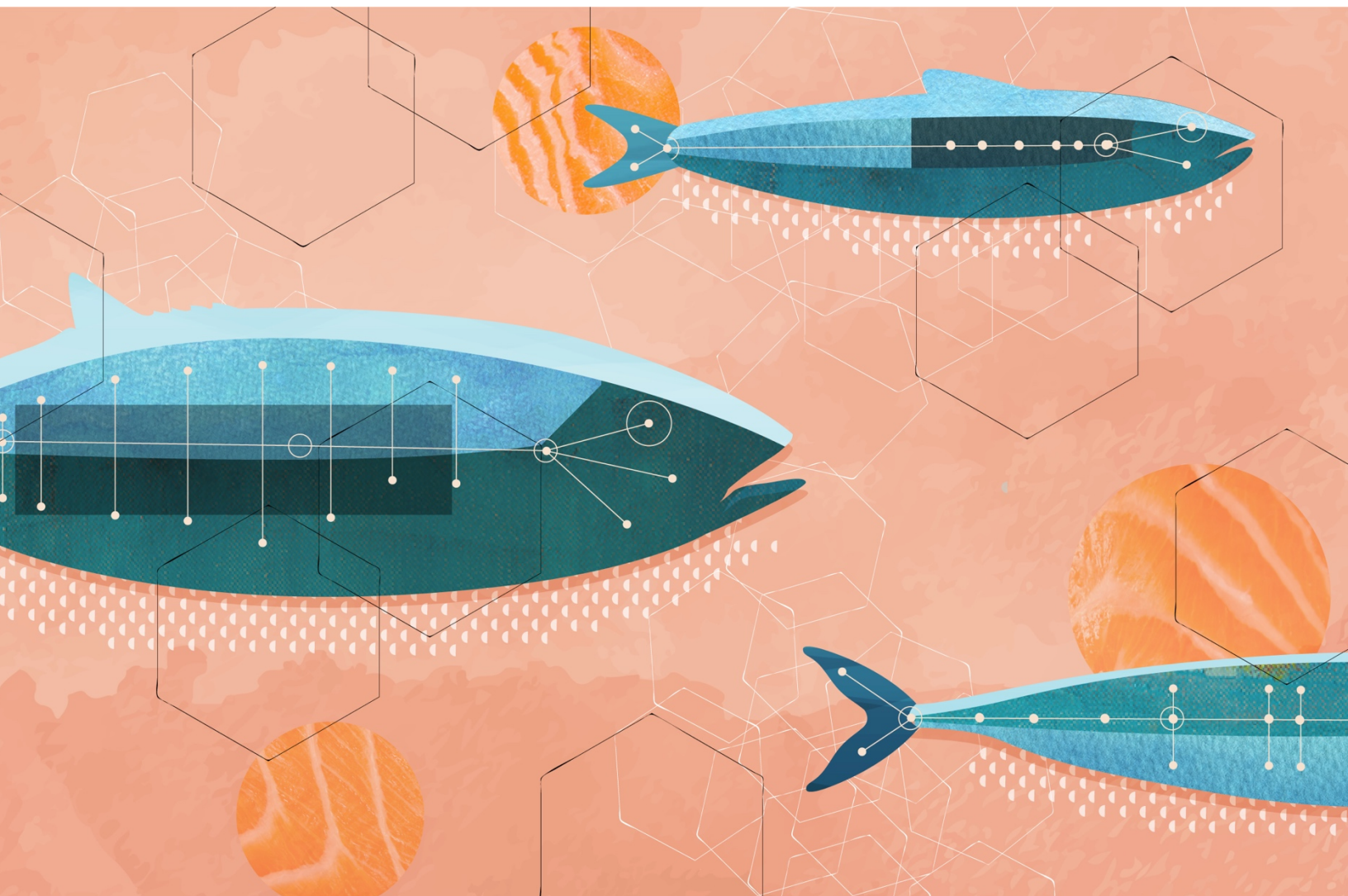


# An Ocean of Opportunity:

Plant-based and cell-based seafood for  
sustainable oceans without sacrifice

January 22, 2019



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## 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 cell-based 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 [10]. 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 (using plant-derived ingredients to replicate the flavor and texture of seafood) and cell-based<sup>1</sup> seafood (produced by cultivating cells from marine animals) is an immensely promising approach for alleviating pressure on both wild fisheries and aquaculture systems. Plant-based and cell-based 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 cell-based versions of a top predator like tuna are essentially the same as those required for plant-based or cell-based versions of species at the bottom of the food chain.

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<sup>1</sup> Cell-based meat has become the industry-preferred term 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 term “cultured” is particularly problematic when referring to cell-based meat as applied to seafood, as cultured seafood is widely understood to mean seafood produced through aquaculture. Thus, the terms cell-based meat and cell-based seafood are used throughout.

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Accelerating the development and commercialization of scalable plant-based and cell-based 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 cell-based 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 sizeable number of highly motivated early-adopters and market entry points for plant-based and cell-based 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 cell-based seafood can be further accelerated by concerted efforts to apply insights from the development, commercialization, and generation of demand for plant-based and cell-based versions of terrestrial animal agriculture products. While many of these insights can be translated directly to plant-based and cell-based seafood, the seafood sector does pose some unique technical challenges for both plant-based and cell-based 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 cell-based 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 virtually no dedicated funding outside of a few companies’ 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 cell-based seafood is on the order of \$10-20 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 cell-based seafood industry.

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# 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 (SDGs). Unfortunately, protecting ocean resources appears to be a low priority. In a survey of over 2,400 leaders in government, industry, and NGOs around the world, restoring and preserving marine life was least likely to be ranked among the six most important SDGs [1], and fisheries aid has fallen by 30% over the past five years [2]. Meanwhile, scientists and reporters are uncovering the true scale of the global fishing industry's harm to aquatic ecosystems [3,4], consumers [5,6], and human rights [7,8]. The risks of business-as-usual operations in commercial fishing are clearer than ever.

## 1.1 Pressing environmental threats

Overfishing and harmful fishing practices have severely depleted global fisheries, damaged fragile marine habitat, and destabilized ocean ecosystems. For decades, fishing fleets have used more and more fuel to catch fewer and smaller fish each year [9]. A 2018 report by the United Nations Food and Agriculture Organization [10] found that one-third of all fish stocks are being depleted faster than they can replenish. Another 60 percent of stocks are fished at the maximum sustainable level, leaving only seven percent of fish stocks that are underfished.

**“One-third of all fish stocks are being depleted faster than they can replenish. Another 60 percent of stocks are fished at the maximum sustainable level, leaving only seven percent of fish stocks that are underfished.”**

Destructive fishing methods have impacts far beyond fish stocks and may be the second-biggest threat to all ocean ecosystems after climate change [11]. Coral reefs, which harbor 25 percent of ocean fish species despite covering just 0.1 percent 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 [11,12]. Bycatch — the unintended, unreported, and often unused catch of birds, turtles, sea mammals, juvenile fish, and other non-target species — represents over 40 percent of the entire global fish catch [13]. Bycatch prevents the population recovery of some protected species and is a critical threat to ocean food chains.

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 [14]. Reducing pressure on global fisheries is critical to allow commercial species and ocean ecosystems a chance to recover from decades of exploitation and mismanagement.

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## 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 [15] to the enslavement of migrants in the South China Sea [8]. 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 [16]. International fishing fleets in particular 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 [17].

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 [18]. 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% within a decade, 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: up to 300,000 newborns in the United States alone are exposed to potentially toxic levels of mercury in the womb each year [19]. Eighty to 90 percent of mercury in the human body can be traced to seafood consumption [20]. 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 [21].

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 percent 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 United States was mislabeled [11]. Often, mislabeled fish are species that tend to be higher in pollutants [22]. 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.



## 2 Plant-based and cell-based seafood as a new solution

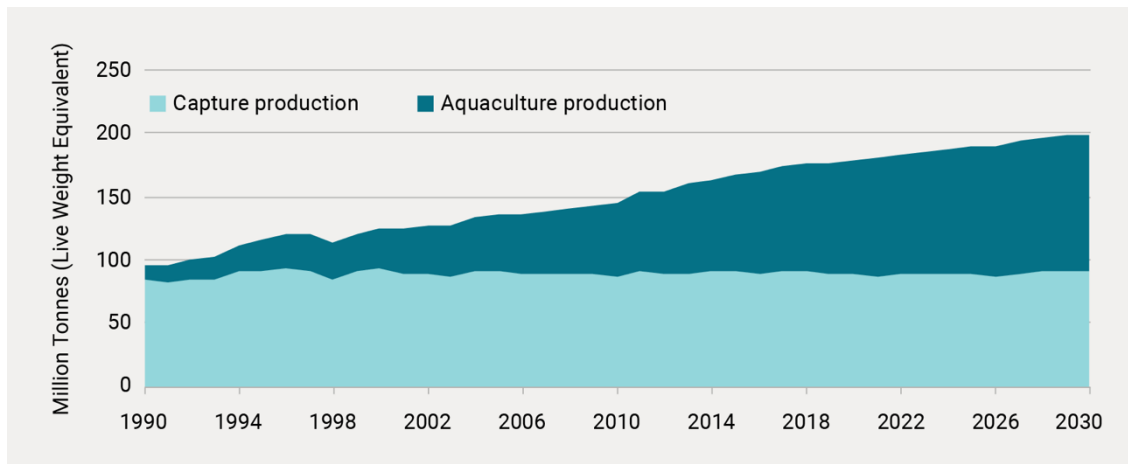
As incomes rise and population increases, the United Nations projects an increase in demand for seafood of more than 45 million tons between the mid-2010s and early-2020s, even after accounting for higher prices [23]. Wild fisheries are already harvested at maximum capacity, and they are increasingly 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 [23]. Thus, there is an urgent and sizable need for altogether new approaches to meet increasing global demand for seafood.

“Wild fisheries are already harvested at maximum capacity, and they are increasingly yielding species that are of low value for human consumption. Aquaculture growth is only anticipated to keep pace with demand for 17 out of nearly 200 countries. There is an urgent and sizable need for altogether new approaches to meet increasing global demand for seafood.”

### 2.1 Shortcomings of sustainable fisheries management

Global fishery yield has been stagnant for decades, with a slight decline (around 1% per year) since its peak in 1996 (Figure 1). While this may at first 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 [10]

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 [16]. 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,

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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 [16].

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 [9]. Correspondingly, only oceans at the polar extremes remain unexploited (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 [9]. 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 (for example, permanent damage to reefs and other ocean-bottom habitats). While total volume has held fairly steady, this is increasingly comprised of smaller and less desirable animals as the populations of larger (and often more lucrative) species are decimated [24]. 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 [25].

“Traditional fisheries management strategies 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.”

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 (highlighted as “disruptive technologies” in the FAO’s most recent report [10]) may inadvertently accelerate ecosystem collapse despite their potential to reduce bycatch, if the target species is a keystone species. 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 [26]. The aquaculture industry has exhibited a meteoric rise in recent years, masking and overcompensating for declining wild-caught



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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 (CAFOs).

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 [27,28]. High disease prevalence within the animals has motivated the practice of subtherapeutic antibiotic administration, which accelerates the emergence of multi-drug-resistant bacterial strains [28].

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 [29]. 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 [30]. Beyond pathogenic concerns, many aquaculture operations pose the threat of releasing non-native species into wild ecosystems [31], destruction of ecologically sensitive habitats, and even risks for local communities by impacting storm-mitigating features like coastal mangrove forests [32].

“Some of 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.”

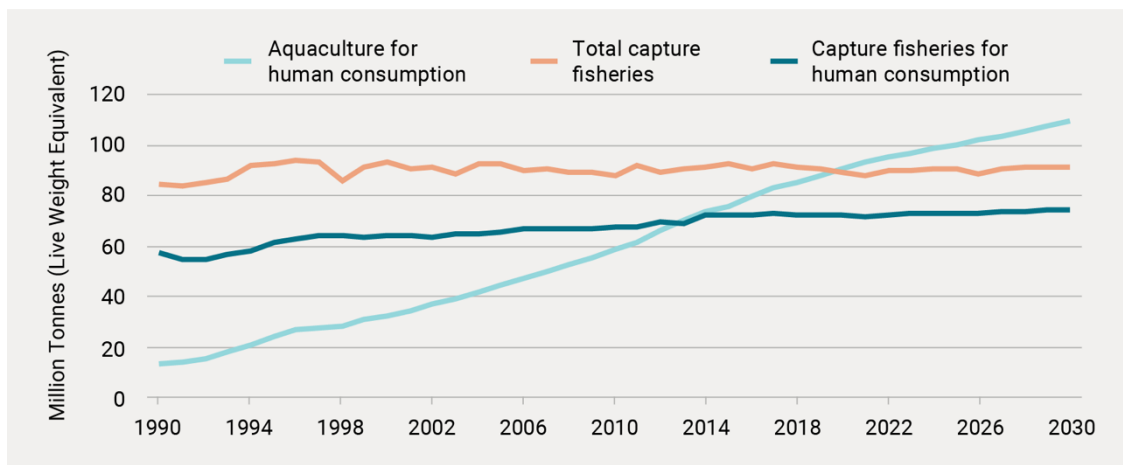
Although some aquaculture facilities employ more sustainable practices and risk-mitigation strategies such as antibiotic-free growth, lower stocking densities, and avoiding sensitive habitats, the vast majority of the aquaculture industry’s growth is occurring in regions where these best practices are seldom observed. For example, China already accounts for approximately two thirds of all aquaculture [10]. Relying on plant-based and cell-based seafood to satisfy a significant fraction of the unmet demand for seafood may prevent the same trends from manifesting at sea that we have seen play out on land.

From a practical standpoint, many desirable species of marine animals simply cannot be reared in captivity. For example, Kinki 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 [89]. 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. Aquaculture currently consumes over 12% of harvested wild fish in the

form of fishmeal and fish oil, and this figure is anticipated to rise to 16% by 2030 [10]. Thus, while the volume of wild harvests is likely to remain near stagnant, an increasing fraction will be used for fishmeal production despite increasing incorporation of plant-based feeds. 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 [33].

**Figure 2: Global Capture Fisheries and Aquaculture Production, 1990–2030**



Source: Food and Agriculture Organization of the United Nations, 2018 [10]

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 [34]. 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 [27].

As has occurred with terrestrial farmed animals, greater consumer awareness of these conditions is likely to contribute to demand for plant-based and cell-based seafood. In recent years, consumers increasingly cite animal welfare concerns as influential in their purchasing decisions [35]. 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

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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. In addition, some animal welfare groups have produced undercover videos of marine animal harvest and farmed fish slaughter [36], akin to the undercover work on animal farms that has spurred intense scrutiny. 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 cell-based 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 (see Terramino Foods and Quorn in Section 4) that can potentially utilize byproduct streams and residual biomass from other agricultural or biological industries as feedstocks. Manufacturing facilities for plant-based and cell-based 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 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. 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 cell-based tuna meat are virtually identical to those required to produce an equal mass of cell-based 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, cell-based 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.

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Furthermore, plant-based and cell-based 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 cell-based 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**

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 cell-based 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.

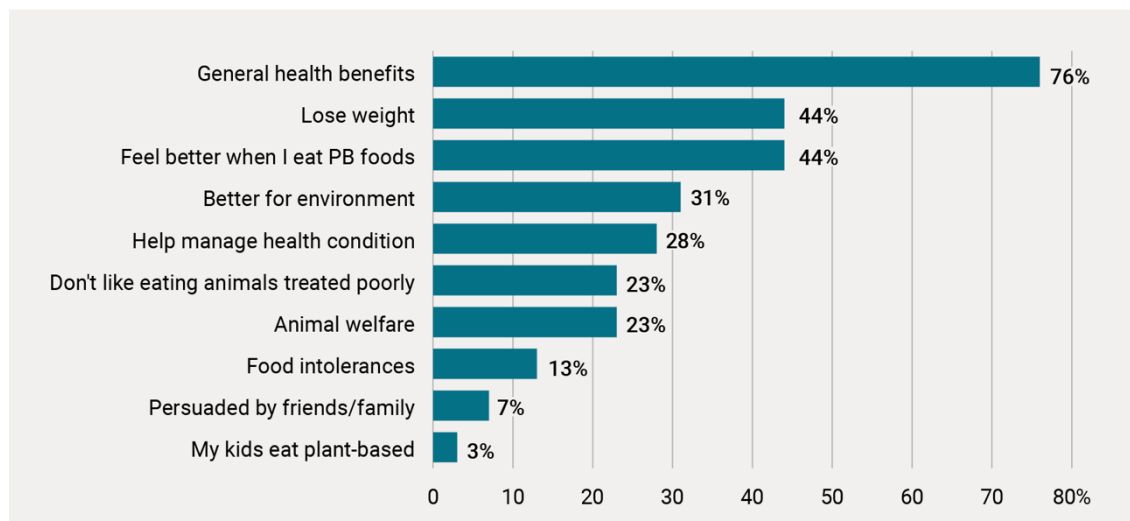
Indeed, the fate of the oceans is intimately intertwined with the advancement of alternatives to terrestrial industrial animal agriculture beyond the translation of learnings from those industries to the plant-based and cell-based seafood industry. Waste and fertilizer runoff from feeding and operating intensive animal farming operations represents the greatest source of ocean eutrophication — spawning ocean dead zones covering upwards of 100,000 square miles [88] — 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 alternatives to meat has exhibited a marked surge recently, with global sales growing 8% annually since 2010 [37]. In recent years these growth rates have continued to accelerate, especially in certain markets. Between July 2017 and July 2018, dollar sales of plant-based meat products grew by 24% in the U.S. [38]. 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.

Plant-based meats have radically improved their taste, texture, and general appeal to mainstream consumers 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 meats 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 alternatives 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**

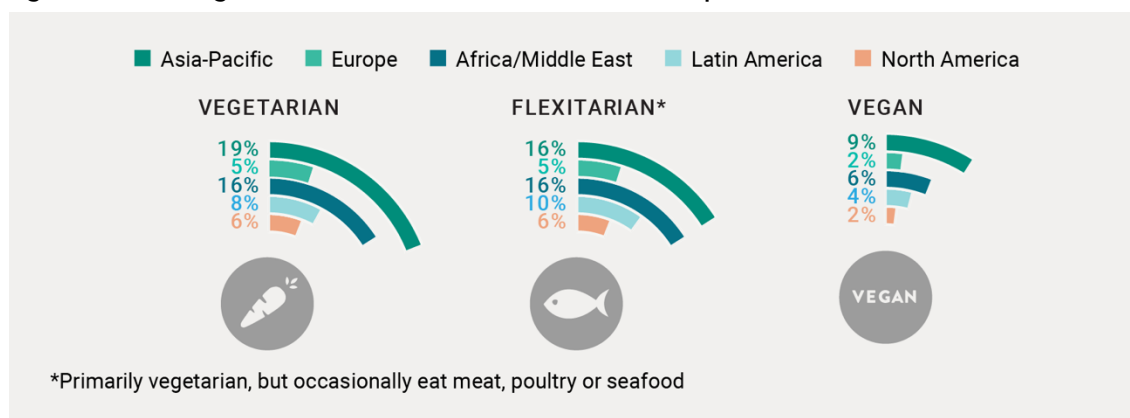


Source: Mattson, 2018; n=1,163 general population U.S. consumers [39]

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 [40]. The majority of growth in demand is not derived from vegans and vegetarians but rather from flexitarians, foodies, Millennials, and other mainstream consumers [41]. A recent survey from market research firm NPD indicated that 14 percent of U.S. consumers (43 million people) regularly consume plant-based alternatives and of those consumers, 86 percent do not consider themselves vegan or vegetarian [42]. 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, enabling them to reach a consumer base that is comprised of 70% meat eaters and substantially increasing their sales [43].

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



Source: Nielsen, 2016 [44]

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 milks (Box 1) provides an instructive case study for other disruptor categories such as plant-based and cell-based 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 starting positioning plant-based milks 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

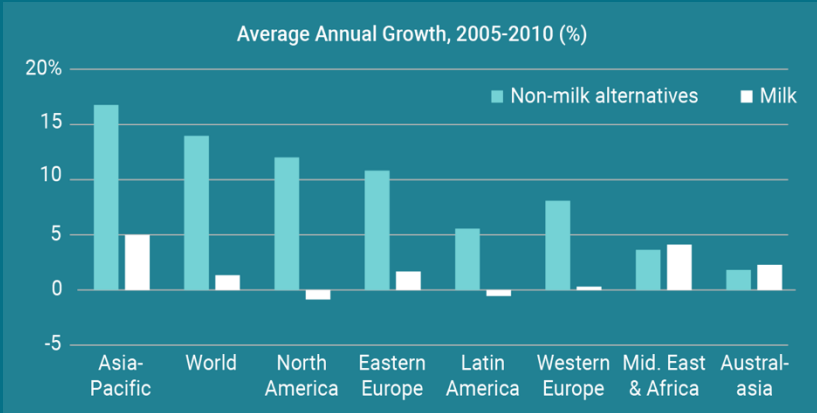
Taking another lesson from the plant-based meat industry, plant-based seafood companies should recognize the value of strategic partnerships early in their company formation. For example, Beyond Meat's partnership with PHW Group, a European meat distributor, facilitated their entry into the European market by providing support for distribution, logistics, and consumer engagement [45]. 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. For example, Tyson Ventures and General Mills' 301 Inc. are both investors in Beyond Meat. In 2017, Field Roast and Lightlife were acquired by Maple Leaf Foods, the largest Canadian meat company, and Sweet Earth Natural Foods was acquired by Nestle, a global food giant. Each of these companies now has access to infrastructure, expanded markets, and food industry expertise that can help propel their growth. For plant-based seafood manufacturers, engaging these partners early and nurturing these relationships will be key to success.



Organizations like GFI as well as groups that have ocean sustainability at the core of their missions and have worked 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 cell-based meat and provide connections between established industry players and startup companies in plant-based and cell-based seafood as a means of empowering the seafood industry to embrace this shift.

**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 cell-based 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 cell-based seafood should incorporate these strategic considerations.

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## **Challenges**

Seafood is often seen as a healthier alternative to other terrestrial animal proteins — 90% of U.S. consumers of all ages associate seafood with positive health benefits [49]. 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. Thus, consumers may be less inclined to seek alternatives to seafood on health grounds, and plant-based and cell-based seafood products will have to emphasize their nutritional equivalence to conventional seafood. Because very few plant-based seafood products (and no cell-based seafood products) exist on the market, it is difficult to forecast projections of consumer demand for these products 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 [50]. 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 cell-based 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. [51]. Over seven million Americans are allergic to seafood [52], with shellfish allergies representing the most common food allergy in the U.S. [53]. 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 [54].

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 [55]. 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 [56]. Thus, the positive association between seafood and health may weaken in coming years.

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Beyond these health-related opportunities to drive consumer demand for plant-based and cell-based 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 was lost due to consumer food waste, discarding of bycatch, or distribution spoilage from 2009 to 2013. Seafood products are highly perishable foods, which presents challenges producers and distributors as well as consumers, as many consumers feel they do not feel comfortable assessing whether seafood is fresh and safe to eat [90]. Plant-based items have a longer shelf life and reduce 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 cell-based 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

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 brands and companies include Good Catch, Terramino Foods, and Ocean Hugger, all of which have formed since 2016. Good Catch has developed flaked fish products such as tuna, crab cakes, and fish burgers. Terramino Foods debuted their prototype salmon burger in April 2018, produced using a fungi-based fermentation platform (see Box 2). 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 meats because it does not require intensive processing methods and does not seek to achieve the protein levels of animal-derived meat. Using fibrous plant materials like marinated jackfruit to mimic the shredded texture of meat is another example of this approach, which has recently been used by Tofuna Fysh for a flaked tuna fish product.

Figure 5: Established and emerging plant-based seafood brands

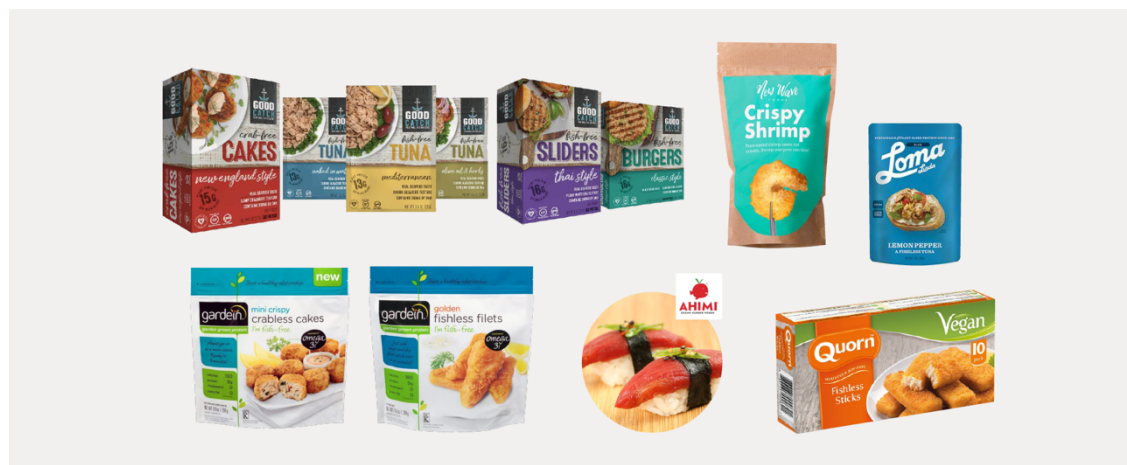


Although the last two years have witnessed the launch of several exciting plant-based seafood brands, there is still a great deal of untapped market potential. Most of the plant-based seafood products currently on the market are ground or minced products rather than whole filets. With more sophisticated 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

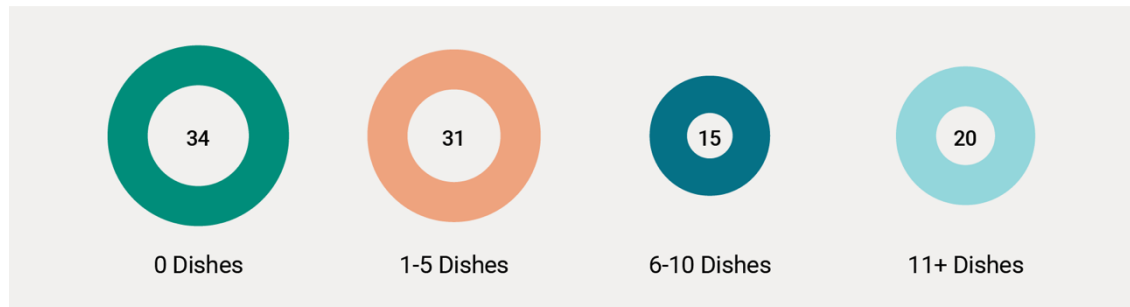
Plant-based seafood can leverage growth trends in the seafood category and the plant-based alternatives category to potentially exceed growth rates in the broader plant-based meat category. There is ample opportunity for existing and new brands to expand their distribution within retail channels. While a variety of plant-based beef and chicken products are available in mainstream grocery stores throughout the U.S., only two plant-based seafood products — Gardein’s Fishless Filets and Crabless Cakes (Figure 6) — are widely available as of early 2019. 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.

Figure 6: Representative pre-market and on-market plant-based seafood product offerings



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 [58]. With their higher margins and large share of the seafood markets, full-service restaurants are one of the easiest entry points for plant-based seafood (and, ultimately, for cell-based 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 7: Number of seafood dishes in top 100 U.S. restaurants by revenue**



Source: GFI original research by Aaron Bergman

Seafood 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 [59]. Main entrees with shellfish account for 4.8% of all dishes and are present on 50% of all menus [60]. 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 [61]. 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 [62]; QSR: quick service restaurant

### 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/species based on limited information.

Within such a decision matrix, consumer receptivity toward plant-based alternatives for specific types of seafood products should be one factor. But 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/nutrition, cost, and convenience — all of which provide clear physical and practical benefits to the individual [63–66]. Consumers are also increasingly motivated by altruistic factors, such as concern for the environment or for animal welfare [67,68]. 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, in some contexts consumers avoid fish that tastes “fishy” (hence the popularity of species like pollock and tilapia, where white color and flaky texture are more important), whereas other species are so prized for their unique flavors that they are served without or with very mild sauces and seasonings.



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Importantly, food choice motivations have varying degrees of influence depending on the individual, though general patterns of influence also emerge among certain consumer groups [69–71]. 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 [69,72,73]. 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 [74], whereas health perceptions decrease consumption of other meat products [75]. 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 cell-based seafood in contrast to the contamination concerns associated with conventional fish. As such, product development and marketing of plant-based and cell-based 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 cell-based seafood industry would benefit from the availability of a detailed molecular and cellular characterization of many seafood products. This 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 cell-based meat products that both emulate the consumer experience (taste, texture, mouthfeel, 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.

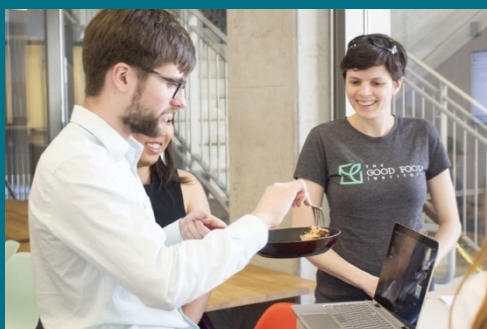
Ingredients like algal omega-3 fats are currently expensive relative to their animal-derived counterparts. Thus, there is a need to further research to reduce production costs of these ingredients. Approaches include increasing cell density, expression yield, and harvesting efficiency of algal strains 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 meats, 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.

Studies examining the health impacts and nutritional quality (including aspects like absorption and bioavailability of various forms of algal-derived omega-3 fatty acids) of plant-based and cell-based seafood relative to conventional seafood would also benefit the industry. 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 cell-based 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: University of California, Berkeley Plant-Based Seafood Collider

In the Spring of 2017, The Good Food Institute worked with Professor Ricardo San Martin at the University of California, Berkeley and SeaCo, LLC (which makes Good Catch Foods) to offer a plant-based seafood “collider”: an entrepreneurship-focused, project-based course designed to offer students instruction in the science and technology behind plant-based seafood, as well as the



The founders of Terramino Foods prepare a prototype for their final presentation in the UC Berkeley course.

opportunity to research and prototype their own products. Students investigated the key biochemical and textural aspects of carp, tilapia, salmon, shrimp, and catfish (which represent a variety of seafood textures) and then used this information to propose an R&D plan for replicating fish flavor and texture using the most sophisticated sensor technologies and analyzers (from the food industry and beyond). The goal of these efforts was to help major plant-based food companies find potential proteins, aromatic compounds, and textures from plants to meet the demand for plant-based fish.

The team of students with the highest-scoring final project, a fungi- and microalgae-based salmon product, went on to form the company Terramino Foods to commercialize their fish-free salmon burger. Within approximately one year of completing the UC Berkeley course, the founder of Terramino had been accepted as a Thiel Fellow and their company had raised over \$4M in a seed round co-led by True Ventures and Collaborative Fund -- both Silicon Valley technology funds whose portfolios predominantly feature digital technology.

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.

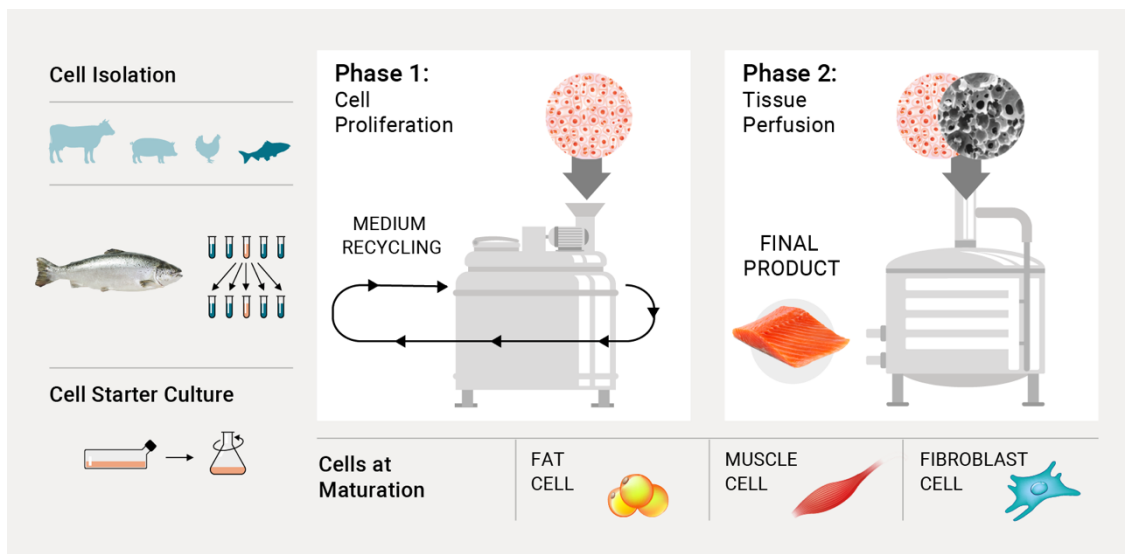
## 5 Cell-based seafood: applying advances in cell-based meat to seafood

While plant-based meat has improved drastically, current evidence indicates that many consumers are likely to continue to demand genuine meat even if presented with highly compelling plant-based options. Furthermore, many plant-based meats are minced or processed products rather than complex structures resembling intact animal muscle tissue. 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 thus may necessitate an approach that can produce the sophisticated structures associated with animal muscle tissue.

### 5.1 Cell-based meat as a platform: cross-applicability to marine animals

The cell-based 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 cell-based 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

Since 2014, more than two dozen startup companies have emerged to commercialize cell-based meat. Of these, only four companies have indicated an exclusive or predominant focus on seafood products. These species comprise only a small portion of the multi-billion dollar market across all marine animals,

leaving immense opportunity for fledgling companies to pioneer work on additional cell-based seafood products from other species. Because the procedures for producing a cell-based seafood product should be relatively transferable across species once optimized, there is potentially a large first-mover advantage for early entrants. Thus, the application of cell-based 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.

**Table 2: Cell-based meat companies with a partial or dedicated focus on cultivating cells from fish and other aquatic animal species\***

Company	Location	First target product	Capital raised
Finless Foods	USA (Berkeley, California)	Bluefin tuna	Seed (\$3.5 million)
BlueNalu	USA (San Diego, California)	Species not announced	Seed (\$4.5 million)
Wild Type	USA (San Francisco, California)	Salmon	Seed (\$3.5 million)
Shiok Meats	Singapore	Crustaceans	Pre-seed (undisclosed)
Seafuture	Canada (Calgary, Alberta)	Species not announced	Not announced
Avant Meats	China (Hong Kong)	Species not announced	Not announced

\*Note that this landscape is rapidly evolving and this represents a snapshot as of January 2019.

### 5.3 Unique challenges and opportunities for cell-based seafood

The mission to create cell-based seafood products exhibits unique advantages and challenges relative to cell-based meat for other terrestrial farmed species. The most notable challenge is that cells from fish and other marine 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 marine 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.

Cell-based 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 (typically conducted at 37°C), fish cell culture can be performed at appreciably lower temperatures (4-24°C for saltwater and 15-37°C for freshwater species) [76]. 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 cell-based 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 cell-based seafood production [77–80].

Cell-based seafood may also pose advantages 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 cell-based fish than for meats like beef or pork.

Much of the appeal for pursuing cell-based 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 marine animals is more likely to be consumed raw or minimally cooked (e.g. sushi, oysters, tuna steaks, and ceviche) compared to meat from other animals. As previously noted, marine 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, cell-based 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 [90], but product loss due to spoilage is a major concern within the seafood industry. Because cell-based 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 cell-based seafood

Cell culture of marine 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, transformation vectors and reporters, full genome sequences, and biomolecular (“-omics”) datasets for cells derived from marine 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 marine species will be orders of magnitude smaller than historical investment to develop these resources for the mammalian research community.

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To facilitate all of this work, a public repository of validated cell lines derived from specific marine animal species representing diverse animal genera (such as bony fish, cartilaginous fish, shellfish, crustaceans, and mollusks) is needed. 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 marine 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 marine species.

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 Bolstering the innovation ecosystem for sustainable seafood products**

While plant-based and cell-based 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 cell-based 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 cell-based 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 cell-based seafood options for meeting global demand and thus alleviating pressure on overtaxed fisheries and aquaculture systems.



**Table 4: A 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%

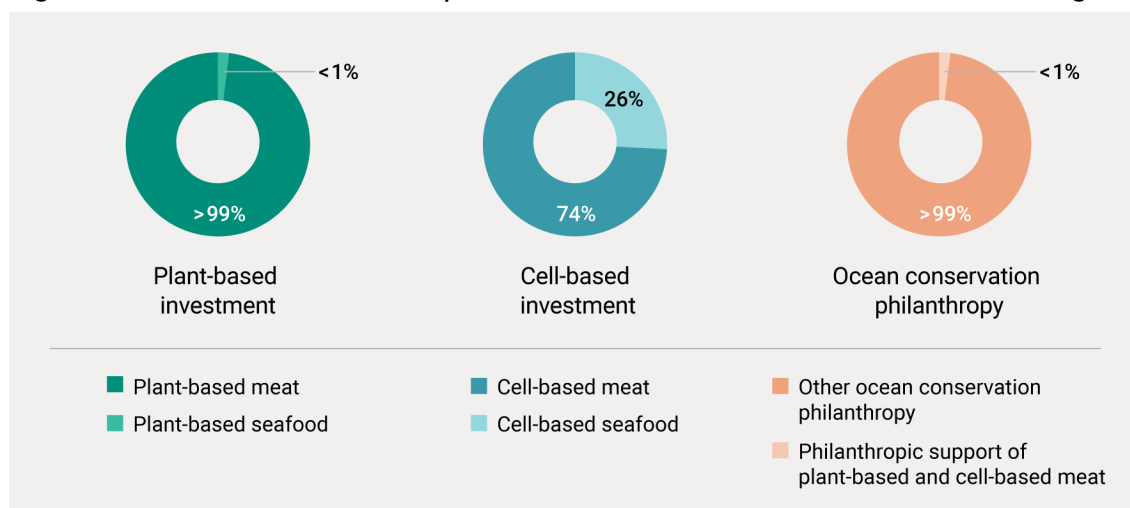
Source: FAO-FIAS 2013 Food balance sheet of fish and fishery products in live weight and fish contribution to protein supply.

## 6.1 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 [11]. 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 United States, Germany, and Norway constituting the top-ranking donors for marine-related grants [11]. However, none of this funding was earmarked for the development of plant-based or cell-based seafood.

Philanthropic foundations play a critical role in supporting neglected areas of scientific research [81]. 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 9: Investment and philanthropic funding for plant-based and cell-based 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 cell-based 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 — across all forms of plant-based and cell-based seafood is on the order of \$10-20 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 cell-based 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 cell-based 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 (Table 3). 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 cell-based 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 cell-based 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 cell-based seafood**

Impact area	Why supporting sustainable plant-based and cell-based 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 cell-based 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.

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## 6.2 Engaging governments

Government action can exert influence over the future of plant-based and cell-based seafood in several ways beyond committing additional public research support. Two approaches are: (1) ensuring that plant-based and cell-based seafood products are not handicapped through labeling laws or standards of identity that privilege conventional seafood, and (2) updating the dietary guidelines to specifically include these products as suitable alternatives to conventional seafood.

In some jurisdictions, plant-based meat, cell-based 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,” even though studies indicate that consumers are not confused when modifiers of these terms are used in conjunction (as in “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 have not yet been raised 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 cell-based 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 conventional seafood.”**

In the U.S., the Dietary Guidelines for Americans (DGAs) directly influence nutrition standards that govern the foods that may be purchased by the federal government or served in public institutions such as schools, which comprise a sizable fraction of the market. The current DGAs recommend dietary patterns abundant in whole plant foods (including fruits, vegetables, and whole grains) and seafood, and lower in sodium, saturated fat, and added sugars [82]. 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 [82,83]. 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 cell-based versions of the most contaminated fish, or avoid seafood altogether [55].

## 6.3 Reducing barriers to entry for plant-based and cell-based seafood commercial activity

For many aspiring entrepreneurs in plant-based and cell-based 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 cell-based 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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**Understand the usage occasion:**  
It's important to understand where your product is likely to be consumed and market it accordingly.  
*"Most consumers eat raw seafood away from home in the form of sushi, poke, and tartar... It made sense to sell to chefs who know how to handle raw fish and can serve consumers where they are used to eating it."* – David Benzaquen, Ocean Hugger Foods

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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, Terramino Foods

–  
**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

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**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.

## 6.4 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 cell-based versions of terrestrial animal products. Plant-based and cell-based 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.

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### 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 cell-based 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 [84]. 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 cell-based seafood among other industry incumbents as they seek to keep abreast of their competitors amidst market shifts.

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

### Ingredient suppliers

Ingredient suppliers such as ADM, Cargill, Axiom, Ingredion, Givaudan, 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 cell-based 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 cell-based seafood startups.

### Restaurants

Restaurant foodservice is among the likeliest market entry points for plant-based and cell-based seafood due to higher margins relative to grocery channels and the strong association between seafood and fine dining. Plant-based and cell-based 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, which generated tremendous consumer interest and garnered culinary respect by first launching their burger in an exclusive set of high-end restaurants with chefs who are unapologetic about their discerning standards for high-quality meat.

### 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 cell-based 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 cell-based 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 cell-based seafood products.

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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 cell-based seafood as high-impact solutions for ocean preservation [85]. 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 cell-based 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 cell-based seafood at their events, offering them in their on-site cafeterias, or even partnering with or endorsing specific brands or products. Plant-based and cell-based 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.”**

## **6.5 Coordinating commercial activity and R&D across the sector**

Plant-based and cell-based 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 cell-based 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 cell-based seafood companies, but 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.

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 cell-based 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 cell-based seafood research and development will likely benefit from participation in consortia around plant-based meat and cell-based 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.



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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 cell-based 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 cell-based seafood industry before workforce limitations become a bottleneck for companies' growth.

## **6.6 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 cell-based 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 FAIRR (Farmed Animal Investment Risk and Return) 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 cell-based 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 cell-based 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.

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 they should be brought into the capitalization table early in a plant-based or cell-based seafood company's funding trajectory.

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## 7 Vision for the future: oceans of abundance

The rate of adoption of new technologies is entirely dependent upon the amount of resources — including financial capital and human capital as well as political support that can spur additional effort — devoted to their development and deployment. 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 (farmed) animals and wild (hunted) 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 [86], 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 [87]. 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 — but this time we 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 cell-based 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. Plant-based and cell-based 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 cell-based seafood development is doubly beneficial for the oceans. Just as the plant-based and cell-based seafood sector can leverage insights from alternatives to terrestrial farmed animal products, learnings from plant-based and cell-based seafood product development will likewise accrue benefits to the larger animal product alternatives landscape. Thus, investment in plant-based and cell-based 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 — aquatic and terrestrial — accelerated by widespread availability of cost-competitive plant-based and cell-based meat and seafood.

In the face of growing global demand for seafood, efficient and scalable plant-based and cell-based 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 cell-based 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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### About The Good Food Institute

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](http://GFI.org).

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