experimental permits, that advance ocean farm technology and innovation. Although the U.S. is not currently a leader in open ocean aquaculture, the country could learn from the early actions of other nations – leapfrogging over some of their missteps and electing to forge ahead in the research and technology niches where there is room to excel. A ready market awaits the sustainable seafood and exportable technology the U.S. could produce in its abundant and still-untapped EEZ.

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