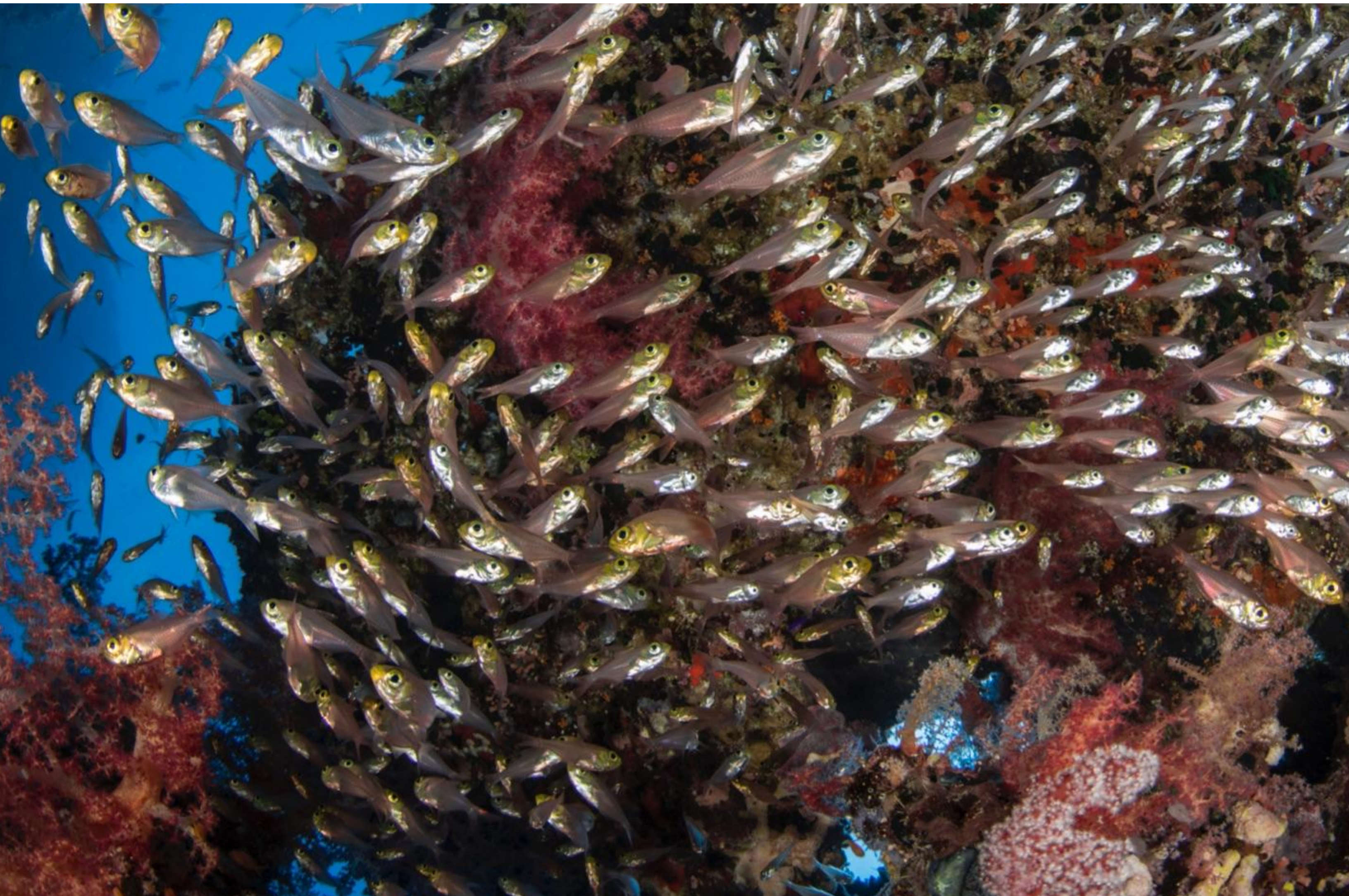
ACTION PAPER

An Ocean of Opportunity:

Plant-based and cultivated seafood for sustainable oceans without sacrifice

September 3, 2021



Executive summary

Our oceans hang in a precarious balance, along with the marine life they harbor and the billions of humans who depend on them for survival and livelihood. Innovative solutions are urgently needed to address the growing global demand for seafood without causing further—and irreparable—harm to ocean ecosystems. Advances in food technology and commercial innovation can drive market-based solutions in the form of plant-based and cultivated seafood, providing consumers with delicious, affordable, and nutritious seafood products without sacrifice.

Across the globe, overfishing and harmful fishing practices have damaged fragile marine habitats, destabilized ocean ecosystems, and severely depleted global fisheries—with over 90% of wild fisheries classified as overfished or harvested at maximal capacity (FAO 2020). As fisheries near coasts are depleted, more seafood is harvested from regions where laws and regulations are difficult to enforce despite the best of intentions for sustainable fisheries management strategies. The opacity of the industry conceals unacceptable occupational hazards, human rights violations like slavery, and rampant unregulated fishing. Despite pressing threats to the environment, global food security, and livelihoods—as well as risks to consumers from chemical and pathogenic contamination, fraud, and a lack of regulatory oversight—global demand for seafood continues to increase. Reducing pressure on global fisheries is critical to allow ocean ecosystems a chance to recover from decades of mismanagement.

The aquaculture industry has expanded rapidly—now providing over half of the global harvest—in an effort to meet the growing demand for seafood in the face of stagnant or declining wild harvests. But aquaculture systems often present severe risks including reliance on fishmeal and fish oil from wild fish, emergence of drug-resistant pathogens, destruction of sensitive coastal habitats, and escape of non-native farmed species into wild ecosystems. While more responsible aquaculture approaches have been demonstrated in some cases, the vast majority of aquaculture occurs in regions of the world where these techniques are seldom practiced, oversight is limited or nonexistent, and adverse impacts can exert global reach. Moreover, it is simply not pragmatic or possible to produce many of the types of seafood that consumers value in aquaculture systems.

Given these shortcomings and limitations of sustainable fisheries management and aquaculture, there is an urgent need for new approaches to complement existing efforts in order to meet increasing global demand for seafood. The development and widespread commercialization of plant-based seafood, which uses plant-derived ingredients to replicate the flavor and texture of seafood, and cultivated[1] seafood, which is produced by cultivating

[1] Cultivated meat has become one of the industry-preferred terms for products made from animal cell culture as a neutral term that is conducive to conversations with the conventional meat industry and with regulatory agencies. Other terms include clean meat—as a nod to the environmental benefits (akin to clean energy) as well as the reduced risk of bacterial contamination—and cultured meat and *in vitro* meat have historically been used as well. The terms cultivated meat and cultivated seafood are used throughout this report.

cells from marine animals, is an immensely promising approach for alleviating pressure on both wild fisheries and aquaculture systems, particularly if pursued in coordination with the right enabling policy frameworks. Plant-based and cultivated meat exhibit fundamentally higher efficiencies than cycling caloric value through animals, and they offer the unique opportunity to level the trophic playing field within seafood production. In other words, the raw materials and resources to create plant-based or cultivated versions of a top predator like tuna are essentially the same as those required for plant-based or cultivated versions of species at the bottom of the food chain.

Accelerating the development and commercialization of scalable plant-based and cultivated seafood products that compete on taste, price, accessibility, and nutritional quality with their ocean-derived counterparts should comprise a core component of global strategies to maintain the vitality and, ultimately, the survival of our oceans. In the last decade, the market has seen massive shifts in consumer demand and product innovation for plant-based alternatives to products of terrestrial animal agriculture. These trends are likely to reflect a similar forthcoming transformation within the seafood industry. In fact, there is reason to believe that the transition of seafood toward plant-based and cultivated meat solutions will occur with more urgency than for products like meat, poultry, and dairy, for which production has largely kept pace with increasing demand. The rapidly growing unmet demand for seafood coupled with the looming collapse of many global fisheries is likely to accelerate this shift. Furthermore, factors like the high incidence of seafood allergies and the high price points of several seafood products—especially products that are consumed raw and thus pose special consumer risks—generate a sizable number of highly motivated early-adopters and market entry points for plant-based and cultivated seafood products.

> "Striking trends in consumer demand and product innovation for plant-based alternatives to animal products like meat, poultry, and dairy are likely to reflect a similar forthcoming transformation within the seafood industry. In fact, there is reason to believe that the transition of seafood toward plant-based and cell-based products solutions will occur with even more urgency."

The transition to plant-based and cultivated seafood can be further accelerated by concerted efforts to apply insights from the development, commercialization, and generation of demand for plant-based and cultivated versions of terrestrial animal agriculture products. While many of these insights can be translated directly to plant-based and cultivated seafood, the seafood sector does pose some unique technical challenges for both plant-based and cultivated approaches. Consumer research providing a more nuanced understanding of seafood purchasing behavior across diverse consumer segments and cultures is also needed, to enable refinement of marketing and product development strategies.

While plant-based and cultivated seafood products will ultimately be produced and supplied through the private sector, the underlying technologies and their path toward commercialization will require a robust innovation ecosystem. Given that very little funding outside of a few companies' research and development (R&D) budgets has been expended in this area and that the estimated *total* global R&D expenditure to date across all forms of plant-based and cultivated seafood is on the order of about $100 million, this industry exhibits tremendous potential to benefit from concerted public and private resource allocation. To accelerate the process from early product development through to widespread market adoption, activities must be coordinated across startup companies, multiple sectors of established industries, private and public funders and investors, governments, trade associations, and academic and other research institutions.

All of these entities–and any individual who envisions a future with sustainable oceans of abundance–should consider this a call to action to contribute to the development and growth of the plant-based and cultivated seafood industry.

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Global threats posed by overfishing and marine ecosystem damage

Photo courtesy of Francesco Ungaro

1 Global threats posed by overfishing and marine ecosystem damage

The health and welfare of billions of people, and indeed the stability of life on earth, depend on ecologically diverse and stable oceans. Across the globe, overfishing has pushed several species to extinction and driven ocean ecosystems to the point of collapse. Restoring and preserving marine life is one of the 17 United Nations Sustainable Development Goals and the years from 2021 to 2030 have been designated the United Nations Decade of Ocean Science for Sustainable Development. Unfortunately, progress to reverse troubling trends for our oceans has been slow. In 2010, the 196 UN member states ratified the Convention on Biological Diversity, which set a goal of protecting 10% of the ocean by 2020. As of early 2020, only 5.3% of the ocean had been established as Marine Protected Areas (MPA), with less than half of that area being protected from fishing activity. Meanwhile, scientists and reporters are uncovering the true scale of the global fishing industry's harm to aquatic ecosystems (Wilhelm 2018; Mooney and Dennis 2018), consumers (Whittle 2018; Price 2018), and human rights (Nakamura et al. 2018; Urbina 2017). While the risks and harms of business-as-usual operations in commercial fishing are clearer than ever, the action necessary to mitigate these impacts is not progressing quickly enough.

1.1 Pressing environmental threats

Overfishing and harmful fishing practices have severely depleted global fisheries, damaged fragile marine habitats, and destabilized ocean ecosystems. A 2020 report by the United Nations Food and Agriculture Organization (FAO 2018) found that one-third of all fish stocks are being depleted faster than they can replenish. Another 60% of stocks are fished at the maximum sustainable level, leaving only 7% of fish stocks that are underfished.

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Destructive fishing methods have impacts far beyond fish stocks and may be the second-biggest threat to all ocean ecosystems after climate change (CEA 2017). Coral reefs, which harbor 25% of ocean fish species despite covering just 0.1% of the sea floor, provide up to $400 billion in economic benefits each year and are easily damaged by bottom trawling. Damaged reefs may take decades to recover (Althaus et al. 2009; CEA 2017). Bycatch—the unintended, unreported, and often unused catch of birds, turtles, sea mammals, juvenile fish, and other non-target species—represents over 40% of the entire global fish catch (Davies et al. 2009). Bycatch prevents the population recovery of some protected species and is a critical threat to ocean food chains.

The conventional fishing industry is increasingly contributing to climate change and the industry's projected future emissions are equally troubling. For decades, fishing fleets have used more and more fuel to catch fewer and smaller fish each year (Tickler et al. 2018). A 2021 study establishing a global conservation framework for the ocean through prioritized MPAs assessed the stored seabed carbon released through bottom trawling. Over 400 years of continuous trawling, the authors estimate annual emissions of about 0.58Pg (580 million metric tons) CO_2.(Sala et al. 2021).

Because many commercial fish species take many years to reach maturity, it can take decades for overfished or mismanaged regions to recover, even when protected. By destroying habitat and threatening marine species with collapse or extinction, mismanagement of fisheries exhibits a cascade of adverse impacts on entire ocean ecosystems. For example, removing large predators through bycatch or overfishing causes disturbances in the food web with high ecological, economic, and social costs around the world (Prugh et al. 2009). Reducing pressure on global fisheries is critical to allow commercial species and ocean ecosystems a chance to recover from decades of exploitation and mismanagement.

1.2 Global food security and sustainable livelihoods

As fisheries near coasts are depleted, more and more seafood comes from the high seas, where laws and regulations are extremely difficult to enforce. Fish are often transferred from small boats to resupply ships that combine the catches of many vessels. Because of this, even tracking a fish back to the vessel that brought it to port does not guarantee it was caught legally.

Widespread illegal, unreported, and unregulated (IUU) fishing has dire consequences for human rights and food security. A 10 billion dollar global business annually, illegal fishing ranges from schemes to misreport catches in New England (Bidgood 2018) to the enslavement of migrants in the South China Sea (Urbina 2017). Though illegal fishing is difficult to track, recent estimates suggest that more than one third of all fish caught around the world are caught illegally or are unreported (Pauly and Zeller 2016). A 2020 investigation from The Economist suggests up to 50% of global catch is illegal (The Economist 2020). In particular, international fishing fleets appear to report only a small fraction of their catch. Scientists estimate that in the seas off the coast of West Africa, fishing boats from the European Union and China reported only 29% and 8%, respectively, of their total haul between 2000 and 2010 (Belhabib et al. 2015).

The costs of IUU fishing are felt hardest by the world's most economically vulnerable populations.
As industrial fishing fleets deplete oceans, little is left for millions of subsistence fishers and coastal communities that rely on a daily catch for food and income. Over 800 million people are at risk of malnutrition if fish populations continue to decline (Golden et al. 2016). As global demand for seafood increases and wild catch decreases or stabilizes, it is clear that combating illegal and unregulated fishing will require dramatic changes across many sectors.

1.3 Risks to seafood consumers

Although global demand for seafood is expected to increase by nearly 30% between 2010 and 2030, seafood products pose unique risks to consumers. Pollution, fraud, and a lack of regulatory oversight lead to contaminated and mislabeled products. Commercial fish meat from many species and many regions around the world contains toxic concentrations of heavy metals, persistent organic pollutants, and plastic. Mercury contamination from seafood affects many millions of people worldwide, impairing brain, liver, and kidney function. In the United States (U.S.), up to 300,000 newborns are exposed to potentially toxic levels of mercury in the womb each year (Mahaffey, Clickner, and Bodurow 2004). Eighty to 90% of mercury in the human body can be traced to seafood consumption (Hong, Kim, and Lee 2012). A 2019 study predicted that climate change and overfishing will further increase mercury concentrations in fish. Long-lasting toxic chemicals such as insecticides and flame retardants accumulate in fish and marine mammals. Plastic can also bioaccumulate in aquatic organisms, with unknown implications for consumers who eat plastic-contaminated fish (Ivar do Sul and Costa 2014).

Despite these risks, many governments recommend consumption of fish to ensure intake of certain fatty acids. The FDA and many other organizations offer lists of fish and seafood species low in mercury to help consumers select foods low in toxic pollutants. Unfortunately, fraudulent and mistaken labeling of seafood makes it impossible for consumers to know for sure what fish they are buying. Twenty to 30% of all fish caught are mislabeled, often intentionally to market low-value fish as high-value ones or to hide illegal fishing in protected areas. One investigation from 2010 to 2015 found that one third of all seafood tested in the U.S. was mislabeled (CEA 2017). A 2021 meta-analysis of 44 studies on 9,000 products found that between 36% of seafood products were mislabeled. Often, mislabeled fish are species that tend to be higher in pollutants (Marko, Nance, and van den Hurk 2014). Alternatives are needed that can supply healthy, nutrient-rich protein without pushing ocean ecosystems and the human communities that depend on them further into crisis.

Plant-based and cultivated seafood as a new solution

Photo courtesy of BlueNalu

2 Plant-based and cultivated seafood as a new solution

As incomes rise and population increases, the United Nations projects an increase in demand for seafood of more than 32 million tons between the mid-2010s and early-2020s, even after accounting for higher prices (Junning Cai 2017). Wild fisheries are already harvested at maximum capacity, and they are increasingly yielding species that are of low value for human consumption, which are instead processed into fishmeal and fish oil. Coupled with projections for a slowed rate of growth of the aquaculture industry in coming years, this creates a severe demand-supply gap. In fact, aquaculture growth is only anticipated to keep pace with increased demand for 17 countries, while around 170 countries will be left with substantial unmet demand (Junning Cai 2017). Thus, there is an urgent and sizable need for altogether new approaches to meet increasing global demand for seafood.

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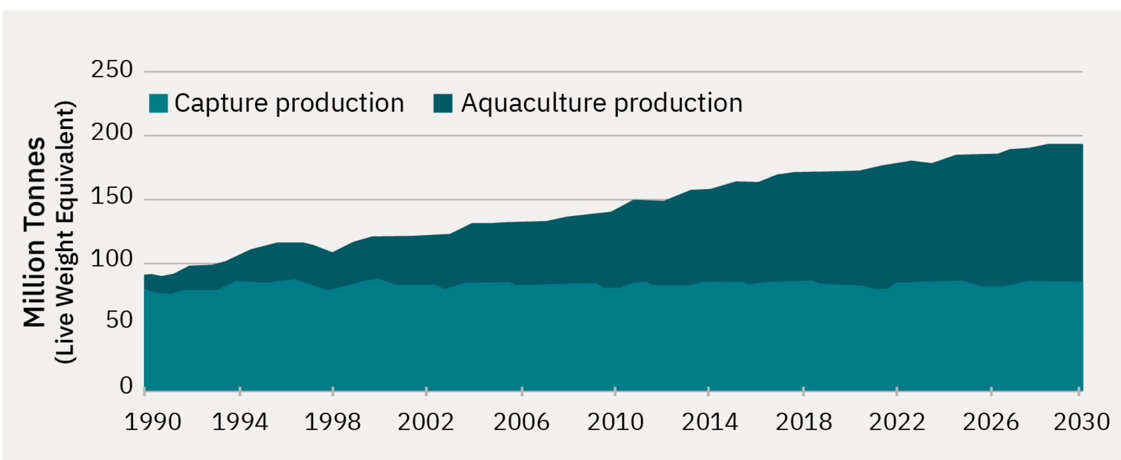
2.1 Shortcomings of sustainable fisheries management

Global fishery yield has been stagnant for decades, with a slight decline of around 1% per year since its peak in 1996 (Figure 1). While this may seem to suggest that a more or less sustainable harvesting strategy has been implemented that allows for consistent harvests each season, these official global yield statistics fail to capture several troubling trends and externalized impacts.

Figure 1: World capture fisheries and aquaculture production, 1990–2030



Source: Food and Agriculture Organization of the United Nations, 2018 (FAO 2018)

Because it is notoriously difficult to track the catch from fishing vessels and because very few resources are expended by governments to enforce catch limits, these figures fail to properly account for illegal fishing. In fact, substantially more (up to 50% more annually) is harvested than is depicted by the FAO's global estimates (Pauly and Zeller 2016). Beyond illegal fishing for desired species that ultimately end up at market, illegal bycatch—including accidental harvesting of critically endangered species—is often discarded at sea, rendering it impossible to track accurately. Estimates that incorporate these data indicate that global harvests have declined rather precipitously in recent years rather than remaining near stagnant, suggesting exhaustion and collapse of fisheries (Pauly and Zeller 2016).

These figures also conceal the fact that significantly more effort and resources must be expended each year to capture harvests of this volume. A recent study found that commercial fishing vessels now travel twice as far as they did in the 1950s but harvest less than a third of what they used to per kilometer traveled (Tickler et al. 2018). Correspondingly, only oceans at the polar extremes remain unexploited, which is fewer than 10%. Because of these travel distances and the resources they require, the fishing industry has become increasingly subsidized in order to remain profitable (Tickler et al. 2018). This system is economically unviable and will become politically unpopular when suitable alternatives are more widely available.

Finally, total yield estimates fail to capture the ecological impact of fishing with regard to population dynamics and other impacts resulting from the harvesting process itself. These impacts include permanent damage to reefs and other ocean-bottom habitats. While total volume has held fairly steady, this is increasingly composed of smaller and less desirable animals as the populations of larger—and often more lucrative—species are decimated (Andersen, Brander, and Ravn-Jonsen 2015). Typical fisheries management strategies entail defining quotas for harvests of specific desirable species that will theoretically allow the same amount to be harvested the following year. But these metrics are shortsighted because even targeted harvesting can upend the population dynamics that maintain a healthy ecosystem balance, leading to fishery collapse even when the total harvest is small and quotas are strictly enforced. Balanced harvesting approaches based on ecosystem modeling have been instituted in some cases, but these too have been critiqued as unrealistic and insufficient to maintain healthy and diverse marine animal populations (Froese et al. 2016).

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Ocean ecosystems are particularly susceptible to the unbalanced depletion of keystone species that form critical nodes in complex trophic interactions across the food web. Thus, new technologies that improve detection, targeting, and capture efficiency of desirable species, which are highlighted as “disruptive technologies” in the FAO’s 2018 report (FAO 2018), may inadvertently accelerate ecosystem collapse if the target species is a keystone species—despite their potential to reduce bycatch. These technologies may further marginalize subsistence fishing communities that cannot afford or access them, as may policies that penalize fishing practices that do not use these new tools—for example, more stringent penalties for off-target bycatch.

2.2 Limitations and long-term risks of aquaculture

Aquaculture is a relatively new phenomenon, with approximately half of all freshwater and marine farmed species having been domesticated within just the last 30 years (Duarte, Marbá, and Holmer 2007). The aquaculture industry has exhibited a meteoric rise in recent years, masking and overcompensating for declining wild-caught harvests. Many methods of aquaculture exist for different species of fish. Each of these methods has its own sustainability metrics and a unique impact on the surrounding environment and local ecosystem. Regardless of production platform, aquaculture often represents an intensification of fish cultivation akin to the intensification of industrialized animal agriculture on land in the form of so-called factory farms or concentrated animal feeding operations.

While these intensive systems increase efficiency on the basis of feed conversion and thereby decrease costs, these systems have resulted in adverse effects such as concentration of animal waste, severe animal welfare implications due to crowding and its attendant stress and aggression, and the emergence of chronic illness and infections (Conte 2004; Watts et al. 2017). High disease prevalence within the animals has motivated the practice of subtherapeutic antibiotic administration, which accelerates the emergence of multi-drug-resistant bacterial strains (Watts et al. 2017).

Importantly, the most alarming and irreversible risks of intensive operations, such as the development of antibiotic-resistant bacteria and novel pathogens, do not limit themselves to the local aquaculture systems from which they emerge. These risks have a high likelihood of negatively impacting the entire industry and threatening nearby populations of wild aquatic animals (Shen et al. 2018). Recent evidence indicates that resistance genes that have spread to wild marine systems can arise even in well-managed aquaculture systems through the inclusion of affected fishmeal, which acts as a reservoir for transferable resistance genes (Han et al. 2017). Furthermore, a recent meta analysis looked at the relationship between warming water and antibiotic resistance. The analysis found that low and middle income countries reliant on aquaculture are both the most susceptible to climate change impacts and the most likely to face risks associated with antimicrobial resistance (Reverter et al. 2020). Beyond pathogenic concerns, many aquaculture operations pose the threat of releasing non-native species into wild ecosystems (Lima et al. 2018), destruction of ecologically sensitive habitats, and even risks for local communities by impacting storm-mitigating features like coastal mangrove forests (Ahmed et al. 2017).

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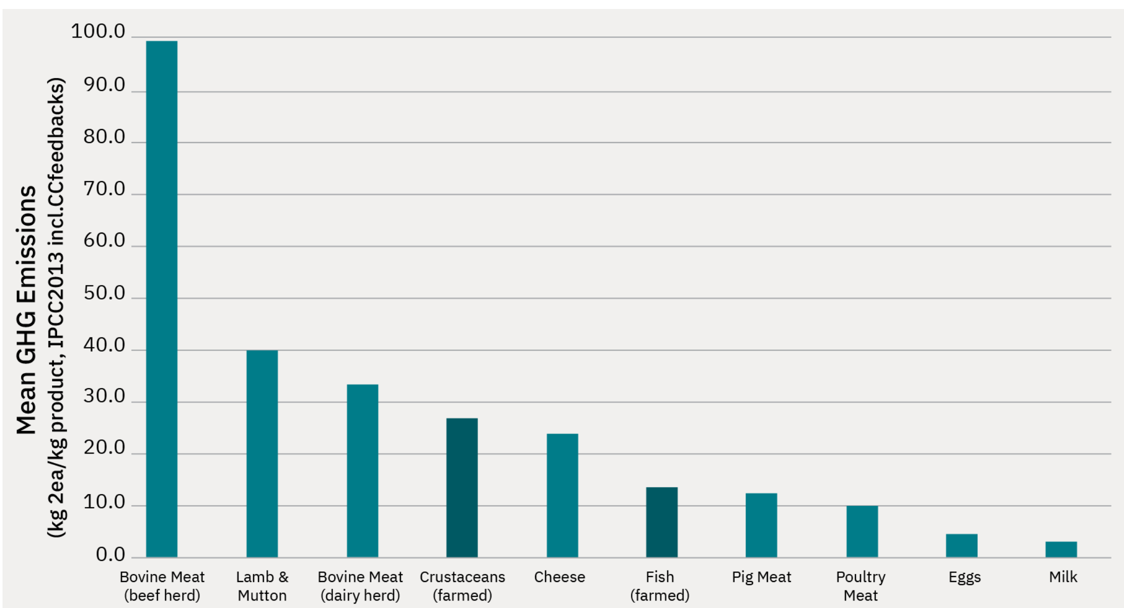
Some aquaculture facilities have employed more sustainable practices and risk-mitigation strategies, such as antibiotic-free growth, lower stocking densities, and avoiding sensitive habitats. However, the vast majority of the aquaculture industry’s growth is occurring in regions where these best practices are seldom observed. For example, China already accounts for approximately two-thirds of all aquaculture (FAO 2018). Relying on plant-based and cultivated seafood to satisfy a significant fraction of the unmet demand for seafood may prevent the same trends that have played out on land from manifesting at sea.

While farming fish and shellfish is associated with lower greenhouse gas emissions than beef, the industry contributes similarly to climate change as pork and poultry (Poore and Nemecek 2018). More specifically, farmed salmon are responsible for similar emissions per kg of protein as farmed chicken (McKuin et al. 2021), while average farmed shrimp emissions fall between those of chicken and pork. Feed production accounts for about 80-90% of farmed fish emissions, but energy use can contribute significantly to emissions profiles, especially for land-based recirculating aquaculture systems (Pelletier et al. 2009).

Figure 2: Emissions from farmed crustaceans and fish, relative to terrestrial animal farming.

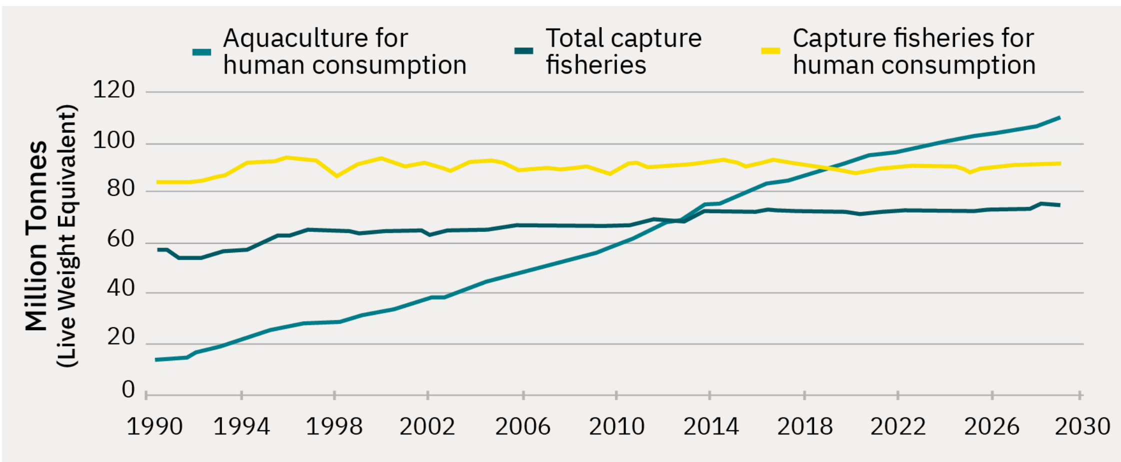


Source: Poore & Nemecek (Poore and Nemecek 2018)

From a practical standpoint, many desirable species of marine animals simply cannot be reared in captivity. For example, Kindai University in Japan conducted decades of research before successfully achieving full-life-cycle bluefin tuna aquaculture, but this species is still not well suited to spawning and growth in captivity due to inherent traits such as size, speed, and predation tendencies as well as a high feed conversion ratio (staff and ABC News 2015). The same is likely to be true for other species of large, predatory, and highly mobile fish species, which tend to comprise many of the highest-value seafood products.

Finally, although innovations in fish-free feed formulations and fish-free omega-3 production show promise for reducing reliance on wild fish, the aquaculture industry is still heavily dependent upon wild-caught biomass to supply its feed. In 2021, aquaculture currently consumes about 18% of harvested wild fish in the form of fishmeal and fish oil. Furthermore, the sustainability of the feed source and the nutritional profile of the final product are often in tension. For example, farmed salmon exhibit much higher fat content than wild salmon but far less omega-3 fats per serving (Sprague, Dick, and Tocher 2016).

Figure 3: Global Capture Fisheries and Aquaculture Production, 1990–2030



Source: Food and Agriculture Organization of the United Nations, 2018 (FAO 2018)

Aquaculture presents a host of sustainability challenges and risks to surrounding ecosystems. Not only can aquaculture not meet the projected demand for seafood in coming decades but it also falls short on delivering nutritional quality—especially as fishmeal and fish oil yield fail to keep pace with the growth in aquaculture. Moreover, it is simply not pragmatic or possible to produce in captivity many of the types of seafood that consumers value.

2.3 Marine animal welfare considerations

Marine organisms are typically not covered under animal welfare legislation and thus no humane slaughter methods are prescribed or enforced. Marine organisms often endure methods of handling and slaughter that are likely to result in prolonged suffering. For example, to maintain freshness, many fish species are packed alive on ice and can be transported in this manner for hours or days. Fish harvested from deep waters are typically suffocated or crushed to death upon their ascent to the ocean surface. Those that do survive harvest and make it onto the vessel may endure hours of slow suffocation (Yue 2008). Many marine animals–both wild caught and farmed–are skinned, gutted, or cooked while still alive and conscious. Furthermore, while some operators do take fish welfare considerations seriously and prioritize lower stocking densities and more humane harvesting practices, conditions within many high-density aquaculture tanks lead to stress, parasite infestation, cannibalism, injuries, and aggression throughout the lifetime of farmed fish (Conte 2004).

As has occurred with terrestrial farmed animals, greater consumer awareness of these conditions is likely to contribute to demand for plant-based and cultivated seafood. In recent years, consumers increasingly cite animal welfare concerns as influential in their purchasing decisions ("Animal Welfare: Issues and Opportunities in the Meat, Poultry, and Egg Markets in the U.S" 2017). In parallel, several recent cultural influences have brought the suffering of marine animals to the forefront of consumer consciousness. The 2013 documentary Blackfish revealing the plight of marine mammals in captivity inspired consumer boycotts of aquatic entertainment parks that negatively impacted companies like SeaWorld. In 2016, Jonathan Balcombe's book What a Fish Knows detailing the latest research on marine animals' cognitive and social capabilities reached The New York Times' best-seller list. The 2021 film Seaspiracy made waves on Netflix and was many consumers' first introduction to concerns about seafood production. In addition, some animal welfare groups have produced undercover videos of marine animal harvest and farmed fish slaughter ("Undercover Investigations at Factory Farms - Mercy For Animals" 2015) and two new groups—the Fish Welfare Initiative and Aquatic Life Institute—have formed to advocate for improvements in fish welfare. All of these considerations indicate that animal-free seafood products are likely to be increasingly well received and ultimately demanded by consumers.

2.4 Solutions that scale

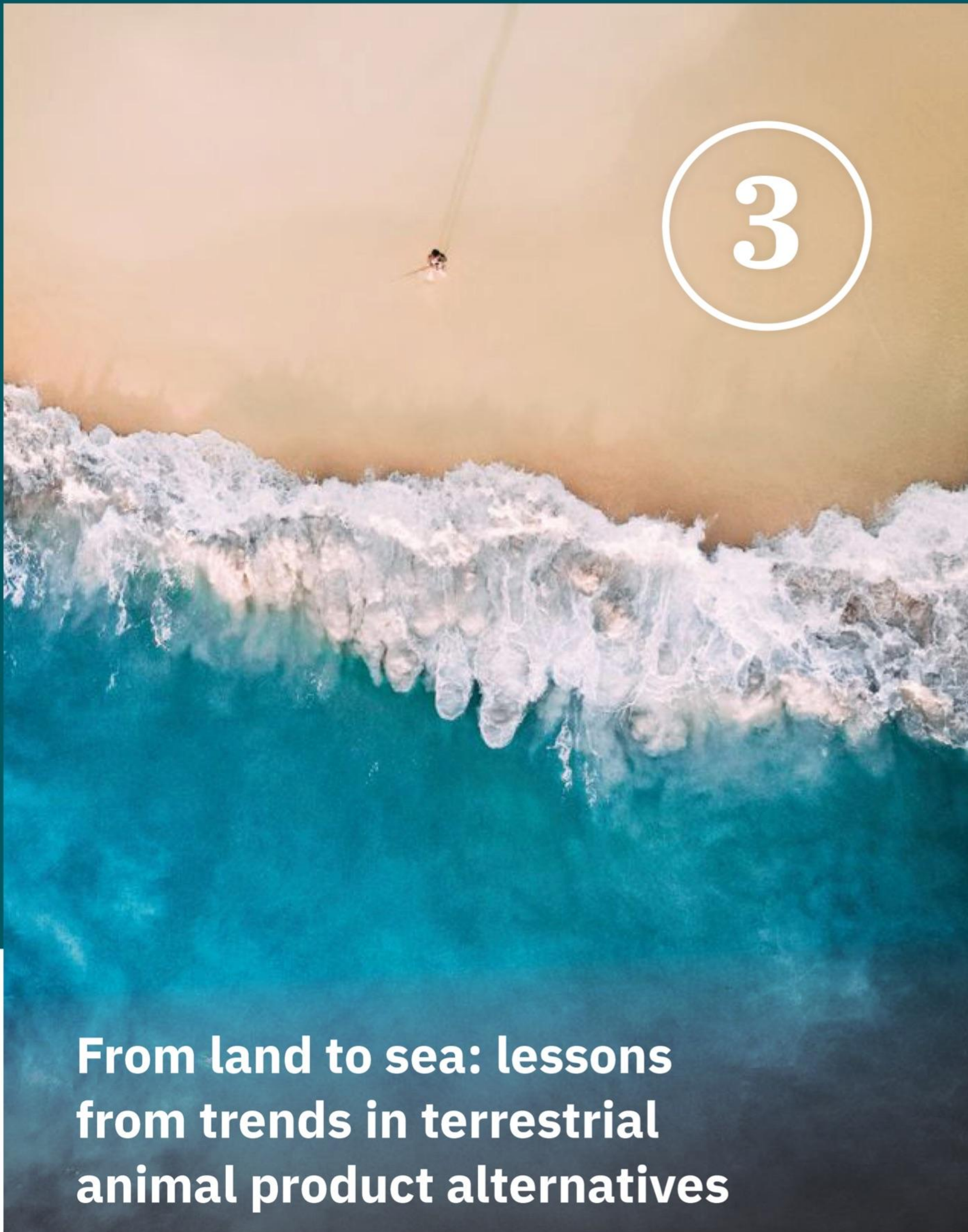
The production of plant-based and cultivated seafood is not limited by considerations like wild population productivity or geographical restrictions. Instead, these production platforms rely on consistent manufacturing and raw material inputs with robust supply chains and unconstrained supply. Some new and established companies are developing seafood product lines made from highly efficient protein sources such as fungi—for example, AquaCultured Foods and Quorn—that can potentially utilize byproduct streams and residual biomass from other agricultural or biological industries as feedstocks. Manufacturing facilities for plant-based and cultivated seafood need not be constructed near sensitive, expensive, and overburdened coastal areas and can instead be situated for most efficient logistical access for raw materials and final product distribution.

Plant-based and cultivated seafood producers are able to generate products in direct response to consumer demand rather than being dictated by availability, in sharp contrast to both wild-caught seafood and farmed seafood. Even though aquacultured species are purposefully farmed, the availability of a given farmed species is partly a matter of consumer demand but also partly derives from the relative ease of culturing that species. For example, we have already seen how species that are relatively amenable to aquaculture have come to dominate farmed fish consumption, despite consumers' very high demand for higher-value species like large predatory fish that are not well suited for aquaculture.

> “Plant-based and cell-based seafood producers are able to generate products in direct response to consumer demand rather than being dictated by availability, in sharp contrast to both wild-caught seafood and farmed seafood. As a result, high-quality and highly desirable products will become more accessible to consumers without the need to monetize low-value species or byproducts.”

By contrast, the resource requirements and raw material inputs for producing cultivated tuna meat are virtually identical to those required to produce an equal mass of cultivated tilapia meat because fish muscle cells grown in cultivators will exhibit essentially the same metabolic requirements regardless of the species of origin. In other words, cultivated seafood production eliminates the multiple compounding layers of energy loss that occur to produce wild tuna due to its higher position on the food chain (trophic level). Likewise, the raw materials and production processes for making plant-based tuna (or any other high-value species or product) are virtually identical to those required to make plant-based tilapia (or any other low-value species or product). The differences in resource requirements and production processes from one species or product to another reside in subtle changes in the formulation and manufacturing process to develop unique flavors and textures mimicking each species.

Furthermore, plant-based and cultivated seafood solve the so-called carcass-balancing problem, thereby reducing waste across the entire food system. This term is most often used in terrestrial animal farming, referring to the need to monetize all parts of an animal carcass while consumers do not demand various cuts in the precise ratio in which they are found on the carcass. For example, one cow carcass yields only about 60% of its weight as edible meat (the rest is inedible parts like bone, hooves, and blood). Of this edible meat, about half can only be utilized in the form of low-value ground beef. Similarly, the seafood industry processes low-value byproducts of filet preparation into minced products like fish sticks or compressed cakes made from deboned fish proteins. These products can be made through plant-based and cultivated approaches, but they will no longer flood the market as low-value byproducts from the production of more desirable cuts. As a result, high-quality and highly desirable products such as whole filets will become more accessible to consumers without the need to monetize low-value waste products.



3

From land to sea: lessons from trends in terrestrial animal product alternatives

Photo by Merr Watson

3 From land to sea: lessons from trends in terrestrial animal product alternatives

In the last decade, the market has seen massive shifts in consumer demand and product innovation for plant-based alternatives to products of terrestrial animal agriculture. These trends are likely to reflect similar forthcoming disruptions to the conventional seafood industry. In fact, there is reason to believe that the transition of seafood toward plant-based and cultivated solutions will occur with more urgency than for products like meat, poultry, and dairy, which have largely kept pace with increasing demand. The rapidly growing unmet demand for seafood coupled with the looming collapse of many of the fisheries that serve as the exclusive source of various highly coveted species of marine animals is likely to accelerate this shift, despite a somewhat slow start relative to terrestrial animal products. This transition can be further accelerated by concerted efforts to apply learnings from the development, commercialization, and generation of demand for plant-based meat and dairy.

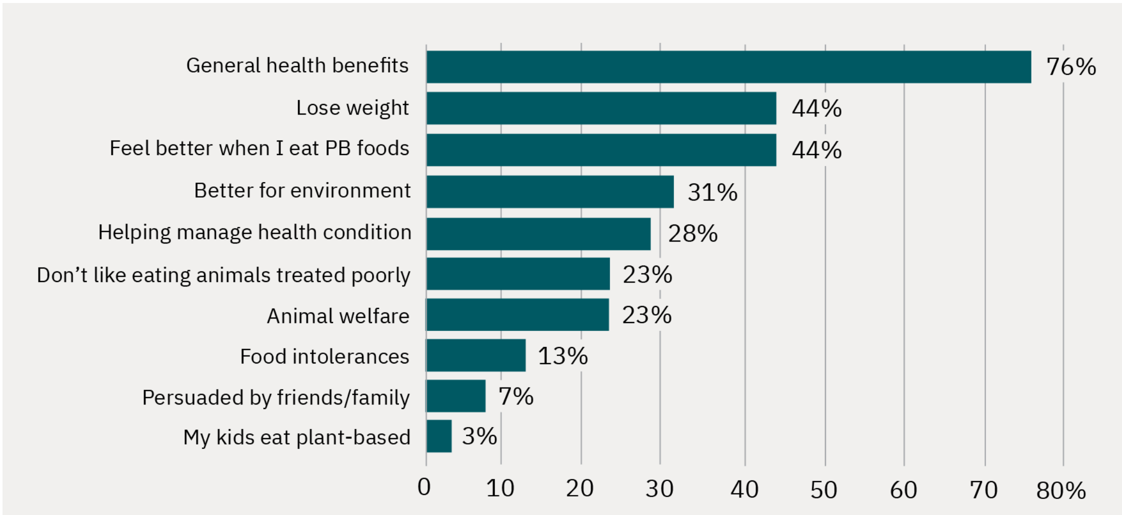
Indeed, the fate of the oceans is intimately intertwined with the advancement of alternatives to terrestrial industrial animal agriculture beyond the translation of learnings from those industries to the plant-based and cultivated seafood industry. Waste and fertilizer runoff from feeding and operating intensive animal farming operations represents the greatest source of ocean eutrophication—spawning ocean dead zones covering upwards of 100,000 square miles (Diaz and Rosenberg 2008)—and animal agriculture is one of the largest greenhouse gas-emitting industries globally, thus accelerating ocean warming and ocean acidification. Thus, the ocean stands to gain from two-way information flows in the development of alternatives to seafood *and* land-based animal products.

3.1 Recent trends in plant-based meat and dairy

Demand for plant-based meat has exhibited a marked surge recently, with global sales growing 8% annually since 2010 (Skerritt and Shanker 2017). In recent years, these growth rates have continued to accelerate, especially in certain markets. Between 2018 and 2020, dollar sales of plant-based meat products grew by 43% in the U.S., almost 2.5 times faster than total food sales over the same period ("Nielsen Data Release 2018 - Plant Based Foods Association" n.d.). While plant-based beef, pork, and chicken are currently capturing the largest share, plant-based seafood can harness the same megatrends that are boosting the broader category: the synergy between development of better plant-based products and rapidly shifting consumer preferences.

The taste, texture, and general mainstream consumer appeal of plant-based meat has radically improved in recent years. While brands like Morningstar, Boca, and Quorn have made products like veggie patties for decades, only recently–largely spurred by the entrance of new companies like Beyond Meat and Impossible Foods–have these companies developed plant-based meat products that replicate the taste, texture, and sensory experience of animal meat products. Despite substantial decades-long efforts by nonprofit organizations to educate consumers on the negative health, environmental, and animal welfare implications of meat, consumer adoption of alternatives remained low until these new products became more widely available. The latest generation of plant-based meat products exhibit widespread appeal to mainstream consumers, especially flexitarians and consumers seeking to diversify their protein intake without eschewing animal products altogether.

Figure 3: U.S. consumers' top three reasons for choosing plant-based foods

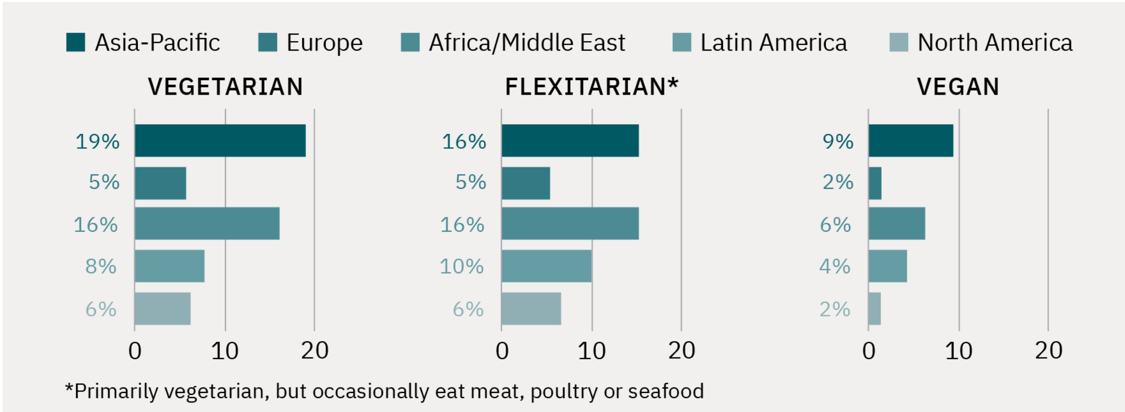


Source: Mattson, 2018; n=1,163 general population U.S. consumers (Mattson 2018)

Coincident with this shift in supply, demand has been shifting too. Emerging demand drivers like health and environmental sustainability have joined traditional drivers like taste, price, and convenience as important decision factors for food purchasers (Gma 2016). The majority of growth in demand for plant-based meat is not derived from vegans and vegetarians but rather from flexitarians, foodies, Millennials, and other mainstream consumers (Acosta 2018). A recent survey from research firm IRI indicated that 53% of U.S. households are buying plant-based meat, and 34% of meat-eating Millenials consume plant-based meat at least four times per week. Conversations with major plant-based meat producers in the U.S. and abroad indicate that consumer demand for these products is growing much more quickly than production capacity, so the growth rates of the category may not capture the true rate of demand growth.

In order to gain visibility and traction within mainstream consumer segments, companies producing plant-based seafood should target their marketing toward flexitarian consumers and strive to gain retail placement in the seafood section of the store. For example, Beyond Meat negotiated retail placement for their plant-based Beyond Burger in the fresh meat aisle, which has enabled them to reach a consumer base comprised of 70% meat eaters and substantially increasing their sales (Watson 2018).

Figure 4: Percentage of consumers who claim to adhere to a special diet



Source: Nielsen, 2016 (Nielsen 2016)

This feed-forward loop—making flavorful, appealing products targeted at broad consumer segments like flexitarians, which then drives consumer demand for additional products within the category—has hastened the growth of terrestrial animal product alternatives. Pursuing this strategy for plant-based seafood will similarly help expand the culinary imagination of global consumers.

The rise of plant-based milk (Box 1) provides an instructive case study for other disruptor categories such as plant-based and cultivated seafood. Consumers with dairy allergies or dietary restrictions were crucial early-adopters, providing plant-based milk producers with a loyal customer base and the opportunity to perfect their products. Plant-based milk sales took off once the target market expanded to include much larger consumer groups like flexitarians. Health claims, environmental claims, and longer shelf life may also attract early adopters, but most consumers did not make the leap until companies started positioning plant-based mils as tasty, inexpensive, and accessible. Mastering the taste/price/convenience trifecta is crucial for any product looking to cross the chasm from niche early-adoption to the mainstream consumer market.

3.2 Early involvement of key stakeholders

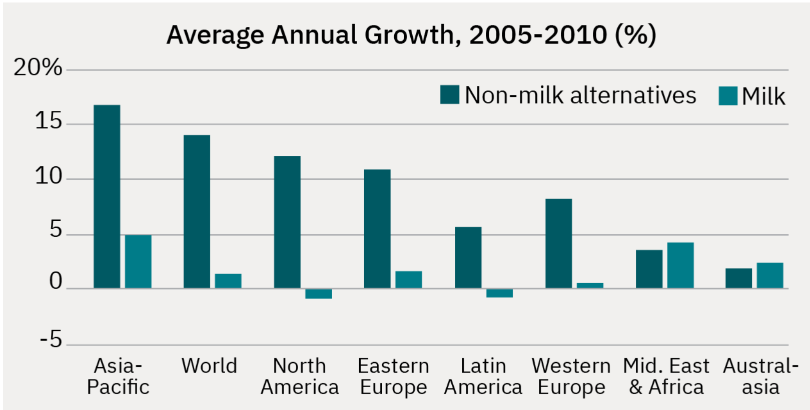
Taking another lesson from the plant-based meat industry, alternative seafood companies should recognize the value of strategic partnerships early in their company formation. For example, Beyond Meat's partnership with PHW Group, a European meat distributor, facilitated their entry into the European market by providing support for distribution, logistics, and consumer engagement (PHW-Gruppe 2018). Partnerships with highly visible and esteemed stakeholders can pay dividends in the foodservice sector as well. Impossible Foods' partnerships with chefs enabled them to position the Impossible Burger as a high-end culinary experience, driving a level of prestige and demand that was unprecedented for plant-based meat.

Strategic partnerships often come in the form of investments and acquisitions. Several such partnerships have begun to emerge in the plant-based seafood space. Thai Union, one of the world's largest seafood companies, invested in and established a partnership with cultivated seafood company BlueNalu in 2021 to collaborate on market development strategies. BlueNalu has also entered into strategic partnerships with Mitsubishi Corporation, Pulmuone, and Sumitomo Corporation of Americas to bring cultivated seafood to consumers around the world. Bumble Bee Foods established a joint venture with plant-based tuna maker Good Catch Foods in 2020 with a focus on distribution. Tyson Ventures invested in plant-based seafood company New Wave Foods in 2019 and again in 2021. For alternative seafood manufacturers, engaging these partners early and nurturing these relationships will be key to success.

Conventional seafood companies and major food companies are also beginning to create their own plant-based seafood products that suit the preferences of their core consumer base. Thai Union now produces its own plant-based products, including plant-based shrimp. The Van Cleve Seafood Co. launched and spun off the Plant-Based Seafood Co. in response to growing consumer demand for plant-based products. Both of these seafood companies have cited their experience with conventional seafood as essential to their ability to produce and distribute alternative seafood products that taste like their conventional counterparts. Nestle—the world's biggest food company—has also developed a plant-based tuna product under their Garden Gourmet brand.

Organizations like GFI as well as groups with ocean sustainability at the core of their missions and who work closely with the seafood industry, often through responsible seafood certification programs, may be able to facilitate these relationships. Trusted nonprofit organizations can educate seafood industry stakeholders on the market trends and motivations driving the transition toward plant-based and cultivated meat. Furthermore, these organizations can empower the seafood industry to embrace this shift by providing connections between established industry players and startup companies in plant-based and cultivated seafood

BOX 1: Case study: the rise of plant-based milks as a model for rapid market shifts toward plant-based alternatives.



Plant-based milks are one of the fastest-growing beverage categories in the U.S., with total U.S. non-dairy sales reaching $2.1 billion last year — a 5-year sales increase of 65% [46]. Twenty years ago, plant-based milks were merely a rounding error in the overall U.S. dairy market; today, they are available in almost every grocery store and coffeehouse and their sales are growing just as fast as sales of cow milk have declined. What contributed to these trends?

Early plant-based milk products from the 1970s -1990s were marketed almost exclusively to niche audiences such as vegans and consumers with dairy allergies. But in the early 2000s, WhiteWave (the parent company of Silk brand) started using familiar gable-top packaging and placing soy milks next to cow milk in grocery store dairy cases. Sales started to accelerate, shifting plant-based milks from marginal curiosity to category leaders. Dean Foods acquired WhiteWave in 2002 and invested heavily in marketing campaigns, driving more and more consumers to try plant-based milks and helping to spur a flood of new competitors.

Today, the formerly staid dairy case now hosts a diverse selection of milks made from almond, coconut, hemp, hazelnut, and even the spent grain from brewing beer. A 2018 survey found that 50% of consumers purchase both plant-based and animal-based dairy products, demonstrating their widespread appeal [47].

3.3 Challenges and opportunities unique to the seafood space

While many of the insights from the explosive growth of plant-based alternatives for terrestrial animal products can be applied directly to plant-based and cultivated seafood products, the seafood sector does pose some unique challenges and an even greater number of distinct opportunities. Efforts to accelerate the development and adoption of plant-based and cultivated seafood should incorporate these strategic considerations.

Challenges

Seafood is often seen as a healthier alternative to other terrestrial animal proteins, with90% of U.S. consumers associating seafood with positive health benefits (Loesch 2016). The negative health and environmental effects of red meat have driven many chefs and consumers to switch to inexpensive lean proteins such as chicken or fish. A 2019 survey from the firm Changing

Tastes found that 30% of consumers want to eat more seafood in the next few years. Thus, consumers may be less inclined to seek alternatives to seafood on health grounds, and plant-based and cultivated seafood products will have to emphasize their nutritional equivalence to conventional seafood. Because very few plant-based seafood products—and no cultivated seafood products—exist on the market, it is difficult to forecast projections of consumer demand with a high degree of confidence.

In addition to challenges posed by consumer perceptions of seafood as healthy relative to other types of meat, structural differences between the seafood industry and the terrestrial meat industry may complicate attempts to garner support from key stakeholders to influence the entire sector. The seafood industry is historically more disaggregated than the heavily consolidated terrestrial meat industry. For example, while 13 companies control about 15% of the global seafood catch (see Section 6), just four companies control over 60% of the world's pork production and about 70% of the world's cattle (Chemnitz and Bechiva 2014). Additionally, harvest is often geographically dispersed from the point of consumption for both wild-caught seafood and farmed seafood, making supply chains more opaque for seafood and requiring complex import and export considerations. This adds a layer of complexity when attempting to exert influence over the major stakeholders in the seafood industry and may present challenges for involving the existing industry as active participants in a wholesale shift toward plant-based and cultivated seafood. This challenge might be partially addressed by working with importers and processors rather than producers, as importation and processing represent points of consolidation within the supply chain.

Opportunities

Despite the overall perception of seafood as healthy, there are notable exceptions and this perception is swiftly changing. A significant portion of the population is excluded from seafood consumption due to health concerns. Fish and shellfish are two of the eight most common food allergens. They are responsible for more than 90% of food allergic reaction episodes in the U.S. ("Food Allergies: What You Need to Know" 2018). Over seven million Americans are allergic to seafood ("Shellfish Allergy" 2015), with shellfish allergies representing the most common food allergy in the U.S. (Acker et al. 2017). Thus, plant-based seafood products have a built-in potential early-adopter market even larger than that of plant-based dairy. Doctors often advise avoiding all seafood if allergic to either fish or shellfish, since many products like imitation crab often contain other fish or shellfish ("Food Substitutes for Fish and Shellfish" n.d.).

Additionally, some people limit seafood consumption due to concern for high levels of mercury and other toxins, and the FDA advises those who are pregnant or breastfeeding to avoid certain species of fish completely ("Eating Fish: What Pregnant Women and Parents Should Know" 2017). Seafood has received considerable press for contamination scares and parasitic infections resulting from consuming uncooked fish. As noted above, fish and shellfish can contain high levels of mercury, PCBs, dioxins, and other health contaminants, and are frequently fraudulently labeled either in species or in origin to evade these concerns. Furthermore, meta-analyses have recently called into question some of the supposed health benefits of seafood products, including those associated with omega-3 fatty acid consumption

(Abdelhamid et al. 2018). Thus, the positive association between seafood and health may weaken in coming years.

Beyond these health-related opportunities to drive consumer demand for plant-based and cultivated seafood, these products also exhibit notable advantages to the industry in terms of increased efficiency and reduced loss throughout the supply chain. Nearly half of the edible U.S. seafood supply from 2009 to 2013was lost due to consumer food waste, discarding of bycatch, or distribution spoilage. Seafood products are highly perishable foods, which presents challenges for producers and distributors. It also presents challenges for consumers, who often feel uncomfortable assessing whether seafood is fresh and safe to eat (Carlucci et al. 2015). Plant-based seafood has a longer shelf life and reduces the need for costly refrigerated transportation while providing an attractive opportunity for local production in landlocked areas. Furthermore, the production process for both plant-based and cultivated seafood is more controllable and predictable, allowing for better real-time response to demand and for much more customized end products that precisely answer this demand. More valuable cuts, product formats, and species of seafood products could be produced without generating low-value byproduct waste. These increases in efficiency create an opportunity for plant-based seafood products to provide a healthier and ultimately less expensive alternative to conventional seafood.

4

Opportunities in plant-based seafood products

Photo by Wildtype

4 Opportunities in plant-based seafood products

While the plant-based seafood industry can learn from and build upon the success of terrestrial meat and poultry alternatives, plant-based seafood has lagged in growth and diversity of products and brands. Many of the fundamental production techniques used to structure plant proteins into fibrous food products resembling animal muscle tissue exhibit cross-applicability to many types of meat, including seafood. Thus, there is ample opportunity for existing plant-based meat companies to pivot a portion of their formulation and product development effort to adapt their recipes and protocols to seafood product lines. However, seafood also presents novel challenges regarding structure (in the case of particularly segmented or flaky forms of fish meat), appealing flavor profiles, and unique ingredient sourcing (such as cost-effective sources of animal-free omega-3 fatty acids). Some of these latter challenges may best be addressed through open-access, publicly funded research.

4.1 Existing and emerging brands and products

Plant-based seafood products comprise a very small fraction of the global seafood market, leaving almost unlimited growth potential in all segments. To date, only a handful of brands carry any plant-based seafood product lines, and these lines cover fewer than a dozen of the hundreds of species of marine animals that are regularly consumed around the globe.

Notable emerging plant-based seafood brands and companies include Good Catch Foods, Kuleana, and Ocean Hugger, all of which have formed since 2016. Good Catch Foods has developed flaked fish products such as tuna, crab cakes, and fish burgers. Kuleana is perfecting texturing technology to make plant-based raw tuna from algae and beets. Ocean Hugger uses the concept of biomimicry to replicate the texture and flavor of sushi using intact fruits and vegetables where their native flavors are replaced with those invoke fish, such as savory umami. This latter approach is fairly novel among plant-based meat products because it does not require intensive processing methods and does not seek to achieve the protein levels of animal-derived meat.

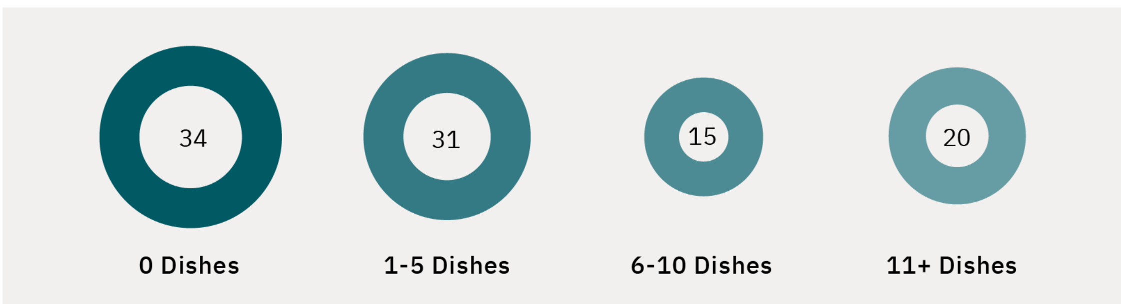
Although the last two years have witnessed the launch of several exciting plant-based seafood brands, there is still a great deal of untapped market potential. Most of the plant-based seafood products currently on the market are ground or minced products rather than whole filets. With more sophisticated manufacturing methods, it may be possible to create the layers of fat, collagen, and protein that give fish its desirable cooking properties like flakiness. Additionally, since far more species of fish are consumed compared to species of land animals, there are nearly endless opportunities to develop novel products.

4.2 Promising market opportunities for plant-based seafood

Plant-based seafood can leverage growth trends in the seafood category and the plant-based alternatives category to potentially exceed growth rates in the broader plant-based meat category. There is ample opportunity for existing and new brands to expand their distribution within retail channels. While a variety of plant-based beef and chicken products are available in mainstream grocery stores throughout the U.S., only a few plant-based seafood products are widely available as of 2021. Furthermore, these products are almost never displayed alongside their conventional counterparts in retailers. Plant-based seafood manufacturers may experience a sales boost by utilizing similar strategies to those employed by other plant-based meat brands, such as placement alongside conventional options.

The foodservice sector is even more devoid of plant-based seafood options and represents a massive untapped opportunity. Nearly two-thirds of all seafood sales in the U.S. are via out-of-home channels such as restaurants and other foodservice outlets (DiPietro 2014). With their higher margin, full-service restaurants are one of the easiest entry points for plant-based seafood—and, ultimately, for cultivated seafood. Using foodservice as a go-to-market strategy has proven highly successful for companies like Impossible Foods, facilitating the trajectory from high production cost and low volume to larger-scale production suitable for entry into the retail market.

Figure 5: Number of seafood dishes in top 100 U.S. restaurants by revenue



Source: GFI original research by Aaron Bergman (2018)

*S*eafood dishes are well represented on restaurant menus. Although top chains like KFC and Taco Bell have no seafood items, 20 of the top 100 restaurants by revenue have 11 or more seafood dishes, including chains such as Red Lobster, Olive Garden, and P.F. Chang's. Within all U.S. chains and independent restaurants, main entrees featuring finfish comprise 4.6% of all dishes and appear on 58% of all restaurant menus (Datassential 2018a). Main entrees with shellfish account for 4.8% of all dishes and are present on 50% of all menus (Datassential 2018c). All told, seafood can be found at four out of five restaurants, with much higher penetration in segments like fine dining and lower penetration at quick service restaurants, though notably present on the menus of fast food giants like McDonald’s and Subway (Datassential 2017). Insights into product-market fit based on price point and volume can be gleaned from the relative availability of seafood dishes featuring various species across restaurants ranging from fast food to fine dining (Table 1). With the exception of exclusively vegan regional chains such as Veggie Grill and some Chinese food restaurants, virtually no restaurants in the U.S. offer plant-based seafood meals. This indicates a tremendous opportunity to leverage restaurants to introduce consumers to plant-based seafood options.

Table 1: Top 15 fish and shellfish dishes by menu availability, U.S. restaurants, by segment

Keyword	QSR	Fast Casual	Midscale	Casual	Fine Dining	All
Shrimp	39.3%	34.6%	70.5%	81.5%	82.6%	64.7%
Salmon	15.4%	25.7%	42.3%	58.4%	85.0%	43.1%
Tuna	35.1%	33.7%	37.7%	36.7%	62.8%	38.0%
Crab	16.0%	9.3%	36.8%	45.7%	65.5%	34.7%
Scallop	8.6%	3.3%	25.6%	35.6%	64.9%	26.0%
Calamari	7.2%	4.5%	22.0%	36.4%	47.1%	24.1%
Clam	10.5%	6.0%	21.2%	28.7%	43.2%	21.7%
Lobster	4.7%	4.8%	13.2%	28.5%	60.4%	19.5%
Anchovy	16.1%	8.7%	16.1%	19.0%	31.5%	17.8%
Mussel	2.5%	1.2%	12.7%	23.9%	41.4%	15.5%
Oyster	3.5%	1.8%	9.3%	19.1%	50.5%	13.9%
Cod	4.3%	2.1%	13.0%	20.0%	25.5%	13.5%
Tilapia	4.4%	3.3%	14.8%	14.9%	7.2%	10.7%
Squid	3.4%	3.3%	12.6%	13.4%	17.4%	10.1%
Ahi Tuna	1.8%	6.0%	5.4%	14.8%	29.1%	9.8%

Source: Datassential, 2018 (Datassential 2018b); QSR: quick service restaurant

The breakdown of species served in U.S. restaurants has remained largely stable over the past decade. Research firm Changing Tastes found some shifts in future menu plans: foodservice operators want to serve more salmon and octopus in the future, while the share of restaurants planning to menu crabs and scallops is falling slightly (Tastes 2020).

4.3 Research to advance the plant-based seafood industry

While recent growth of the plant-based seafood industry has proven that commercially successful products are within reach today, further commercialization of high-quality products can be accelerated through open-access research across many areas spanning food science, biotechnology, and social science. The plant-based seafood industry can build upon insights in formulation, structuring, and marketing of other plant-based products, but several research areas are unique to the seafood sector.

Market and consumer research

The development of a rigorous decision matrix for guiding commercial product focus based on the intersection of several attributes—including market size, consumer receptivity, geographical relevance, and multiple metrics of adverse impact for harvesting or farming the target species—would guide product roadmapping by new entrants and existing plant-based companies. In contrast to terrestrial animal products,the vast majority of which derive from fewer than a dozen species,the sheer number of species and products within the seafood sector can be inhibitory when deciding on a target. Without standardized tools for comparing across many options and articulating the product focus decision, both companies and investors can become sidetracked in deliberation and market analysis prior to commencing work, or otherwise may choose a target product or species based on limited information. GFI has commenced work on such a standardized comparison tool with the development of the ArcheType Library of Alternative Seafood, also referred to as "ATLAS" Continued collaboration with experts on each of the criteria used to evaluate species archetype will further improve the usefulness of the tool.

There is a need for more granular insights on motivational factors driving or inhibiting consumer demand for plant-based seafood productions. Food choice motivations that consistently apply to the broad population typically include taste, personal health and nutrition, cost, and convenience—all of which provide clear physical and practical benefits to the individual (Aggarwal et al. 2016; Glanz et al. 1998; A. C. Hoek et al. 2017; "Food and Health Survey" 2018). Consumers are also increasingly motivated by altruistic factors, such as concern for the environment or for animal welfare (Apostolidis and McLeay 2016b; Elzerman, van Boekel, and Luning 2013). However, even within an attribute like taste, consumer attitudes toward seafood are complex and are heavily informed by cultural contexts and specific types of seafood products. For example, some consumers avoid fish that tastes "fishy," which has led to the popularity of species like pollock and tilapia, where white color and flaky texture are more important. Comparatively, other species are prized for their unique flavors and served with minimal sauces and seasonings.

While initial GFI-commissioned consumer research begins to answer many of the questions above, several urgent research questions remain. First, research assessing consumer preferences for alternative seafood based on species and product form will help the industry develop the right products for the early adopter audience. Second, cross-country comparisons of openness to and preferences within the alternative seafood category will help the industry continue to expand outside of the U.S. Finally, additional study methods beyond surveys, such as shop-alongs and focus groups, can add to the understanding of consumers' preferences within the alternative seafood category.

Importantly, food choice motivations have varying degrees of influence depending on the individual, though general patterns of influence also emerge among certain consumer groups (Apostolidis and McLeay 2016a; de Boer, Schösler, and Aiking 2017; Graça, Calheiros, and Oliveira 2015). However, much of the consumer literature has focused on perceptions of early plant-based beef and chicken products rather than seafood or the high-fidelity products available on the market today (Apostolidis and McLeay 2016a; Elzerman et al. 2011; Annet C. Hoek et al. 2013). The role of health as a driver for seafood consumption differs from terrestrial meat products. For seafood products, perceived nutritional health is often a motivation to increase consumption (Verbeke and Vackier 2005), whereas health perceptions decrease consumption of other meat products (Neff et al. 2018). This difference should be considered when developing marketing approaches across various consumer segments. For example, focusing on sustainability rather than health may be more compelling for some consumer groups. For other consumer groups, it may be more effective to highlight the health benefits of plant-based and cultivated seafood in contrast to the contamination concerns associated with conventional fish. As such, product development and marketing of plant-based and cultivated seafood products would benefit from a more nuanced understanding of consumer engagement with these products.

Technical research

There is a need for fundamental technical research in a number of areas ranging from food science to biotechnology that would specifically advance the development of higher-fidelity, lower-cost plant-based seafood. First and foremost, the entire plant-based and cultivated seafood industry would benefit from the availability of a detailed molecular and cellular characterization of many seafood products. GFI has initiated this work through the establishment of the PISCES database. Additional characterization should include comprehensive analyses to define the molecular composition of muscle tissue from a number of different species as well as biophysical and analyses of the structural patterns, cellular arrangements, and textural properties that define these products. These data will inform the design requirements for plant-based and cultivated meat products that both emulate the consumer experience, including taste, texture, mouthfeel, and aroma, and provide a comparable or superior nutritional profile.

Because seafood products are derived from animals whose food sources are aquatic organisms rather than terrestrial plants, compositional analyses may reveal a need for ingredients that are not readily sourced from terrestrial crops. Obvious examples are long-chain omega-3 fats such as DHA and EPA, which accumulate in fish tissue because they are ingested from DHA- and EPA-rich algae. This paradigm can be expanded further by canvassing the algal kingdom for novel ingredients and biosynthetic pathways that contribute components for flavor, aroma, and pigmentation that are unique to seafood products for use as ingredients in plant-based seafood. This endeavor can benefit from collaborations with research groups that have explored natural products and biosynthetic pathways in algae for use in other applications such as biofuels and green chemistry as well as algae-based aquaculture feeds.

Ingredients like algal omega-3 fats are currently expensive relative to their animal-derived counterparts. Thus, there is a need to further research to reduce production costs of these ingredients. Approaches include increasing cell density, expression yield, and harvesting efficiency of algal strains that already produce these components, or co-culturing multiple strains to increase robustness and improve resistance to biotic stresses and contaminants.

Again, efforts for addressing scale-up and cost reduction can build upon research within the algal biofuels and bioremediation communities. Alternatively, these metabolic pathways can be engineered into well-established industrial biotechnology production hosts to alleviate challenges associated with large-scale, low-cost algal cultivation. Ultimately, it may make sense to cultivate algae as the primary protein source for these plant-based seafood products if algal protein can exhibit the functionality required for replicating the structure and texture of fish and shellfish.

In addition to identifying novel ingredients suited for seafood applications, innovation is needed for methods of achieving appropriate structure and texture. Seafood exhibits unique structures relative to most terrestrial meat products. The flaky, delicate texture of many finfish may require dedicated optimization of existing techniques like high-moisture extrusion that are routinely used to make tougher plant-based meat products, or it may require novel manufacturing methods altogether. For example, co-extruding thin, alternating layers of protein-rich and fat-rich material and binding them into tissues resembling filets may require novel equipment design rather than adaptation of existing techniques.

Table 2: Comparison of structuring techniques for plant-based seafood

	Technological Maturity	Advantages	Disadvantages	Suitable applications
Extrusion (low/high moisture)	High (large commercial scale)	Established technology; high throughput; infrastructure and equipment already exists	Capital-intensive equipment; requires skilled operators; homogeneous composition; doesn't tolerate fat well	Minced/ground products (low moisture) like crabcakes or fish sticks; thin strips of homogeneous product (high moisture)
Shear cell technology	Medium (pilot scale)	Lower energy requirements than extrusion; creates thicker tissues	Still in development for translation to commercial scale; batch process so low throughput	Thicker sheets of homogeneous product (filets of whitefish meats with little structural striation)
3D printing	Low (prototype scale)	Precise control over patterning and textures; highly tunable properties	Currently small scale and expensive; many printing materials currently in use are not suitable for food applications	Products where heterogeneous textures are critical (e.g., layers of fat and protein in a salmon filet)
Fiber spinning techniques (hydrospinning, electrospinning)	Low (prototype scale)	Produces fibers at scales that resemble muscle fibers; can deposit fibers with precision	Currently small scale and expensive; not all methods are currently suitable for food; likely needs to be combined with other methods	Developing scaffolds for hybrid plant-based/ cultivated products; adding longer fiber integrity for larger whole cuts
Whole plant biomimics	Medium-high (limited commercial scale)	May be perceived as less processed; reduced infrastructure needs	Limited capacity to replicate the texture and flavor of meat because of reliance on fairly unprocessed plant forms	Products whose structure and form are similar to existing plant foods (bacon from seaweed; sashimi slices from tomato and eggplant)

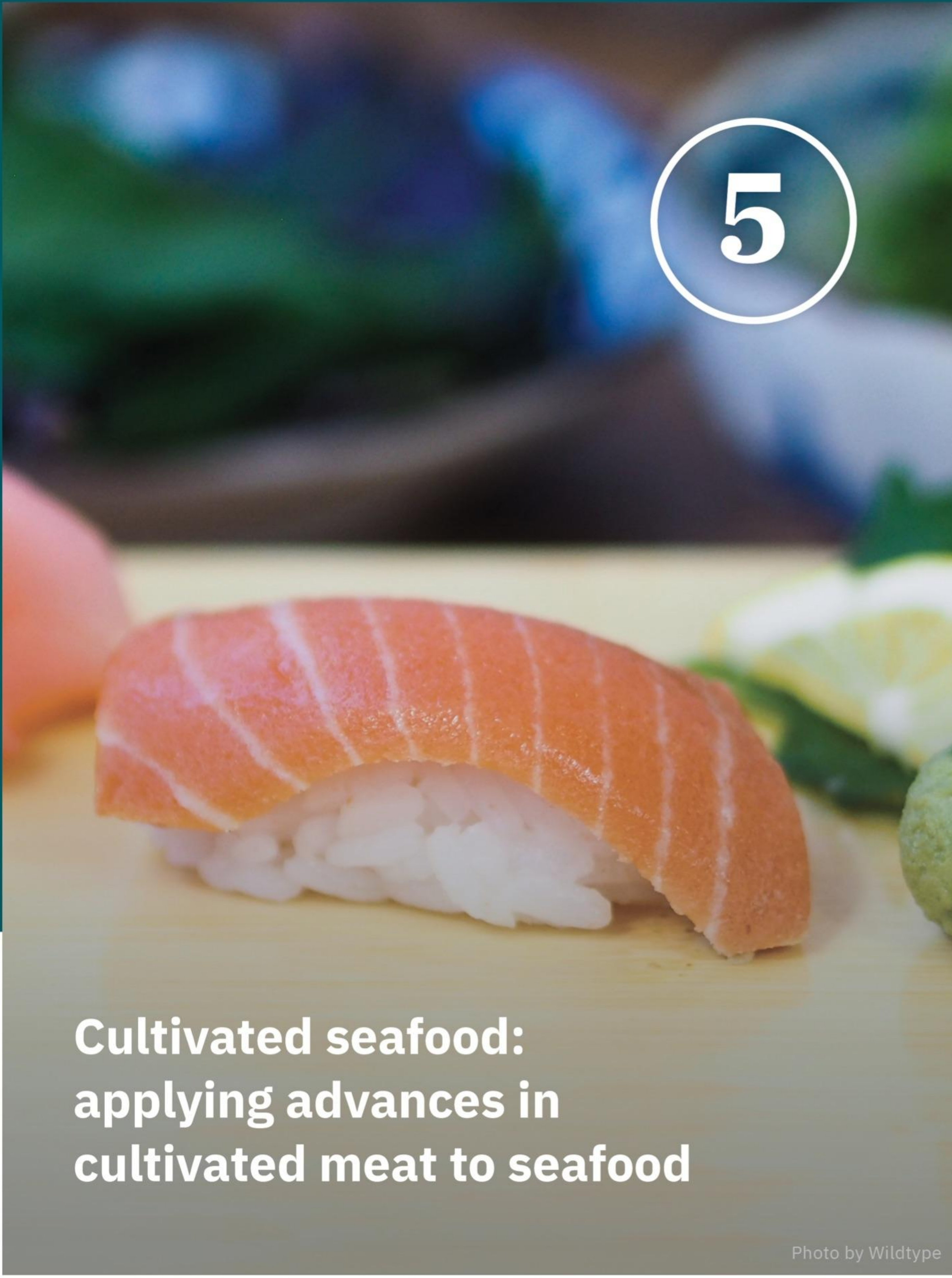
Studies examining the health impacts and nutritional quality of plant-based and cultivated seafood relative to conventional seafood would also benefit the industry. This includes studies examining aspects like absorption and bioavailability of various forms of algal-derived omega-3 fatty acids. Data on nutritional content and digestibility are typically required to propose substitutions in programs like school lunches, so these studies could facilitate access to broader distribution channels. Rigorous, independent studies assessing the sustainability metrics of plant-based and cultivated seafood relative to wild-caught and farmed seafood are also needed to identify areas within the production process where sustainability can be improved even further.

BOX 2: Case study: XPRIZE Feed the Next Billion

In December 2020, the nonprofit XPRIZEm which hosts public competitions for solutions to public problems, launched the Feed the Next Billion prize. The multi-year competition seeks entrants creating whole cuts of chicken breast and fish fillets. The goal is to incentivize the production of 4-ounce products that meet their conventional counterparts on taste, nutrition, and structure via methods—plant-based, cultivated, or blended protein—with a lower environmental footprint. Of the 28 semifinalists, 9 are focused explicitly on alternative seafood: Another Fish, Bluenalu, Brew51, CELL AG TECH, Kuleana, Revo Foods, SeaSpire, and Wildtype.

XPRIZE®

To spur research in all of these areas, faculty across many disciplines at academic institutions should develop concerted programs to address these challenges. Researchers should work closely with their technology transfer offices and industry collaborators to ensure their findings are commercially relevant and rapidly adopted. Entrepreneurship challenges to solicit innovative thinking from multiple academic disciplines, such as the UC Berkeley plant-based seafood Collider course (Box 2), can be used to crowdsource disruptive and non-obvious approaches to address open-ended challenges in plant-based seafood.



5

Cultivated seafood: applying advances in cultivated meat to seafood

Photo by Wildtype

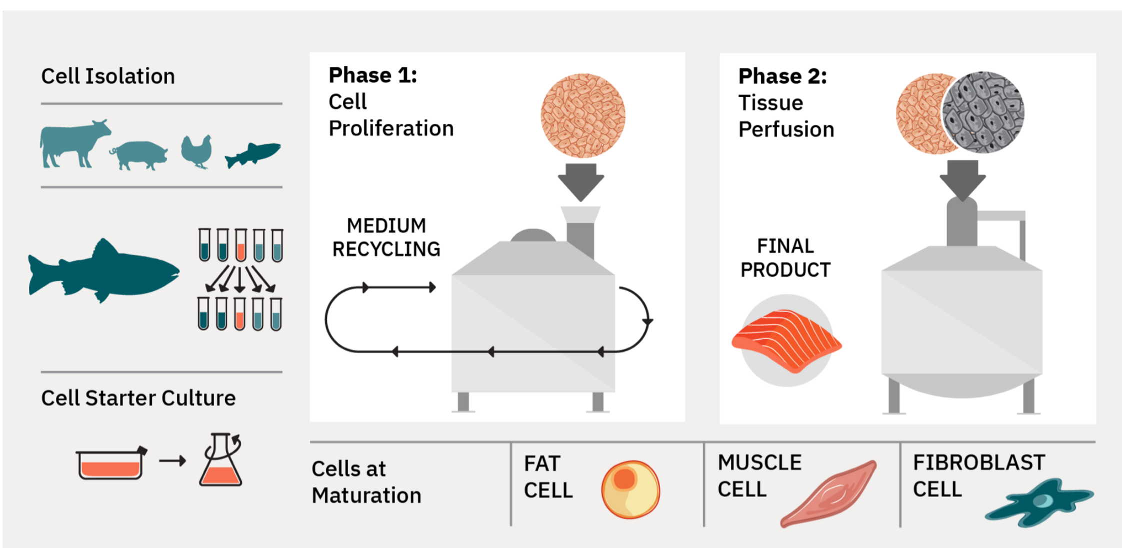
5 Cultivated seafood: applying advances in cultivated meat to seafood

While plant-based meat has improved drastically, current evidence indicates that many consumers will continue demanding conventional meat even if presented with highly compelling plant-based options. Furthermore, many plant-based meat products are minced or processed rather than mimicking the complex, three-dimensional structure of whole cut meat. While a large fraction of seafood exists in the form of minced or processed products such as fish sticks, crab cakes, and surimi, many high-value products are intact muscle tissue of fish, shellfish, mollusks, and crustaceans. These products may prove more difficult to recapitulate with plant-based ingredients and may necessitate an approach that can produce the sophisticated structures associated with animal muscle tissue.

5.1 Cultivated meat as a platform: cross-applicability to marine animals

The cultivated meat production process relies on providing animal cells with molecular and environmental cues that govern developmental organization of the skeletal musculature, adipose, and connective tissues. Regardless of species of origin, the fundamental biological requirements of these cell types are largely similar across species, as developmental pathways are conserved by evolution in organisms ranging from annelids to vertebrates. Thus, the general process workflow for cultivated meat production should look similar for marine animals as for more established mammalian or avian systems. Modifications to the general process and optimization for each final product will be required because the repertoire of growth factors and the precise nutrient requirements of different cells will vary slightly.

Figure 8: Cell-based meat production schematic for seafood



5.2 The current competitive landscape

While several companies are working to bring cultivated seafood to market, the species they are working on represent a small portion of the multi-billion dollar market across all marine animals. This leaves an immense opportunity for fledgling companies to pioneer work on additional cultivated seafood products from other species. Because the procedures for producing a cultivated seafood product should be relatively transferable across species once optimized, there may be a large first-mover advantage for early entrants. Thus, the application of cultivated meat bioprocessing to seafood is a very young endeavor and the allocation of even modest levels of additional resources toward this effort is likely to contribute substantially to the technological maturity and commercial readiness of the field.

5.3 Unique challenges and opportunities for cultivated seafood

The mission to create cultivated seafood products exhibits unique advantages and challenges relative to cultivated meat from terrestrial farmed species. The most notable challenge is that cells from fish and other aquatic animals are not routinely cultured in most research labs, so protocols optimized for these cell types are not readily available in most cases. Additionally, resources such as sophisticated genome annotations for seafood-relevant species are limited compared to common laboratory species (e.g. mouse, rat, fly) or even common livestock species (e.g. cow, pig, chicken), and species-specific reagents like validated antibodies are not generally commercially available for most aquatic animals. Thus, this field lacks established protocols and a rich scientific literature from which to draw, thereby requiring significant up-front investment in basic R&D by companies entering this space.

Cultivated seafood exhibits several potential advantages over mammalian or avian cell culture. Cells grown in culture perform best when growing conditions mimic the natural environmental conditions for that particular animal. In contrast to mammalian cell culture, which is typically conducted at 37ºC, fish cell culture can be performed at appreciably lower temperatures of4-24ºC for saltwater and 15-37ºC for freshwater species (Lannan 1994). Many fish species also undergo muscle hyperplasia as juveniles, leading to rapid expansion in muscle cell number and biomass. This rapid growth ability may offer higher yield of skeletal muscle tissue in a shorter time when translated to a cultivated meat production environment. Additionally, many fish and crustaceans retain high expression of the enzyme telomerase in multiple tissue types, which may enable long-term proliferative capacity or facilitate the establishment of immortalized cell lines for research use and, ultimately, commercial cultivated seafood production (Klapper, Kühne, et al. 1998; Klapper, Heidorn, et al. 1998; Belair et al. 1997; Peterson, Mok, and Au 2015).

Cultivated seafood may also pose both advantages and unique challenges regarding developing tissues that mirror the structural patterns found in fish muscle. Meat in finfish exhibits a simple structure relative to muscle tissues found in many terrestrial animals, which tend to form complex and stochastic vasculature and marbling. This suggests that scaffold fabrication to encourage differentiation into muscle and fat in defined patterns may be more straightforward for cultivated fish than for meats like beef or pork. At the same time, the more regular fish structure may make any differences in cultivated fish more obvious, necessitating finer control over the structure. Scaffolds for fish will also need to recapitulate the properties of fish connective tissue, such as its lower melting temperature compared to that of terrestrial meat (Listrat et al. 2016).

Much of the appeal for pursuing cultivated seafood relates to consumer issues around how seafood is consumed as well as market considerations, as many types of seafood command very high prices per pound. The meat of aquatic animals, such as oysters and tuna steaks, is more likely to be consumed raw or minimally cooked compared to meat from other animals. As previously noted, aquatic animals carry a variety of bacteria, viruses, and parasites that frequently cause foodborne illness.

Given that raw consumption increases the likelihood of foodborne illness and these raw dishes tend to command fairly high price points from consumers, these items may present an ideal entry market for introducing high-end, contaminant-free, cultivated seafood products prior to introduction of mainstream seafood products, which may take longer to achieve price parity at scale. Lastly, many consumers place a premium on fresh seafood that has not been frozen (Carlucci et al. 2015), but product loss due to spoilage is a major concern within the seafood industry. Because cultivated seafood will be produced in aseptic cultivators, product shelf life may be dramatically improved without having to resort to freezing.

Table 3: Per-kilogram pricing for several seafood products on the European wholesale market

Species	Price per kg (low end)	Price per kg (high end)
Swordfish	$8	$14
Atlantic salmon	$5	$15
Sole	$11	$25
Turbot	$10	$28
Norway lobster	$6	$30
Great Atlantic scallop	$5	$44
Common shrimp	$13	$51

Source: FAO European Price Report, December 2018, rounded to nearest dollar. Note that many specimens command much higher wholesale price points for particular use cases—for example, for sushi-grade fresh meat.

5.4 Research endeavors to advance cultivated seafood

Cell culture of aquatic species is not prevalent in academic research. There is a substantial need to develop the tools and resources that are already well established for mammalian cell culture, such as cell lines, robust protocols, commercial reagents, transfection vectors and reporters, full genome sequences, and biomolecular ("-omics") datasets for cells derived from aquatic species. These data and research tools would contribute greater mechanistic insights into the metabolism, growth, and developmental cell biology of these species, which may differ from the canonical pathways that are well characterized in mammalian species. Because of the development of less expensive, higher-throughput techniques for performing all of this work, the required investment in terms of funding, effort, and time to develop comprehensive data sets for each aquatic species will be orders of magnitude smaller than historical investment to develop these resources for the mammalian research community.

To facilitate this work, GFI has entered a partnership with Kerafast to establish a public repository of validated cell lines derived from specific aquatic animal species that represent diverse animal genera, such as bony fish, cartilaginous fish, shellfish, crustaceans, and mollusks. At present, the difficulty of obtaining such cell lines is a significant barrier to entry for both academic researchers and commercial ventures. Fresh primary cell isolates for terrestrial farmed animals can typically be obtained by partnering with a slaughterhouse, a school of veterinary medicine, or a university animal science department. However, most veterinary medicine and animal science departments do not typically work with aquatic species, and the majority of fish slaughter occurs at the site of harvest rather than at a centralized slaughter facility. Furthermore, it is exceedingly difficult to obtain fresh tissue for exotic species or deep-ocean species, and it can be virtually impossible to obtain embryonic tissue–which is often desirable for high proliferative capacity and its ability to generate all meat-relevant cell types–for species that are not bred in captivity, which suggests that induced pluripotent stem cell lines may be particularly valuable. Protocols for deriving these cell types need to be developed and optimized for aquatic species. Research projects at Mote Marine Laboratory and Tufts University aim to develop novel cell lines from species commonly consumed as seafood.

The development of open-source optimized culture media formulations for aquatic cell growth is another area with great potential to benefit the growing cultivated seafood industry, and enable further academic research into methods for cultivating seafood. Finfish cells will generally grow in media formulations similar to those used for cells from other lineages, but further research is needed to remove FBS and other animal-derived components without sacrificing performance, optimize formulations for specific species or cell lines, and ensure optimal nutrition profiles in the final product. Ongoing research at Virginia Tech aims to address this problem by using machine learning to optimize media for growth of finfish cells.

These research endeavors provide multiple opportunities for proactive engagement with the existing seafood industry and other entities that protect fisheries and ocean ecosystems. Obtaining access to high-quality primary tissue may require partnering with marine research or conservation organizations, aquariums, aquaculture facilities, or even industrial or recreational fishers. Collaborations involving aquaculture research institutes may prove particularly valuable because the aquaculture industry is experienced in handling aquatic species at all stages of maturity including embryos, and it routinely uses fish cell culture for advanced breeding and to monitor stocks for pathogens.


6
Fermentation and
alternative seafood
Photo by Philip Hamilton

6 Fermentation and alternative seafood

Fermentation has taken off as an enabling technology for the entire alternative protein sector. In 2020 alone, 13 new companies were formed in the category, bringing the total number of companies working on fermentation for alternative protein to 51. During this same year, the first dairy product produced using precision fermentation was launched: Perfect Day's brand Brave Robot was the first product in stores to provide consumers with animal-free dairy made with precision fermentation-enabled real whey protein.

This emerging fermentation technology has the potential to revolutionize alternative seafood. While Quorn has been producing mycoprotein-based fish sticks for years, the use of biomass, traditional, and precision fermentation to recreate the sensory and functional benefits of alternative seafood and alternative proteins more broadly is still relatively uncommon.

Several new startups are taking advantage of technological advances in fermentation for alternative protein to grow the alternative seafood category: Meati has hinted at a mycelium-based flaky fish product, 3F Bio recently announced a prototype of a 3D-printed mycoprotein tuna steak, and recently formed startup Aqua Cultured Foods is producing whole muscle seafood products through fermentation.

Several companies are creating products using microalgae, which is a highly scalable biofactory for omega-3 fatty acids. Odontella is in the process of commercializing a seaweed and microalgae-based line of seafood products, including salmon, scallops, and tuna. Triton Algae Innovations and Algama are also developing microalgae-based seafood products. A full summary of the alternative seafood industry landscape, including those companies using fermentation technology, can be viewed in the 2021 State of the Industry report for alternative seafood..

The application of fermentation technology to alternative proteins is just beginning. Further research is urgently needed to take full advantage of the available techniques for alternative seafood. GFI's Advancing Solutions database includes several high-priority research areas in this space, including increased titers and yields of target molecules and protein biomass strain engineering to allow for the use of less expensive feedstocks. In addition, research from GFI India on the development of the micro and macroalgae supply chains in India resulted in several top priorities for the industry.

7

Bolstering the innovation ecosystem for sustainable seafood products

7 Bolstering the innovation ecosystem for sustainable seafood products

While plant-based and cultivated seafood products will ultimately be produced and supplied through the private sector, the underlying technologies and their path toward commercialization will require a robust innovation ecosystem. To accelerate maturation from early product development through to widespread market adoption, activities must be coordinated across startup companies, multiple sectors of established industries, private and public funders and investors, governments, trade associations, and academic and other research institutions. All of these entities should consider this a call to action to contribute to the development and growth of these sustainable alternatives to conventional seafood.

Given the global nature of the seafood industry, it is imperative to formulate appropriate regional strategies for bolstering this innovation ecosystem. The seafood industry at present is dominated by Asia in terms of both production and consumption, but much of the innovation in plant-based and cultivated seafood is currently occurring in North America. Regional differences in the aquaculture industry are even more striking: the Asia Pacific region accounts for over 90% of global aquaculture production, while North America is responsible for less than 1%. Because of this significant regional skew, the strategy for advancing plant-based and cultivated seafood in each region should account for unique considerations such as policy, availability of investment capital, nutritional needs, impact on livelihoods, projected demand growth, and other locally relevant factors. It is especially critical to maintain a global perspective regarding consumer attitudes, product/species selection, and the involvement of governments and NGOs in order to maximize the impact of plant-based and cultivated seafood options for meeting global demand and thus alleviating pressure on overtaxed fisheries and aquaculture systems.

Table 4: Global perspective: production and per-capita seafood consumption across the world

Region	Regional seafood production (million tons, live weight)	Per capita supply (kg per person per year)	Percent of total protein supplied by seafood
Americas	22.0	14.3	4.0%
Europe	16.4	21.9	6.4%
Asia	113.3	23.1	7.9%
Africa	9.5	9.9	4.3%
World	162.6	19.7	6.6%

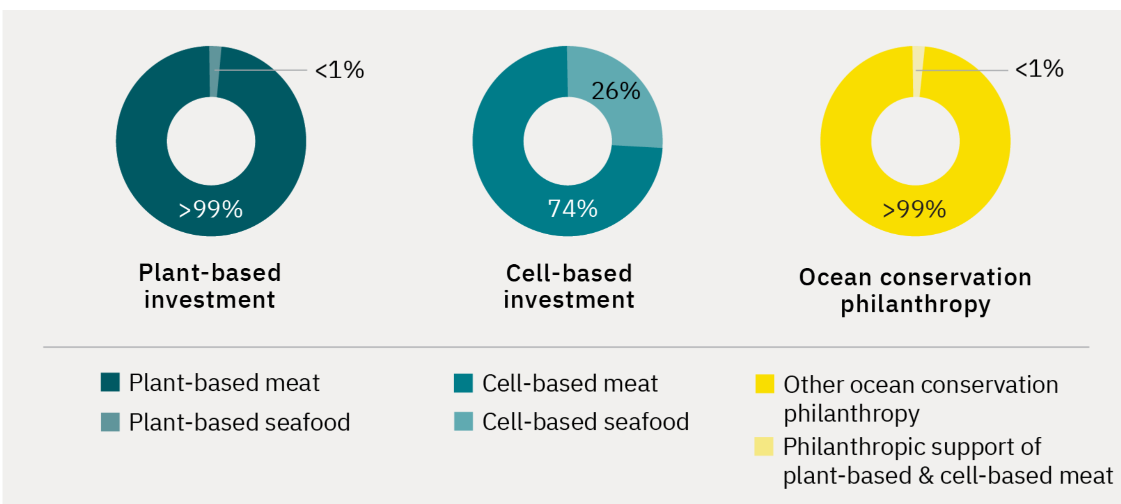
Source: FAO-FIAS 2013 Food balance sheet of fish and fishery products in live weight and fish contribution to protein supply.

7.1 Advocating for increased government and philanthropic research funding

Overall funding from ocean-related philanthropic grantmaking has increased in recent years,from U.S. $252 million in 2010 to an estimated U.S. $399 million in 2015, concomitant with the entrance of new foundations to this field (CEA 2017). During this same time period, official development assistance marine-related grants increased slightly from U.S. $339 million in 2010 to U.S. $372 million in 2015, with France, Japan, the Global Environment Facility, European Union institutions, the U.S., Germany, and Norway constituting the top-ranking donors for marine-related grants (CEA 2017). However, none of this funding was earmarked for the development of plant-based or cultivated seafood.

Philanthropic foundations play a critical role in supporting neglected areas of scientific research ("| How Foundations Can Have an Outsize Impact on Scientific Research [Alliance Blog]" n.d.). To effect substantial change, philanthropic groups should identify overlooked research areas that do not receive much public funding, support initiatives that individual universities or corporations may not be well-positioned to lead—such as multi-institution partnerships—, and become directly involved in the creation of new tools and infrastructure to advance scientific research.

Figure 6: Investment and philanthropic funding for plant-based and cultivated seafood is strikingly neglected relative to other alternative proteins and relative to other ocean conservation strategies



Based on these criteria, funding agencies can have an outsized impact on scientific research aimed at the development of plant-based and cultivated seafood. This is a research area with virtually no dedicated funding outside of a few companies' R&D budgets. The estimated *total* global R&D expenditure to date, including both private and public capital and across all forms of plant-based and cultivated seafood, is in the order of $100 million. Thus, even modest investments in primary research are likely to generate substantial returns to the industry. Moreover, this area is ripe for multidisciplinary collaborations to generate public knowledge and goods such as high-quality characterization data sets, relevant cell lines, technical protocols, and other research tools. By supporting research and development in plant-based and cultivated seafood, funders can simultaneously advance basic scientific research and address pressing environmental threats, public health risks, and global food insecurity stemming from overfishing and marine ecosystem damage.

Resource allocation toward plant-based and cultivated seafood development is in alignment with many philanthropic foundations and government agencies whose mission or scope is not directly related to ocean sustainability or preservation. Governments and private foundations across many sectors are encouraged to consider how their missions–whether to serve the public good, improve global food security and safety, create a sustainable food supply, or conserve marine ecosystems–may be advanced through efforts to support plant-based and cultivated seafood.

Governments whose constituents are heavily economically dependent upon seafood production or vibrant oceans (for example, for ocean-related tourism) should be especially motivated to support innovation in plant-based and cultivated seafood. For example, countries like Singapore and Israel have demonstrated leadership in supporting alternative protein innovation motivated in part by food security and independence due to their high fraction of imported food.

Table 5: Examples of agency and foundation impact areas outside of a direct focus on ocean conservation that align with supporting research for plant-based and cultivated seafood

Impact area	Why supporting sustainable plant-based and cultivated seafood is important
Sustainable food and agricultural systems	The global food production system does not rely solely on land-based agriculture. Oceans contribute substantially to food and feed, and truly sustainable food systems must promote the health of both terrestrial and aquatic ecosystems.
Food safety	Seafood and shellfish are responsible for a large number of foodborne illnesses resulting from consumption of contaminated animal products.
Food security	A large number of people, particularly in developing countries, rely on seafood for a large fraction of their daily caloric intake and nutritional needs, but subsistence fishing communities are threatened by the rate at which global demand is rapidly outpacing supply and putting pressure on local fisheries.
Malnutrition	Plant-based and cultivated seafood can provide landlocked communities with a locally-produced source of mercury-free omega-3 fats and other important nutrients obtained from fish and reduce global pressure on fisheries that serve as primary nutritional reservoirs for subsistence fishing communities.

Basic science	Techniques of cell culture and other basic science methodology for aquatic species lag far behind that of mammalian land animals; increased work in this area can elucidate key biological differences between diverse evolutionary branches.

7.2 Engaging governments

Government action can exert influence over the future of plant-based and cultivated seafood in several ways beyond committing additional public research support.

Three approaches are:

1. Ensuring that plant-based and cultivated seafood products are not handicapped through labeling laws or standards of identity that privilege conventional seafood
2. Updating the dietary guidelines to specifically include these products as suitable alternatives to conventional seafood.
3. Proactively supporting private sector development for alternative seafood.

In some jurisdictions, plant-based meat, cultivated meat, and plant-based dairy products have recently been challenged in an attempt to prevent these products from using common, recognizable terms like “meat” and “milk.” This is despite studies indicating that consumers are not confused when modifiers of these terms are used, such as “almond” milk or “plant-based” meat. These challenges would have the practical intent of marginalizing plant-based products by forcing them to use terms that are less familiar to consumers. While similar issues are not yet significant in the seafood sector, trade associations and nonprofits with lobbying capacity should prepare to advocate for legislation and regulatory policies that allow plant-based and cultivated seafood to compete on a level playing field with conventional seafood.

“Trade associations and nonprofits with lobbying capacity should prepare to advocate for legislation and regulatory policies that allow plant-based and cell-based seafood to compete on a level playing field with cultivated seafood.”

In the U.S., the Dietary Guidelines for Americans (DGAs) directly influence nutrition standards, which govern the foods that may be purchased by the federal government or served in public institutions such as schools. Institutional foodservice comprises a sizable fraction of the overall food market. The current DGAs recommend dietary patterns abundant in whole plant foods and seafood, and lower in sodium, saturated fat, and added sugars (USDHHS and USDA 2015). The practical implication is that conventional seafood may be prioritized over plant-based seafood if the plant-based options are higher in sodium or other nutrients that the government discourages (USDHHS and USDA 2015; USDA Food and Nutrition Service 2012). The most powerful way for individuals and organizations to influence dietary guidelines in the U.S. is to provide input on the composition of the advisory committee that proposes the guidelines to the government.

Additionally, government recommendations to limit consumption of certain fish species due to mercury or other contaminants may affect consumption, depending on whether consumers switch to other species, choose plant-based and cultivated versions of the most contaminated fish, or avoid seafood altogether ("Eating Fish: What Pregnant Women and Parents Should Know" 2017).

Governments can also proactively support the development of the alternative seafood industry through private sector incentives. By implementing tax credits or other financial instruments, governments can encourage the scaleup of the industry, further ensuring the provision of affordable nutritious alternative seafood in the future. These incentives could be incorporated into broader ocean policy frameworks, such as the Ocean-Based Climate Solutions Act of 2020 introduced in the U.S. House of Representatives.

7.3 Reducing barriers to entry for plant-based and cultivated seafood commercial activity

For many aspiring entrepreneurs in plant-based and cultivated seafood, the sheer plethora of potential product targets in the seafood space can present a barrier to entry. The decision matrix described in Section 4.3 could reduce the amount of time spent developing a product roadmap strategy and exploring market receptivity toward potential products. Alternatively, prospective investors can articulate solicitations for companies addressing specific product types or categories. These targeted solicitations would signal to entrepreneurs or existing plant-based or cultivated meat companies where their resources are best spent in order to secure investment. Startup incubators and philanthropic foundations with the capacity to make private investments can also solicit specific solutions.

BOX 3: Lessons learned from entrepreneurs in plant-based seafood.

Because so few plant-based seafood companies exist, insights from these founding teams are particularly helpful in identifying challenges and developing resources to reduce the barriers to entry for future brands and products. We interviewed three founders of plant-based seafood companies about their experience launching, and some common themes emerged.

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Importance of customer feedback:
Getting your product into the hands of chefs and mouths of consumers is critical for informing product development.
"When choosing which products to pursue, doing a lot of customer validation and discovery is important." – Kimberlie Le, Prime Roots

–

Pair great chefs with great food scientists:
Products must be chef-driven to resonate with consumers, but food scientists are critical for production and scaling.

–

Lack of institutional knowledge:
While plant-based seafood product development can be informed by the meat alternatives industry, less is known about how to address the unique challenges associated with seafood.
"There is a very delicate balance between something that tastes like the sea and something that tastes fishy. A few extra drops of algal oil is the difference between these two." – Chris Kerr, Good Catch Foods

–

Lack of production infrastructure:
A challenge that is shared with the plant-based meat industry is the lack of co-packers with high-moisture extrusion capability.

–

Abundant white space:
The variety of potential products and use cases is unparalleled, and technological innovation provides further opportunity for product diversification and improvement.
"We eat between 200-300 sea creatures and about 30 different types of land animals... seafood is a lot broader than chicken and beef." – Chris Kerr

A systematic solicitation for letters of interest from various stakeholders such as retailers, distributors, and foodservice outlets would also provide insight into desirable product types and the volume and pricing targets required to secure these contracts. These letters of interest would also de-risk the investment by demonstrating market receptivity and unmet demand despite the fact that many of the companies in this sector are currently pre-revenue.

7.4 Forging strategic partnerships with the existing seafood industry and beyond

Strategic relationships with the meat, consumer packaged goods, agriculture, industrial biotechnology, and life science industries have proven critical to the success of plant-based and cultivated versions of terrestrial animal products. Plant-based and cultivated seafood manufacturers can employ a similar strategy by partnering with traditional seafood companies, ingredient suppliers, and nonprofit organizations early in the emergence of this industry.

Major global commercial players in seafood
Companies already involved in seafood harvesting, production, processing, and distribution are well poised to invest in plant-based and cultivated seafood. They can leverage their existing assets, diversify their supply chains, and position their product portfolios to appeal to future consumers.

Although the global fishing industry is highly fragmented, with millions of small boats and subsistence fishermen, 13 “keystone” corporations (enumerated below) control 19-40% of the largest and most valuable stocks and 11-16% of the global marine catch (“Keystone Actors Shape Marine Ecosystems - Stockholm Resilience Centre” 2015). The annual revenues of the 160 largest seafood companies exhibit a distinct keystone pattern, with the top 10% of companies accounting for over one third of total revenues. Systematic engagement of these influential companies can spur additional interest in plant-based and cultivated seafood among other industry incumbents as they seek to keep abreast of their competitors amidst market shifts.

1. Maruha Nichiro (Japan)
2. Nippon Suisan Kaisha - Nissui (Japan)
3. Thai Union Frozen Products (Thailand)
4. Marine Harvest (Norway)
5. Dongwon Industries (South Korea)
6. Skretting (Norway)
7. Pescanova (Spain)
8. Austevoll Seafood (Norway)
9. Pacific Andes (Hong Kong, China)
10. EWOS (Norway)
11. Kyokuyo (Japan)
12. Charoen Pokphand Foods - CP Foods (Thailand)
13. Trident Seafood (US)

Ingredient suppliers

Ingredient suppliers such as ADM, Cargill, Axiom, Ingredion, Givaudan, Kerry, and others can make excellent strategic investors or partners for emerging plant-based brands. These companies sell the commodities that comprise plant-based seafood, including proteins, flavorings, fragrances, coloring agents, and lipids, as well as many of the raw materials that will contribute to cultivated seafood nutrient medium. The size, market insight, scientific expertise, and distribution networks of these suppliers make them strong partnership candidates even for early-stage plant-based and cultivated seafood startups.

Restaurants

Restaurant foodservice is among the likeliest market entry points for plant-based and cultivated seafood due to higher margins relative to grocery channels and the strong association between seafood and fine dining. Plant-based and cultivated seafood companies could partner with chefs and restaurant concepts to create splashy product launches and drive critical initial sales. This model has been employed with great success by companies like Impossible Foods. The company generated tremendous consumer interest and garnered culinary respect by launching their burger in an exclusive set of high-end restaurants with chefs who are unapologetic about their discerning standards for high-quality meat. Eat Just was the first company to begin selling cultivated meat, with their GOOD Meat Cultured Chicken launching at a restaurant in Singapore at the end of 2020.

Despite the challenges faced by the foodservice industry during the Covid-19 pandemic, plant-based seafood startups are pursuing foodservice partnerships to spread the word about their products. Companies like New Wave Foods, Novish, and Hooked all debuted their products in foodservice in 2021. Good Catch Foods expanded from retail to foodservice through partnerships with Veggie Grill and Whole Foods Market. Cultivated seafood companies, such as Wildtype, are beginning to form partnerships with chefs to bring their product to diners in the future.

Nongovernmental organizations and other consumer-facing partners

Aquatic and oceanographic research institutes can serve as valuable partners for directing resources toward species that are particularly threatened or whose harvesting tends to be most highly disruptive to ocean ecosystems. Plant-based and cultivated seafood companies could partner with certifying bodies such as the Marine Stewardship Council, the Aquaculture Stewardship Council, and the Global Aquaculture Alliance to obtain existing or new certifications for their products, as plant-based and cultivated seafood would clearly meet all the metrics for reduced environmental impact. Environmental certifications, such as seals that can be added to product packaging, would serve to familiarize consumers with novel plant-based and cultivated seafood products. Already, the World Sustainability Organization's Friend of the Sea certification is open to plant-based seafood products that meet the organization's standards for sustainable agricultural products.

Aquariums such as the Monterey Bay Aquarium have spearheaded efforts to publicize and implement sustainability certification systems and could likewise lead campaigns to promote plant-based and cultivated seafood as high-impact solutions for ocean preservation ("Seafood Eco-Certification Programs from Seafood Watch at the Monterey Bay Aquarium" n.d.). Furthermore, many of these organizations have cultivated strong relationships within the seafood industry. These groups may be instrumental in garnering involvement from the existing seafood industry to capitalize on this transformation rather than risking disruption, akin to companies like Tyson, Cargill, PHW Group, and others taking a leading role in funding and supporting plant-based and cultivated meat alongside their activities in conventional meat production.

Additionally, private corporations that interface with the ocean-concerned public, such as private aquariums or ocean-based tourism companies, could engender positive public relations by serving plant-based or cultivated seafood at their events, offering them in their on-site cafeterias, or even partnering with or endorsing specific brands or products. Plant-based and cultivated seafood offer a unique opportunity for these companies to demonstrate their commitment to preserving the marine ecosystems they seek to share with their clientele. Many forward-thinking workplaces beyond the ocean realm use their corporate cafeterias to showcase their sustainability and social responsibility campaigns, and products like New Wave Foods' plant-based shrimp and Ocean Hugger's plant-based tuna have been featured by several prominent Silicon Valley technology companies' dining services. These contracts tend to garner significant positive press for the plant-based seafood companies as well, thereby elevating the status and visibility of these products.

"Plant-based and cell-based seafood offer a unique opportunity for ocean-focused companies and organizations to demonstrate their commitment to preserving the marine ecosystems that they seek to share with their clientele."

7.5 Coordinating commercial activity and R&D across the sector

Plant-based and cultivated seafood producers may benefit from creating a coalition to respond to regulatory, labeling, and anti-competitive legislative challenges. Such challenges have arisen for other segments of the plant-based and cultivated meat industries. For example, the state of Missouri passed a law in 2018 making it unlawful to misrepresent a product as meat if it is not from slaughtered livestock or poultry. Currently there are no trade associations dedicated solely to plant-based or cultivated seafood companies. However, plant-based seafood companies can join the Plant Based Foods Association, which represents the interests of companies that make a variety of plant-based foods, and cultivated seafood companies can join the Alliance For Meat, Poultry And Seafood (AMPS) Innovation, a policy-focused industry group for cultivated meat and seafood companies.

Systems for regulatory oversight and maintaining global supply chains are significantly different for seafood products than for land-based animal agriculture. Thus, although the production platforms for manufacturing plant-based seafood and cultivated seafood are rather similar to their terrestrial animal agriculture counterparts, dedicated consortia and associations for these industries may be necessary to effectively advocate for their unique considerations.

Technical aspects of plant-based and cultivated seafood research and development will likely benefit from participation in consortia around plant-based meat and cultivated meat more broadly. For example, government-funded technology and advanced manufacturing centers in industries ranging from nanotechnology to biopharmaceuticals have spearheaded academic/industry/government collaborations that accelerate the translation of fundamental research into commercial significance. These endeavors often also incorporate workforce development and training programs to ensure the availability of a highly skilled workforce for new manufacturing methods. The plant-based and cultivated meat sectors have already experienced a shortage of technical talent trained to enter these industries. The establishment of concerted training programs should prepare skilled technical workers for the burgeoning plant-based and cultivated seafood industry before workforce limitations become a bottleneck for companies' growth.

7.6 Risks and opportunities: educating investors at all levels

Investors have been among the most active participants in the early-stage emergence of plant-based and cultivated seafood because seasoned investors in disruptive technologies recognize the harbingers of a wholesale disruption of the seafood industry. Immense pressures on a finite resource—wild fish stocks—arise not only from overfishing and increased demand but are substantially compounded by less predictable but equally disruptive influences like climatic shifts or severe weather patterns. Overfishing of keystone species, pollution, and climate perturbations can collapse marine ecosystems in an irreversible manner, which generates substantial financial risk for investors with commercial interests in the seafood industry.

The task of articulating these risks can again take a page from the playbook of terrestrial animal agriculture. A UK-based initiative called the Farmed Animal Investment Risk and Return or "FAIRR" is a collaborative network of investors that raises awareness of the risks associated with investment in animal farming and highlights protein diversification as a key strategy for responsible asset management. Developing a similar coalition among investors with financial interests in the seafood industry to position investment opportunities in plant-based and cultivated seafood as critical de-risking components of their portfolio could facilitate a substantial shift in financial resources.

"Investors have been among the most active participants in the early-stage emergence of plant-based and cell-based seafood because seasoned investors in disruptive technologies recognize the harbingers of a wholesale disruption of the seafood industry."

Early-stage investors in plant-based and cultivated seafood companies include not only mission-aligned firms such as New Crop Capital, Stray Dog Capital, and Blue Horizon Ventures but also traditional Silicon Valley venture capital firms that have historically had little or no involvement in food technology or consumer brands. Concerted efforts to educate these investors about the current state and existing challenges of this nascent industry will ensure that expectations are aligned and that projections are realistic and achievable, which ultimately positions early-stage companies to successfully achieve milestones to unlock larger follow-on investments.

Investors interested in sustainable aquaculture development are also beginning to view alternative seafood as another strategy for alleviating wild fishing pressure. One example is Hatch, which is a fund and accelerator historically focused on aquaculture. Hatch now explicitly brands itself as a supporter of alternative seafood innovation. The sooner investors begin incorporating alternative seafood into their definitions of sustainable seafood production technology, the sooner the industry can achieve the scale to meet growing global demand for fish and shellfish.

Strategic investors from the food, ingredients, and seafood industries can also serve a crucial role. These types of investors will be particularly important for accelerating growth through leveraged infrastructure and distribution networks, and should be brought into the capitalization table early in a plant-based or cultivated seafood company's funding trajectory. Animal nutrition company Nutreco formed a strategic partnership with BlueNalu in 2020, which will help the startup develop expertise in fish nutrition and procure essential raw materials and ingredients.

8

Vision for the future: oceans of abundance

Photo by Tracey Jennings

8 Vision for the future: oceans of abundance

The rate of adoption of new technologies is entirely dependent upon the amount of resources devoted to their development and deployment, from the financial and human capital focused on innovation to the political support that can spur additional effort. The present moment presents a pivotal opportunity to leapfrog over stopgap measures such as fishery management strategies and intensive aquaculture to develop a truly sustainable, scalable means of satisfying growing global seafood demand.

Globally, humankind's current relationship to seafood is akin to our relationship to terrestrial animal meat several thousand years ago, when domesticated or farmed animals and wild animals contributed roughly equally to meat consumption. Now, with farmed meat accounting for virtually all terrestrial meat consumption—on a scale far greater than wild animal populations could have ever sustained—our civilization is realizing that even the most efficient, intensive animal farming is simply too inefficient to feed a population nearing 10 billion people by 2050. Livestock now constitute far more biomass than all wild terrestrial vertebrate animals combined (Bar-On, Phillips, and Milo 2018), and animal agriculture's high resource burden has squeezed terrestrial habitats—and the biodiversity they once contained—to the brink. Sufficient arable land to cultivate the inputs for terrestrial animal agriculture on the scale required to meet projected demand this century simply does not exist (Poore and Nemecek 2018). Even if feasible, the amount of animal waste generated through such a system would wreak catastrophic environmental consequences.

And yet, we find ourselves on the same trajectory regarding the oceans. However, we now have the foresight to innovate ourselves out of the situation where harvesting and farming marine organisms encroaches upon, and ultimately irreversibly undermines, marine ecosystems. We can implement plant-based and cultivated meat production to not only satisfy global demand that simply cannot be met in the short term through wild harvests or aquaculture but also, in the long term, to avoid the negative consequences of the otherwise inevitable progression toward intensive aquaculture. At the right scale and with supportive policy frameworks, plant-based and cultivated seafood can satisfy consumer demand with far greater resource efficiency, market responsiveness, regard for environmental stewardship, and consideration of both human health and ecological health than any method of conventional seafood production.

It should also be noted that resource allocation toward plant-based and cultivated seafood development is doubly beneficial for the oceans. Just as the plant-based and cultivated seafood sector can leverage insights from alternatives to terrestrial farmed animal products, learnings from plant-based and cultivated seafood product development will likewise accrue benefits to the larger animal product alternatives landscape. Thus, investment in plant-based and cultivated seafood benefits oceans both directly and indirectly: it directly alleviates demand for wild-caught and farmed seafood, and it indirectly supports a shift away from industrialized *terrestrial* animal farming, which is intimately intertwined with ocean health through waste runoff and greenhouse gas contributions. Therefore, the oceans benefit immensely from a wholesale shift away from animal product consumption, including both aquatic and terrestrial animals, accelerated by widespread availability of cost-competitive plant-based and cultivated meat and seafood.

In the face of growing global demand for seafood, efficient and scalable plant-based and cultivated seafood production offers a new approach for maintaining vibrant and abundant oceans without compromising food security, complementing existing strategies in fisheries management and sustainable aquaculture. Accelerating the development, commercialization, and widespread availability of plant-based and cultivated seafood should constitute a core pillar of the strategic plan of all entities whose vision includes responsible stewardship of both land and sea while ensuring human prosperity.

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The Good Food Institute is a 501(c)(3) nonprofit organization dedicated to creating a healthy, humane, and sustainable food supply. Our work is 100% powered by gifts and grant support. GFI's team of scientists, entrepreneurs, lawyers, and policy specialists are laser focused on using markets and food innovation to transform our food system away from industrial animal agriculture and toward plant-based and cell-based meat. To learn more, please visit GFI.org.

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