# SUSTAINABILITY CONSIDERATIONS FOR THE EXPANSION OF US OPEN OCEAN AQUACULTURE

## Aquaculture Feed

Environmental Defense Fund

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

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# Sustainability Considerations for the Expansion of US Offshore Aquaculture: Aquaculture Feed

## Executive Summary

Global seafood production is expected to grow 14 percent by 2030 due to population growth and increased global demand for seafood (FAO SOFIA, 2022). Growing a sustainable U.S. aquaculture sector to meet that projected demand will require focusing on the sustainability of the feed that supplies 70 percent of farmed seafood globally. Feed is the largest cost to farmed fish production and the most significant contributor to aquaculture's environmental impact.

Aquaculture feed production is inextricably linked to the availability and price of raw materials contributing to the ingredients. Feeds must be carefully developed to supply optimal nutrition to farmed fish. Fish meal and fish oil (FMFO), derived from wild-caught forage fisheries, traditionally supplied the necessary nutrients. However, plant-based proteins and oils now dominate feed formulations and crops show promise as raw materials for novel ingredients. This trend has increased the interface of aquaculture and terrestrial agriculture, emphasizing a need to consider systemic performance indicators, including food: feed competition, and targets for industry sustainability. Aquaculture feed can be produced using less land, water, and energy, leading to more efficient use of resources and a reduced environmental footprint. Attention to sourcing all ingredients and widespread adoption of novel ingredients derived from common crops, food system by-products, insects, and single-cell proteins, will support the sustainable use of natural resources and protect biodiversity.

Additional research is needed to evaluate tradeoffs in aquaculture feed formulations. However, investing in aquafeed technologies and practices to increase the industry's environmental performance will likely create new economic opportunities, especially in rural and coastal areas, including jobs in research and development, feed production, and aquaculture operations.

As a result of research, including peer-reviewed and industry publications, supplemented by communications with fish farmers, professionals in the feed industry, public policy experts, and scientists, we offer this analysis on aquaculture feed, evaluating 1) sustainability advances in conventional ingredients, 2) opportunities presented by development of novel ingredients and 3) feed conversion efficiency and related innovations, and providing discussion of opportunities for heightened sustainability in the aquafeed sector. Where appropriate, we identify other relevant analyses on aquaculture feed published near this report's release.

## Sustainability Advances in Conventional Ingredients

Dependence on marine aquaculture feed ingredients has decreased over the last 30 years due to improved feed efficiency, the use of alternative ingredients, and the inclusion of by-products. Concerns about ecological and social impacts resulting from the large-scale harvest of raw materials (both wild-caught fish and their crop-based replacements, specifically soy) have demanded increased transparency in the feed supply chain to support responsible sourcing from well-managed systems and have resulted in increased efforts to reduce dependence on marine ingredients and increased participation in certification programs, which have reduced the volume of unsustainable fish and soy in aquaculture feed globally. By-products from human food systems, such as fisheries, aquaculture, and livestock processing, provide a growing proportion of raw materials for aquaculture feed, increasing overall circularity in the food system.

## Innovations in the Development of "Novel" Ingredients

Significant research and development continue to identify unconventional feed ingredients with demonstrated nutritional value, support for a circular business model and mitigated environmental risks. Microalgal and plant-based oils and proteins from fermented or genetically modified crops, insects, and bacteria could play a useful role in the future, given their potential for increased environmental performance, while meeting cost, scalability, and digestibility criteria. Once their value is widely accepted, various functional, non-nutritive ingredients will continue to improve feed efficiency and fish health through increased immunity or reduced pathogens. Widespread and significant incorporation of novel ingredients is hampered by inconsistent quality, insufficient supply, and high costs, resulting in the continued reliance on marine ingredients for superior performance in the aquaculture feed industry. Evaluating the environmental performance of current and future novel ingredients will support the identification of tradeoffs between these and their conventional counterparts. It will help to further identify key sustainability performance indicators and targets in the industry.

## Advances in Efficient Use of Resources

There have been substantial improvements in feed efficiency since 2000, especially for widely-cultivated species, through enhanced fish growth, health and immunity, and improved feed delivery. Understanding species-specific nutrient needs and developing precision feeds, enhancing nutrient utilization by fish through selective breeding and genetic technologies, and optimizing feed intake through precise delivery systems are innovative approaches that decrease waste in aquaculture food systems generally and reduce impacts on biodiversity, water quality, and availability, land, and energy use. There has also been increased efficiency in converting raw crop materials to ingredients. If adopted globally, these types of approaches could significantly improve the environmental performance of aquaculture systems.

## Opportunities to Support Increased Sustainability

Standards for responsibly sourced feed down to the raw materials and throughout the supply chain ensure optimal fish health and a nutritious and sustainable seafood supply. A consistent methodology to measure sustainability is needed to support such standards. *Comprehensive U.S. science-based legislation* should harmonize and codify standards that (1) enable growth and innovation in the aquaculture feed industry and (2) prioritize conservation and management of global natural resources and the well-being of value chain participants and surrounding communities. Support for *global sourcing transparency, including consistent measurement of targets,* will increase the ability of stakeholders and end-users to evaluate sustainability tradeoffs among ingredients. *Early-stage innovation funding* can address the environmental footprint of feeds, while *partnerships* can improve the early adoption of technologies. More broadly, *prioritization of feed ingredients that avoid human food conflicts* will address aquaculture as part of a broader food system that supports food security and nutrition outcomes.

Consumers are increasingly concerned about the sustainability of the food they consume. The aquaculture feed industry embraces innovations in feed ingredients and technological approaches to improved feed efficiency. Continued research, widespread adoption of these innovations, and diverse education initiatives could ensure food security, conservation of resources, and reduction of the footprint of aquaculture feed in the United States and globally.

## Acknowledgments:

This paper focuses on the aquaculture feed industry that is likely to support the development and expansion of a large-scale U.S. offshore aquaculture industry. The information contained in this paper does not apply to many aquaculture operations globally. Farms in developing nations, small-scale farms, or farms that grow species that do not require compound feed face different options and barriers for sustainable aquaculture feed, may lack the resources to increase the sustainability of their feed or may be unable to evaluate the relative impacts of their supply chain.

The following experts provided their insights into aquaculture sustainability issues and advances and inspired the authors of this report to look towards a bright future of innovations in aquaculture feed that will support healthy people and a thriving planet. However, their generous participation in interviews with Council Fire does not reflect their endorsement of this paper:

Nadege Audiffrin, Communication Manager, Innovafeed

Kevin Fitzsimmons, Professor, University of Arizona, Chair, F3Challenge

Halley Froelich, Assistant Professor, University of California, Santa Barbara

Aaron Hobbs, Executive Director, North American Coalition for Insect Agriculture

Don Kent, President, Hubbs-SeaWorld Research Institute

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# Sustainability Considerations for the Expansion of US Offshore Aquaculture: Aquaculture Feed

## Introduction

Global aquaculture production is at a record high. It is forecast to expand an additional 14 percent by 2030, which is increasingly important in providing access to safe, nutritious, and relatively low-greenhouse gas (GHG) emission food to the growing human population. More than 70 percent of farmed seafood (minus algae) is fed species, and compound feeds are at the core of this industry, supporting its growth (FAO SOFIA, 2022). Feed is its highest cost and the feed value chain is its largest source of tradeoffs, accounting for more than 90 percent of environmental impacts in the aquaculture food system (Little et al, 2018).

The dietary demands of carnivorous finfish have direct and indirect ecological, social, and climate impacts complicated to assess due to the broad geographical sourcing of dozens of raw materials used in feed (Little et al, 2018). To address sustainability in this industry, including considerations of overfishing, deforestation/land conversion, greenhouse gas emissions/decarbonization, and social/human rights, a holistic view of economic, environmental, and social impacts is needed. As with all food production industries, culturing fish requires examining and accepting tradeoffs.

Fish meal and fish oil provide the “perfect” diet of required nutrients, such as protein and fatty acids (EPA, DHA), that closely mimic the natural diet of the farmed species in the wild. Global demand for these ingredients in animal feeds (both for terrestrial and aquatic farming) prompted the development of large-scale fisheries for small pelagic fish, like anchovy, sardines, and krill, that provide the raw materials for fish meal and fish oil (Newton et al., 2023; Henriksson et al., 2013). These species play a valuable role in their ecosystems, and removing large quantities of individuals reduces their availability as forage for marine predators and artisanal fishermen who supply fish for direct human consumption (Pikitch et al., 2014). The continued demand for this global commercial harvest to support the projected growth in aquaculture, along with uncertain impacts from climate change, spark concerns about fish stock vulnerability, including the risk of stock collapse. Fish meal and fish oil remain prominent in many aquaculture feed formulations; however, they are also increasingly demanded by various uses, from humans to pets and livestock.

Forage fish populations are notoriously variable and demand conservative use in feed formulations. Since the 1970s, scientists and fish farmers have sought alternatives, driven by a desire to mitigate financial risks due to fluctuating supply and the resulting spikes in fish meal and fish oil prices. They continue to seek replacement ingredients that optimize nutritional content and digestibility for the cultured species, price, and availability and support the growing demand for aquacultured products.

As a result of a broad literature review of peer-reviewed and industry publications supplemented by communications with those in the fish farming and aquaculture feed industries, as well as public policy experts and scientists, we offer this analysis on aquaculture feed, evaluating advances in raw materials/ingredients and feed conversion efficiency, and providing a discussion of opportunities for heightened sustainability in the aquaculture feed sector. This paper encompasses the innovative trends in aquaculture feed ingredients and efficiency. Still, it is not inclusive of many other research topics currently being explored in this landscape, such as the benefits of polyculture in marine aquaculture systems, sustainability gaps between producer countries and the related equity implications, traceability of ingredients in feed, and incorporations of specific live or functional feed ingredients (Hossain et al., 2022; Bohnes et al., 2022; Blaha et al., 2023; Hossain et al., 2023).

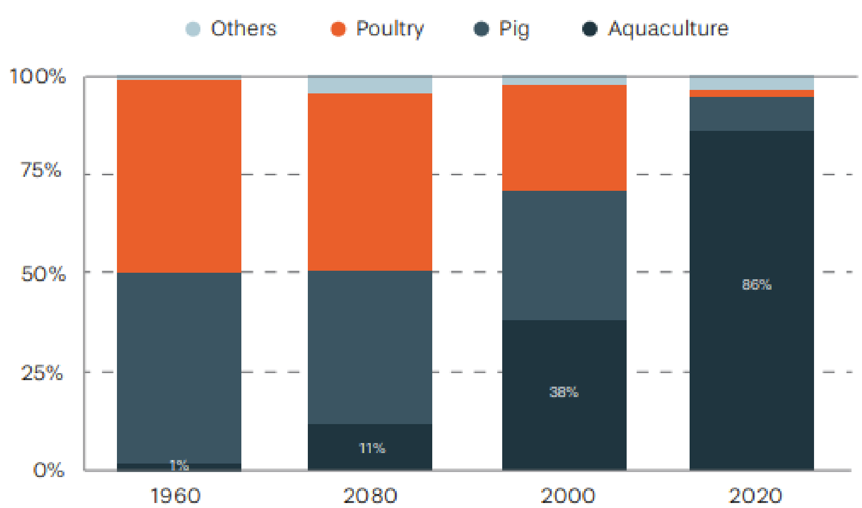


**Figure 1:** Fishmeal Inclusion Across Animal Feed Markets; 1960-2020. *SOURCE: Hatch Blue. "Emerging Protein-Rich Ingredients for Aquaculture." Hatch Blue & Hatch Innovation Services & Gordon and Betty Moore Foundation, 2024.*

The increasing demand for aquacultured seafood will continue to drive the rapid development of innovative approaches to address economic, social, and environmental concerns of feed producers, fish farmers, seafood consumers, and all those who value strong environmental and social standards to ensure their food is produced sustainably. This paper informs on the vast potential for advancement in sustainable aquaculture feed, which is necessary to contribute to sustainable seafood production.

## Trends in "Conventional" Ingredients

### Marine Ingredients

Fish oil and fish meal are prized for their nutritive, cost-effective contributions to aquaculture feeds. The fish meal provides the essential amino acids (the building blocks of proteins) fish need for growth and is palatable, digestible, and rich in other nutrients. Fish oil contains highly desirable long-chain fatty acids (DHA and EPA).  When consumed by fish and incorporated into their flesh, these polyunsaturated oils become valuable to seafood consumers. Fish oil, however, requires more fish per unit produced than fish meal, and decreased forage fish landings have created a bottleneck in this sector; the increasing price of fish oil due to limited supply is a major driver in the search for alternatives (Naylor et al, 2021).

More broadly, the continued decline in the marine harvest of forage fish due to overfishing, natural variability in population size, and more recent climate change impacts has resulted in the widespread adoption of a range of plant-based ingredients that can substitute for marine ingredients. The proportion of fish meal included in total feed use has declined substantially since 2000. While volatility has been fairly constant in forage fisheries, the potential for increased fishmeal production is fairly low for the next few decades (Glencross & Bachis, 2021; Glencross et al., 2024). These forage fisheries are threatened by climate change, IUU fishing, and poor fisheries management (Halpern et al., 2019; Zhang et al., 2019).

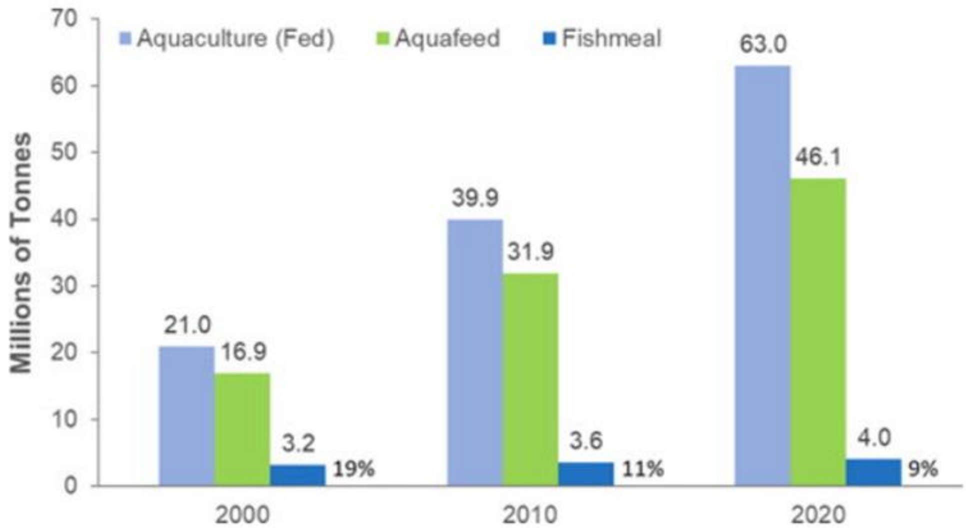


**Figure 2:** Global aquaculture production of fed species, aquaculture feed production, and fishmeal use in aquaculture feeds (as absolute and proportional use) in 2000, 2010, and 2020. (All values are in millions of metric tons. Percent values are the overall inclusion of fishmeal as a proportion of total feed use.) *SOURCE: Glencross et al, 2024., Brett, Xiaowen Ling, Delbert Gatlin, Sachi Kaushik, Margareth Øverland, Richard Newton, and Luisa M. P. Valente. "A SWOT Analysis of the Use of Marine, Grain, Terrestrial-Animal and Novel Protein Ingredients in Aquaculture Feeds." Reviews in Fisheries Science & Aquaculture, (2024), 1–39. doi:10.1080/23308249.2024.2315049.*

## Terrestrial Ingredients

**That Was Then…**

Shift in aquaculture feed ingredients from "ideal" diet of fish meal and fish oil to significant substitution with plant-based ingredients created increased complexity in feed formulations, to accommodate limitations of plant-based meals and oils.

Terrestrial plant-based ingredients (soy, wheat, peas, and other vegetable proteins and oils, starches) currently make up most of the feed fed to carnivorous fish; in some cases, they are more sustainable, efficient, and economically viable than their marine counterparts. However, they have nutritional and digestibility limitations, which can affect the performance and nutritional quality of the seafood produced on these feeds (Zlaugotne et al., 2022). Compensating for these limitations, including a dearth of omega-3 fatty acids, requires adding ingredients to round out the nutritional profile of plant-based feed.

Research has demonstrated that reducing fish meal and fish oil (65 percent to 18 percent reduction of fish meal and 24 percent to 11 percent reduction of fish oil) is possible while maintaining optimal nutrition for the farmed salmon through greater inclusion of plant-based ingredients (GSI Salmon). As a result, plant proteins and oils remain foundational ingredients in today's aquaculture feeds. They could expand farmed fish diets by another 15 percent to make up 75 percent of the protein in aquaculture feed (Aquafeed Media, 2023). This shift towards plant-based ingredients is supported by using "functional feed ingredients" as additives in small amounts per formulation that improve performance or provide fish health benefits (New England Aquarium & SeaAhead, 2023).

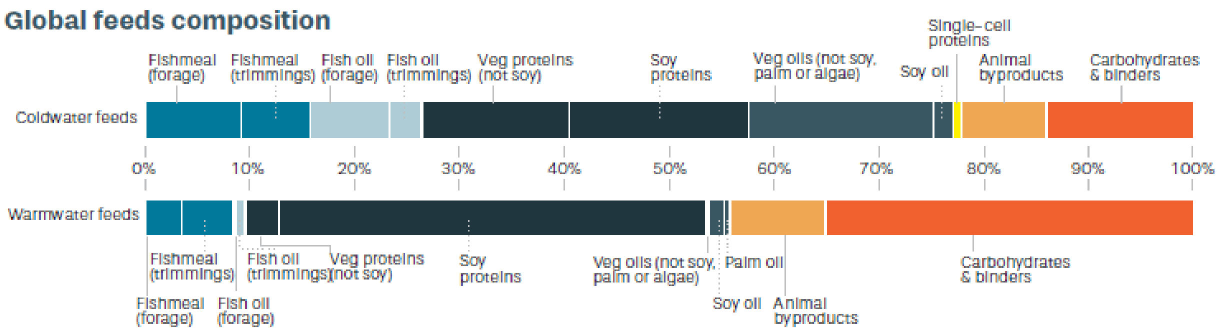


**Figure 3:** Global Feeds Composition. *SOURCE: Cargill. "Cargill Aqua Nutrition Sustainability Report 2022." Cargill, 2022, www.cargill.com/doc/1432219325606/cargill-aqua-nutrition-sustainability-report-2022.pdf.*

## Mindful Sourcing of Fish and Crops

Feed ingredients have an impact on reared fish and also on the environment. To hedge against variability in supply and prices, the aquaculture feed industry has long sought to broaden the sources and types of raw materials used in their compound feeds; this diversification has resulted in sustainability gains by those in the industry who are committed to ethical and sustainable production. Despite increased transparency in traceability and reporting, largely due to certification requirements, responsible sourcing of raw materials/ingredients, both aquatic and terrestrial, continues to be hindered by poor traceability more broadly throughout the supply chain and a lack of effective governance.

Several feed companies are committed to sourcing fish meal and fish oil from sustainably managed fisheries. Engaging with Fishery Improvement Projects in areas of weak governance will continue to improve the environmental performance of wild-caught fisheries supplying FMFO. Adopting a precautionary, ecosystem-based approach to forage fishery management will increase protection for the marine ecosystem and possibly accelerate the adoption of alternative aquaculture feed ingredients as prices rise, decreasing dependence on fish meal and fish oil.

Alternatively, utilizing low-trophic marine resources may boost the sustainability of aquaculture feed (Idenyi et al., 2022).

Agricultural products from large-scale crop production (predominantly soy and wheat) that now supply a large proportion of aquaculture feed ingredients are associated with all of the region-specific impacts that accompany that terrestrial industry, including land conversion/deforestation, biodiversity loss, soil and water degradation, eutrophication and climate concerns (Shahbandeh, 2024). However, the Amazon Soy Moratorium is an example of an effective effort to support sustainability by reducing deforestation. Despite emerging challenges, the moratorium is being sustained to extend that success (Heilmayr et al., 2020). U.S. regulations to restrict deforestation in the supply chain could partially align with the European Union Deforestation Regulation (EUDR) and provide a framework for sustainable sourcing.[1]

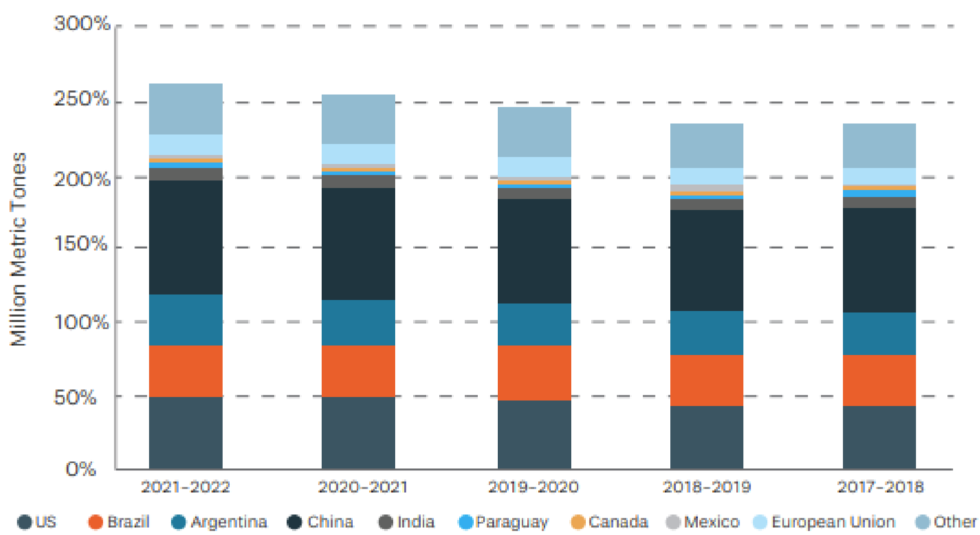


**Figure 4:** Global soybean meal production by region: 2017-2022. *SOURCE: "Emerging Protein-Rich Ingredients For Aquaculture." Hatch Blue & Hatch Innovation Services & Gordon and Betty Moore Foundation, 2024.*

[1] The EU has adopted regulations to eliminate deforestation in imports of several major commodities, including soy; https://environment.ec.europa.eu/topics/forests/deforestation/regulation-deforestation-free-products_en

Based on an assessment of past and future U.S. soy production and exports, the United States could provide affordable crops in suitable volumes for the aquaculture feed industry and has enjoyed an increased share of the aquaculture feed ingredient market recently (40 percent of the aquaculture feed demand for soy in 2020 was sourced from U.S. crops). Corn and barley-derived products show promise (Hatch Blue, 2024).

**TREND**: Soybean meal costs significantly less than fish meal and fish oil and is available in large volumes. Improved sustainability of soy can be achieved through careful attention to responsible sourcing, and support for land, water, and biodiversity protections in all agricultural regions, including the United States.

"In 1990, fishmeal and fish oil dominated, while in 2020, plant resources such as protein and oil dominated fish feed." (Zlaugotne et al, 2022)

Therefore, increased aquaculture demand could provide a buffer against recent decreased U.S. soy exports (Shahbandeh, 2023). Regardless, the market for U.S. raw materials (fish and crops) may be limited by the aquaculture feed industry's preference for a globally diverse supply to mitigate risks. While the United States has a strong reputation for fisheries and agricultural practices that *could* exceed the environmental performance of raw materials from other regions, ecosystem/biodiversity concerns remain associated with overfishing and the production of crops. Engaging with regions outside the United States to increase the sustainability of their raw materials further increases the environmental performance of the entire global aquaculture feed system. The following figure demonstrates the difference in GHG emissions, depending on the source.

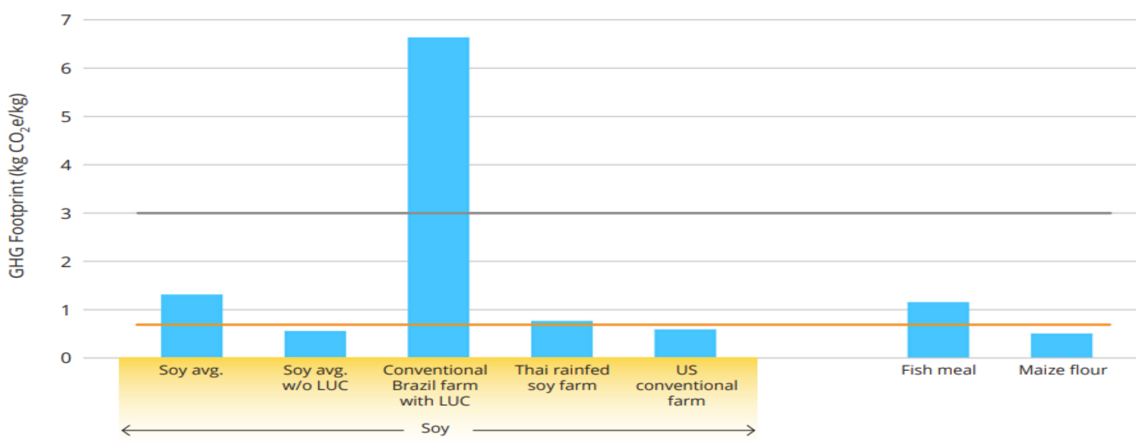


**Figure 5:** Feed ingredient footprint, based on source and considering recent land use conversion (LUC), fish meal is average. *Source: WWF. "Feed of the Future: Transparent and Traceable." WWF, 6 March 2024, www.worldwildlife.org/publications/feed-of-the-future-transparent-and-traceable*.

**The Efficiency and Equity of Food-Feed Competition**

The current growth of aquaculture requires increased production of protein for feed and has resulted in heightened consideration of feed ingredients. Food-feed competition exists in global aquaculture systems because of competing end-uses of many different natural resources such as marine, insect, and plant-based raw materials, as well as edible by-products from human food systems (Breewood & Garnett, 2020). These ingredients, which are high in protein, essential fatty acids, and/or micronutrients needed for human growth and development, are thus diverted from human food systems. As consumer demand for high-trophic aquaculture grows, competition for forage fish or other low trophic edible marine species, crops, and marine and plant-based food system by-products may also grow, with the potential to impact *human nutrition and food security,* raising significant equity issues. This is not a new discussion, having been raised in multiple terrestrial and marine animal conversations (feeding corn to cows, etc.). Food and feed don't just compete for land, but also other resources such as labor, water, and capital and while marine and terrestrial food system by-products are used in aquafeed, they provide only a piecemeal solution to the problem of limited resources (Muscat et al, 2020). Setting a broad policy prioritizing human food allows for tradeoffs to be addressed.

When aquaculture is considered in the global context, it is clear that switching to aquafeed that mainly relies on non-food-competing ingredients could decrease environmental and social impacts of this industry (Van Riel et al, 2023). Additional gains can be made by *improving feed conversion efficiency* (with feed additives or technologies), *increasing the human edible yield* from aquaculture products, and *balancing the species grown* (promoting omnivores and unfed species) (Chary et al., 2023).

Consumer preferences affect the demand for direct consumption of aquafeed ingredients and consumer choices can affect production practices greatly with regard to species raised (carnivorous seafood products over small pelagic fish, insects, or plant-based meals), and drive supply towards more sustainable seafood. Because competition from aquafeed could reduce resilience of global food systems, and given the complexity of aquafeed formulations, a broader interdisciplinary discussion is needed around aquatic foods and their role in broader food systems (Chary et al., 2023; Pounds et al., 2022).

## Incorporation of "Novel" Ingredients

Responding to concerns around the price, supply, performance, and sustainability of conventional ingredients and to ensure projected increased demand for aquaculture feeds can be met, the aquaculture feed industry continues to seek new raw materials and ingredients from plants and animals to meet nutritional and other growth and performance requirements. Because there are far fewer potential sources of long-chain fatty acids than proteins, novel sources of these molecules are particularly sought after. Alternatives to fish oil, fish meal, and the now ubiquitous plant-based meals are being explored and incorporated when they are economically and technically feasible. Novel ingredients include conventional ingredients that have been developed to provide better nutrition and unconventional feed ingredients from plants, animals, or inorganic sources that can be adopted as suitable replacements at scale. A key benefit of many novel ingredients produced thus far is their potential contribution to circularity in the broader food system– due to the direct use of processed by-products for aquafeeds or the use of food system waste as a substrate/feedstock for the production of feed ingredients (e.g., insects).

As their moniker implies, novel ingredients have not been brought to a scale and affordability for widespread adoption by the aquaculture feed industry. The following is a summary of emergent areas of novel ingredient research that still require development, expansion, and standardization to be suitable as alternative options to more common feed ingredients. Life cycle sustainability analyses that evaluate formulations that include these novel ingredients are ongoing.

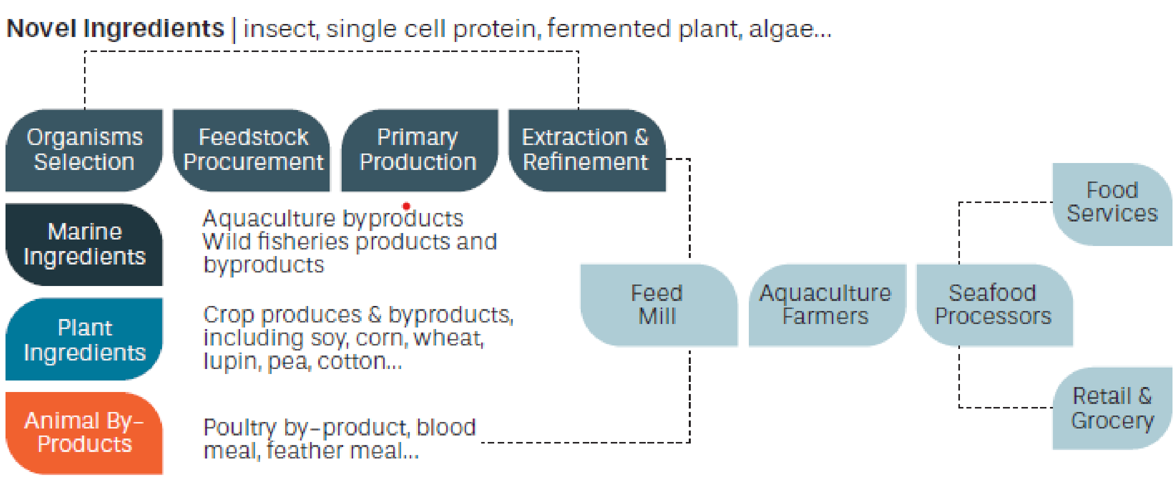


**Figure 6:** Simplified aquaculture feed system. *Source: Hatch Blue. "Emerging Protein-Rich Ingredients For Aquaculture." Hatch Blue & Hatch Innovation Services & Gordon and Betty Moore Foundation, 2024.*

## Algal and GM Oils as Replacements for Fish Oil

*Oil derived from microalgae* currently is considered to hold the highest potential to replace fish oil in aquaculture feed (Cottrell et al., 2020); research has shown that completely replacing fish oil with marine microalgal strains improves feed efficiency and growth performance (Sarker et al., 2016), and provides an effective probiotic and immunostimulant (Nagappan, 2021). While

Japan, the U.S., China, and Australia can produce large quantities of microalgae, they are currently diverted to human health foods. Algal oil production of the magnitude needed to replace fish oil in aquaculture feed is not imminent, as microalgae are more difficult to scale than their terrestrial-based counterparts. As a result of production challenges, microalgal oils have not been widely adopted in the aquaculture feed industry to date (New England Aquarium & SeaAhead, 2023).

*Genetically modified canola (rapeseed) oil* (ω3 canola oil) with equivalent levels of omega-3 as fish oil also can meet the energetic and growth demands of carnivorous fish. It is generally considered safe for fish and humans and has been approved in aquaculture feeds in the U.S., Canada, and Australia (Mackintosh et al., 2023; Davis & Devine, 2023; Aquaterra, 2023). Price and availability will ultimately determine the success of these products.

## Use of Food System By-Products: Crop, Livestock, and Fish Proteins

**This is Now…**
Shift to greater use of food system waste to supply protein and fatty acids decreases reliance on wild-caught forage fish and can reduce greenhouse gas emissions. In 2022, 38% of fish meal and fish oil came from by-products.

By-products are widely accepted in aquaculture feed, providing a safe, sustainable, cost-effective, and circular source of nutrients from livestock, fisheries, and aquaculture itself; their use is increasing and contributes to a more circular economy (Glencross et al., 2024).

*Fish "trimmings" and by-products* from the processing of wild-caught and aquacultured seafood provide a replacement for an increasing share of fish meal and oils, augmenting the use of wild-caught fish, reducing fish processing waste and improving environmental conditions resulting from its disposal (FAO SOFIA, 2022; Jackson, 2010). In 2021, up to 30 percent of global production of fish meal and 50 percent of fish oil was derived from by-products of fish processing (IFFO, 2024). However, further uptake of by-products for FMFO is likely to happen slowly due to decentralized processing of the supply and competition for some portion of these raw materials for incorporation into pet, livestock, and human food products (e.g., sauces and soups) and fuels (FAO SOFIA, 2022; Institute of Aquaculture, 2016). Regardless, by-product availability may not be sufficient to meet the projected demand for marine ingredients (Newton et al., 2023), and consideration must be made for varying nutritional profiles that do not always match those of wild-caught fish (Cottrell, 2020). Because of these reasons, the contribution of fish by-products to the pool of aquaculture feed ingredients will need to be used strategically (Kok et al., 2020).

Rendered animal by-products can also meet the need for protein in aquaculture feeds. Skretting, one of the largest global aquaculture feed producers, reports that 10 percent of their protein needs are met by terrestrial animal proteins (largely blood meal and feathers) (Skretting, 2022). Some of these ingredients, such as hydrolyzed feather meal, have demonstrated increased sustainability and contribute to a circular economy (Heuzé et al., 2020). Furthermore, crop residues also play a role in aquaculture feeds; which carries the benefit of reducing agricultural waste while also reducing pressure on wild marine fish stocks, however, the expanded use of agricultural by-products further increases the interface between agriculture and aquaculture and highlights the need to turn our attention to environmental performance of land-based ingredients. Overall, terrestrial by-products are expected to contribute significant volumes to aquaculture feeds soon (Hatch Blue, 2024).

## Novel Plant-Based Proteins

New approaches have been developed to efficiently transform crop by-products into traceable sources of lower-carbon nutrition, such as protein concentrates. Although not yet widely incorporated, they have demonstrated promise as aquaculture feed ingredients to complement soy and fish meals for several cultured species. These high-quality, uniform products provide higher protein and digestibility, and their quality is consistently compared to soy meal (United Soybean Board et al., 2015). Barley protein concentrate has been identified as a forerunner (Hatch Blue, 2024).

Fermenting technologies also have been used to transform plant products leading to improved nutritional outcomes (concentrated protein; improved nutrient availability, palatability, and digestibility) in aquaculture feed formulations. The accelerated replacement of wild-caught fish with fermented ingredients may increase sustainability without sacrificing fish nutrition and health. Fermentation can also preserve feed ingredients, particularly by-products, by inhibiting pathogenic contamination (Siddik et al., 2024). While aquaculture feed fermentation has limitations, fermenting high-quality raw ingredients sourced with an eye for sustainability, and produced under optimal production methodologies, could be a viable solution for the nutritional enrichment of aquaculture feed ingredients. Fermented soybean meal and fermented corn protein have been identified as promising plant-based proteins (Hatch Blue, 2024).

## Single Cell Proteins (SCP)

Single celled entities are now available as safe and sustainable aquaculture feed ingredient replacements, using lab fermentation technology and based on food waste as a substrate. Microbial or single cell proteins (microalgae, yeast and fungi, and bacteria-marine and terrestrial) have proven to be able to replace the nutrient deficiencies of plant-based meals and, combined with plant-based products, reduce the need for fishmeal in aquaculture feed formulations without sacrificing nutrition (Jones et al., 2020). Several advancements have been made in the recent past concerning the use of SCP in aquaculture feeds, including finding new strains, developing new methods of production (e.g., different waste stream substrates), and researching effects on various aquacultured finfish species (Pereira et al., 2022; The Fish Site, 2019; Responsible Seafood Advocate et al., 2024, Jones et al., 2020). Single cell proteins have also been used as additives because of their secondary benefits, such as improved gut health and immune function in farmed fish (Sarker et al., 2016). These additional benefits may justify their higher costs. A possible limitation of single cell proteins is the possibility of accumulated contamination. These products may require enhanced regulatory oversight to ensure safety.

## Insects

Insect meal from various species is viewed as a safe, viable replacement for some of the marine and soy-based ingredients in aquaculture feeds, and insects can provide an additional meal source (FAO, 2022b). A particular fly larva, the Black soldier fly (*Hermetia illucens*), is currently the most common insect cultivated globally as a protein source for animal feeds. The *mealworm* industry is also evolving through research and improved production practices (Zlaugotne et al., 2022). It should be noted that while insects can be fed on food system waste, they do not add to the total volume of protein available for feed. They can, however, improve the *quality* of the fish protein produced (Glencross et al., 2024). Regardless, insect farming is an efficient protein production system; it requires less land and water and less production time than other conventional protein ingredients (De Jong & Nikolik, 2021).

The insect industry has been experiencing growth in the United States regarding animal feeds and human consumption, and innovations in insect feed formulation and production practices continue to improve its scalability. Partnerships between insect farming companies and various industries promote efficiency through access to crop by-products for insect feedstock and waste heat and steam and support sustainable supply chains. One "partnered" facility is expected to create more than 280 direct and 400 indirect jobs in the U.S. Midwest (Innovafeed, 2024).

Although trials have been conducted for over a decade using insect meal as an ingredient in aquaculture feed for various species, it still cannot compete with fish meal, fish oil, or plant proteins in volume or price ("Insect Meal in Aquafeeds", 2022; Idenyi et al., 2022, Hatch Blue, 2024). It has been estimated that insect production for aquaculture feeds will reach 200,000 MT by 2030, but demand is predicted to reach 500,000 MT by that time (De Jong & Nikolik, 2021). Furthermore, like many other novel ingredients, the insect industry struggles to demonstrate consistent nutritional profiles, thus limiting adoption. Some in the insect industry estimate that a plausible threshold for success would be 10-20 percent inclusion in aquaculture feeds in the next decade.

Notwithstanding the above challenges, insects are considered by some to be a promising new ingredient that will provide protein in volume and also have an overall positive effect on fish health (Aragão et al., 2022). Furthermore, insect cultivation may support a more circular aquaculture feed economy by providing sustainably sourced fertilizer (frass) for terrestrial agricultural applications.

**TREND**: Novel ingredient inclusion will help to meet the growing demand for sustainable aquaculture feed by replacing and augmenting traditional marine and plant-based ingredients to optimize fish growth and nutrition, while increase environmental performance of the overall aquaculture food system.

## Functional Feed Ingredients

One of the most important factors affecting fish growth, immunity, and performance overall is diet. Functional feed additives have been developed through extensive research and promote fish health, partly by counteracting the negative impacts of some plant and animal proteins commonly used in feeds, resulting in physiological benefits (Waagbø, 2020). Plants, probiotics, prebiotics, enzymes, and other compounds are added to feed "recipes" and although some may have limited or no nutritional value, they can enhance performance, which may command price premiums (Hatch Blue, 2024).

## Threats to Development and Inclusion of Novel Ingredients

Multiple threats prevent the establishment of novel ingredients in aquaculture feed markets, predominantly economic ones (Jones et al., 2020). Several other factors also hinder the widespread adoption of these ingredients in commercial aquaculture feed formulations, including inconsistent nutritional profiles and insufficient "batch" size compared to the needs of industrial feed companies. In some cases, governance barriers also threaten growth in the novel ingredient sector. At this time, the inclusion of novel ingredients in aquaculture feed is minimal. For example, in 2022, Skretting's sustainability report indicated only 1 percent of aquaculture feed consisted of novel ingredients (Skretting, 2022). The feed industry seeks to source its ingredients from multiple geographic regions, so restricted production could also hinder uptake if risks are perceived higher when sourcing from a single area (e.g., climate/weather risks).

*Economic Barriers:* Currently, novel ingredients cannot compete with traditional marine or terrestrial ingredient prices. Reductions in price of alternative ingredients will not be realized until capital and operating expenses decrease, which may be achieved through research and adoption of innovative approaches, but the high costs of production of novel ingredients remain an obstacle to scaling (Fletcher, 2022; Jones et al., 2020; Larouche et al., 2023). Demonstration of secondary and tertiary benefits (e.g., improved nutrient uptake and then growth) may justify elevated prices by some novel ingredient producers.

In addition, capital is needed for infrastructure to scale novel ingredient production. Progress will be faster in countries where governments support scaling (e.g., insect production in Asia). Private investment currently supports the production of many of these products but funding is needed to support ongoing innovations.

*Inconsistent Quality:* Due to their variable cultivation techniques (changing substrates, variable species among producers), novel ingredient producers struggle to demonstrate consistent nutritional profiles, and feeds that incorporate their products cannot always demonstrate consistent subsequent performance gains.

*Insufficient or Inconsistent Supply:* The aquaculture feed sector competes for ingredients with other industries, particularly those with higher margins (e.g., pet food, human nutrition) (Higa et al., 2021) and production of all novel ingredients cannot meet overall demand for several reasons, including expensive energy costs and startup technology, and still-developing production methods, including safety optimization ("Insects to Feed the World", 2022). Logistical hurdles exist for current small batch sizes of novel ingredients, as larger feed mills cannot even trial these products due to storage considerations or formulation variations they would require. Additionally, the aquaculture feed sector may have to compete for a limited supply of novel ingredients with higher margin sectors, such as pet food. Even within the aquaculture feed sector, higher-margin salmon and shrimp feeds may outcompete feeds from smaller aquaculture markets (e.g., species likely to be cultivated offshore in the U.S.) (Hatch Blue, 2024).

*Governance Barriers:* Aquaculture feed is a global industry, subject to country-specific legislation, and there is a need to develop consistent policies, including risk assessment protocols, to support the emerging novel ingredient sector (Larouche et al., 2023; Alfiko et al., 2022; Pereira et al., 2022]. In the United States, existing policies may slow innovation as they do not explicitly consider certain novel ingredients in agricultural regulations and policies (e.g., insects are currently considered as "animals"), and funding opportunities, as currently written, may not apply. The industry is stymied by confusing, slow, and unpredictable regulatory review processes related to including the novel, especially functional feed ingredients (AFIA, n.d.). Furthermore, the expansion of a U.S. industry likely will rely on cold-water feed mills in Canada, whose governance framework must also be considered (Innovafeed, 2024).

## Comparing Overall Sustainability of Aquafeed Formulations

*"The notion of a single perfect ingredient should be considered fantasy (*Glencross et al., 2024*)."*

In the aquaculture feed industry, ingredients are merely a delivery vehicle for nutrients and compound feed formulations are complex. Continued progress in developing sustainable aquaculture feed solutions requires adequate evaluation methods to compare alternatives; feed formulations' environmental performance depends on many factors. Unknown impacts from feed ingredient supply chains may create unintentional risks and leave the aquaculture feed industry vulnerable, particularly for companies committed to sustainable feed production. Several tools are available to evaluate environmental, social, and economic impacts to identify the most sustainable practices in aquaculture production. In addition to more transparency in supply chains which would provide additional data useful in comparisons of ingredients, holistic multi-criteria evaluation methodologies are needed to evaluate nutritional and ingredient tradeoffs (Ghamkhar & Hicks, 2021). These methodologies should include analysis of ecological, climate, and economic impacts, as well as social welfare, particularly in supply chains of aquaculture feed ingredients (Govindan et al., 2021).

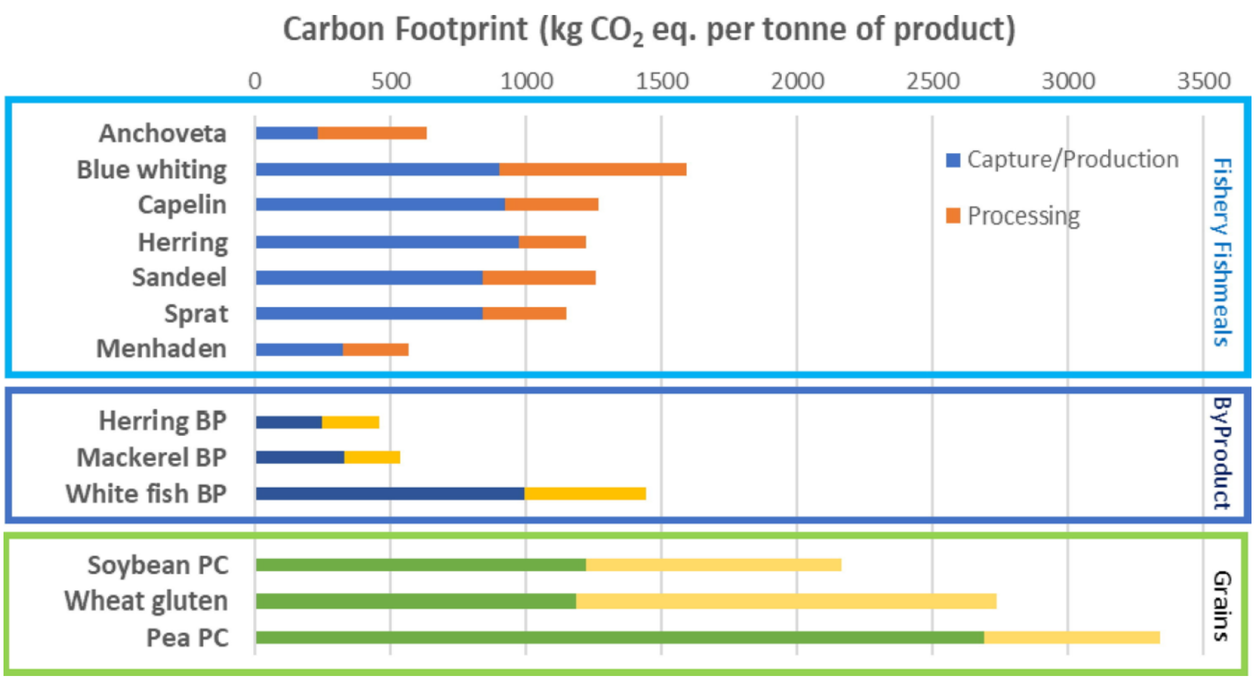


**Figure 7:** Carbon footprint (as Global warming potential; excluding land use change) of key fishmeal and plant protein concentrate resources. *Source: Glencross, Brett, Xiaowen Ling, Delbert Gatlin, Sachi Kaushik, Margareth Øverland, Richard Newton, and Luisa M. P. Valente. "A SWOT Analysis of the Use of Marine, Grain, Terrestrial-Animal and Novel Protein Ingredients in Aquaculture Feeds." Reviews in Fisheries Science & Aquaculture, (2024), 1–39. doi:10.1080/23308249.2024.2315049.*

Life Cycle Analysis (LCA) calculations are increasingly used for this purpose; they can quantify the impacts of the aquaculture feed value chain, which incorporates impacts from raw materials, ingredients, processing, and feed conversion efficiency. They do not, however, consider all impacts, especially community impacts, labor rights, human health, or fish welfare. This type of system analysis evaluates tradeoffs between conventional and novel ingredients and their production systems, such as GHG emissions, land, water, and energy use. Appendix 2 provides general conclusions about the sustainability of various ingredients mentioned above, as derived from a review of such LCAs. The figure below demonstrates the carbon footprint of various conventional aquaculture feed ingredients (Glencross et al., 2024). It should be noted that data specific to individual operations are not widely available.

Hatch Blue (2024) provides general information from a LCA about climate change, water consumption, and land occupation impacts from their considered protein sources. However, that analysis utilizes data from the literature and does not include data from specific applications. The results indicate significant tradeoffs between and within novel and conventional ingredients.

It should be noted that Grieg, in partnership with the World Wildlife Fund, has recently created an ESG tool for the feed industry to address animal feed sourcing risks (WWF, 2024). The Aquaculture Stewardship Council (ASC) recently released a feed standard for their clients (ASC, 2023). Sustainable (and certified) ingredients/formulations could garner price premiums as consumers, retailers, and feed producers seek sustainable options (Hatch Blue, 2024).

**TREND:** When assessing sustainability of novel feed formulations, novel ingredients are evaluated to ensure that they not only perform better in the same impact categories as conventional feeds, but also refrain from shifting the environmental burden into other impact categories.

## Resource Conservation: Optimizing Feed Conversion Efficiency

The growth in aquaculture will require additional protein sources, which will need to be used more efficiently. Regardless of the source (terrestrial or marine), optimizing resource efficiency is essential for the financial success (feed is a major cost for producers) and environmental sustainability of all animal-rearing operations for food production (Kause et al., 2022). Feed is a major contributor to waste from aquaculture systems, from uneaten feed going straight into marine environments or undigested/unabsorbed nutrients released as fish feces. In addition to negatively affecting water quality, uneaten feed, and unused nutrients represent squandered resources and decrease feed conversion efficiency. Reduction of waste in food systems should be a priority in aquaculture expansion. The conversion of feed to edible protein for humans is one measure of efficiency, and high-quality feed can reduce the amount of feed used to meet growth and performance goals.

However, metrics for evaluating animal feed conversion efficiency have evolved over time, and various uses exist. Each metric has limitations and value propositions; many are focused on the conversion efficiency of marine ingredients, specifically (See Appendix 2). Feed conversion ratios (FCR) simply compare the weight of feed to the weight gain of the harvested fish and provide a simple way to track progress. LCAs incorporating multiple feed efficiency considerations throughout the supply chain (including impacts of terrestrial *and* marine ingredients) and the Forage Fish Dependency Ratio (FFDR) metric (focused on wild-caught fish raw material efficiency) are widely used to compare feed formulations. It should be noted that data specific to feed production and fish farming operations are not widely available.

## Current Estimates

Generally speaking, feed conversion efficiency *decreases* as wild-fish raw materials are replaced in aquaculture feeds. Replacement ingredients reduce overall efficiency, but there are improvements in efficiency when considering just marine ingredient utilization. Formulations containing insects as a foundational ingredient were the most *efficient* of the replacement diets (Cottrell et al., 2020). Improvements in overall efficiency are victories for both the environment and fish farmers.

There have been substantial increases in feed conversion efficiency since 2000 as a result of shifts in ingredients (fish to crops), incorporation of functional feed ingredients, and genetics (Zlaugotne et al., 2022; Waagbø, 2020; Elvy et al., 2022). There have also been efficiency improvements in turning raw materials into protein ingredients, especially plant materials. Most feed conversion efficiency improvements have been made in feed designed for several widely cultivated species. Marine finfish FCRs have changed from 1.48 (2000) to 0.96 (2020) ("eFCR Calculation", n.d.). Still, Atlantic salmon is the most effective animal at converting feed into body weight, and innovations in salmon aquaculture over the past two decades have resulted in reduced FCR from 2.4 to 1.15 while maintaining optimal nutrition for the farmed salmon (GSI Salmon, n.d.). In contrast, wild salmon require 4.5 kg of prey for every 0.45 kg of weight gain (Olin & Tom, 2010). Pigs need approximately twice as much food as salmon; sheep need almost 6 times as much to gain one kg (Skretting, 2024). To increase efficiency for all species, particularly in the developing world, greater adoption of innovative approaches is needed (Larouche et al., 2023; FAO, 2023).

FFDR reflects only the use of wild-caught fish in aquaculture feed. While efficiency measured by this metric depends on species raised and production location, it also depends on the feed "recipe", itself dependent on the availability of raw materials/ingredients in a given year (Skretting, 2022). The events of the last several years have caused dramatic volatility in the feed ingredients market- COVID disrupted supply chains globally, the war in Ukraine disrupted the sourcing of grains, and climate-related events in Peru have decreased the availability of forage fish from that region. Regardless, FFDR has reduced significantly for marine finfish over recent years, as reported by the industry (1.77 in 2000 to 0.52 in 2020) ("FFDR Data", n.d.).

## Advancements that Increase Feed Efficiency

Feed efficiency improvement approaches do not face the lengthier governance or economic barriers that prevent scaling of novel ingredients, and companies that venture into offshore aquaculture are likely to have access to capital to invest in advanced hardware and software technologies that support increased feed conversion efficiency. In response to the need for continued improvement in this area, there have been recent innovations in feed manufacturing and nutrition expected to contribute to optimizing the efficiency of feed conversion across varying feed formulations and for multiple farmed species in the future (Cottrell et al., 2020). Similar to terrestrial livestock feed advances, efficiencies in aquaculture feed are also found through adoption of new approaches to processing raw materials into protein concentrates and through fermentation (see Novel Ingredients section above).

### ***Precision Nutrition: Understanding Nutrient Needs and Developing New Feeds***

Precision diets that meet fish's metabolic and health requirements and reduce feed loss *and* waste can now be developed for certain aquacultured species/developmental stages. Such "precision nutrition" uses species-specific genomic data to develop flexible "recipes" with additives such as enzymes (commonly used in pig and poultry sector feed) to optimize digestive processes, including microbiomes, and enhance nutrient utilization (Zhang et al., 2020). Most research has focused on Atlantic salmon, nile tilapia, and rainbow trout. Gains in feed conversion efficiency are slowing for these species, but a better understanding of requirements and feed management for less developed species will likely result in increased feed conversion efficiency across multiple feed formulations and throughout the global aquaculture food system (Xing et al., 2023). Future "functional feeds" could provide specific adaptability to on-farm conditions like varying water temperatures or improve seafood quality, which may provide climate resilience (Hua et al., 2019; New England Aquarium & SeaAhead, 2023).

### *Precision Genetics and Genomics: Enhancing Nutrient Utilization*

Like the terrestrial livestock sector, the aquaculture sector relies on genetic improvements for more sustainable and efficient human food production. Selective breeding programs to develop more efficient and climate-resilient types of cultivated species are largely underutilized globally (FAO, 2023; Free et al., 2022). However, for certain high-value species, they have proven to enhance growth (feed uptake and nutrient utilization) and fish health (Naylor et al, 2021). For example, for 1 kg of rainbow trout produced today, half of the feed was needed compared to the 1980s, largely attributed to a breeding program (Kause et al., 2022). The subsequent potential use of molecular technologies for selective breeding (such as molecular markers to select valuable traits) exists. However, much of this research is likely not in the public domain. While much of the public information concerns salmon (43 percent of studies), these technologies are expected to be increasingly adopted for other high-value aquacultured species, as they have been for certain livestock (Yanez et al., 2022).

Gene editing is a precise breeding technology that is currently experimental in aquaculture but is likely to be employed to increase feed conversion efficiency, disease resistance, and controlled reproduction if technology and policy allow. Progress is much quicker than for selective breeding (Gutasi et al., 2023).

### *Precision Feed Delivery: Optimizing Feed Intake*

Improving the utilization of *existing* feeds results in increased efficiency in aquaculture operations and a reduced environmental impact. Technology that optimizes feed intake through mechanical timing is widely used in several types of aquaculture, but this type of static feeding protocol can result in under or overfeeding (Zhang et al., 2023). Better still is precision feeding technology that exists to monitor, adjust, and optimize feeding based on machine vision, machine learning, and artificial intelligence (AI). Many of these digital components are already in place or are being developed (Zhang et al., 2023). These systems, which couple underwater monitoring with extensive information about genetic background, nutritional requirements, fish behavior, satiety, health, and the living environment, provide valuable information to those fish farmers who can afford them (Zhang, 2020).

### *Reducing Waste by Improving Circularity in the Aquaculture Feed System*

Adopting circular economy strategies that reduce food loss and waste, reduce feed: food competition, and more efficiently use resources will increase efficiency in the U.S. aquaculture food system and support the use of a diverse range of safe, climate-resilient ingredients. The aquaculture feed system already benefits from circular business models by using by-products as substitutes for conventional raw materials or as feedstock/substrates for novel ingredients. This has resulted in improved performance and could lower feed costs, create jobs and additional income sources for fishermen, farmers, and fish farmers, and save consumers money. Co-location of processing plants allows waste energy to be used in ingredient production.

Reducing the carbon footprint of feed ingredients will require efficient production methods, sustainable sourcing, and research and support for novel, sustainable ingredients. Success in improving the industry's sustainability depends on thoroughly understanding the current and future possibilities and tradeoffs to balance economic opportunity with food security, environmental protection, and equity issues. Methodologies to evaluate aquaculture feed supply chains, processing, and efficiency will continue to develop with the support of the industry. Results from these assessments and consumers who recognize the health and economic value of seafood to communities will support policies and public and private funding for innovative technology development.

**Increasing Diversity of Aquacultured Species**

Policies that support technological innovations in aquaculture measure outcomes in terms of weight of fish produced and feed efficiency. However, a focus on food security demands consideration of nutritional components of harvested fish and climate-resilience of operations (Nicholson et al., 2021). Increasing the diversity of species cultured is seen as a potential strategy to improve nutritional outcomes, climate resilience, and environmental performance, and promote locally-appropriate species.

Promoting “crop” diversity, however, is at odds with advances in precision feed technology (nutrition, genetics, and delivery), which currently are tailored to specific widely-cultivated species. Context-dependent innovations will be necessary and tailored to distinct aquaculture food systems. Combining science and engineering advances with public policies and culture preferences will ultimately support improved sustainability in the aquaculture food system (Barrett et al., 2020).

## Opportunities for a Bright Future for Sustainable Aquaculture Feed

Boosting the development and expansion of sustainable aquaculture in the United States, generally, is likely to result in increased jobs and spending in coastal areas and will increase demand for sustainable aquaculture feeds, supporting scaling of novel raw materials. Specifically addressing aquaculture feed affordability, availability, efficiency, *and* sustainability could also provide socio-economic and ecological benefits to both coastal and inland (especially rural/agricultural) communities and businesses in the United States.

The United States currently is a small player in the global aquaculture feed market with little control over prices or production practices, but the predicted growth scale of U.S. offshore aquaculture operations will require a significant supply of species-specific aquaculture feed formulations (FAO SOFIA, 2022; NOAA, 2011).[2] This challenge allows U.S. businesses to expand aquaculture feed production based on U.S. strengths in agricultural production, seafood processing, fish nutrition expertise, and animal feed infrastructure. As offshore aquaculture grows in U.S. waters, likely, feed producers will also grow in the U.S., increasing support for regional crop farmers and producers of novel ingredients, creating additional domestic economic opportunities to support rural communities, and potentially, if carefully regulated, boosting the sustainability of aquaculture feeds overall ("5 Things About Aquafeeds", 2022).

The following are aquaculture feed policy issues that support improved environmental and social performance of the aquaculture industry in the United States and globally:

| POLICY ISSUE | DESIRED OUTCOME |
|---|---|
| **Improved data collection to support transparency, and responsible sourcing of raw materials/ingredients.** | Stricter reporting requirements for sourcing raw materials and ingredients |
| **Increased circularity in the food system to reduce waste/loss.** | Increased use of restorative and circular feed raw materials/ingredients, including marine and terrestrial agricultural ingredients |

[2] The sourcing of which may prove to be challenging in the U.S., a less developed aquaculture nation.

| | |
|---|---|
| **Reduced feed: food competition.** | Support for global development goals related to food security and the use of human food for feed |
| **Sustainably managed wild marine resources used as raw materials** | Consideration of overfishing, IUU fishing, and climate change impacts to fish populations, especially in areas where governance is weak and food nutrition and security needs are high |
| **Reduced land and water impacts from feed production (raw materials through value chain).** | Reduction of deforestation/land conversion from terrestrial agriculture production of raw materials in both the United States and other regions. |
| **Increased fish health outcomes and nutrient outcomes for human seafood consumers.** | Increased quality of feed ingredients: nutrition affects not only fish health but nutrient outcomes in humans |
| **Reduced carbon emissions by aquaculture feed value chain.** | Systemic evaluation needed |
| **Streamlined approvals and resources to promote the widespread adoption of safe, novel ingredients and technologies, especially those that support affordability, availability, and sustainability.** | Even limited adoption of novel ingredients could reduce dependence on forage fish harvests and support global food security by increasing aquaculture's sustainability (Cottrell et al., 2020). |
| **United States government commitment to developing and maintaining partnerships to facilitate technology transfer.** | This will ensure accessibility to these novel ingredients and approaches, helping address food safety and security issues in the United States and globally. |
| **Global consideration of progress and solutions and supporting engagement rather than local/regional impacts.** | How does the aquaculture feed value chain impact global food systems? |
| **Corrected popular misconceptions about aquaculture.** | Due to the novelty of aquaculture in the United States, compared to terrestrial agriculture, the health and climate benefits of aquacultured foods are often overlooked. |

The following are issues related to research needed to improve environmental and social sustainability:

- Use of best available methods for comprehensive comparative assessments of ecological and socio-economic impacts of current and future aquaculture feed formulations.
- Advanced feed production technology/practices, including the use of alternative energy sources: Retrofitting feed plants to incorporate local/regional ingredients, the latest technologies, and water and waste management can improve the efficiency of feed production and reduce energy usage overall.
- Endowed aquaculture research centers to support early-stage innovation in critical areas of novel ingredient production and feed efficiency, with shared data output. Technologies should be scrutinized to ensure they benefit people, nature, and the aquaculture industry.

## Conclusion

A broad range of non-human food competing raw materials and ingredients is needed to produce aquaculture feeds that meet the needs of the growing global aquaculture food system. With FMFO production approximately 20 percent lower in 2023 than in 2022, sustainably expanding marine finfish aquaculture will require affordable, efficient, and available raw materials, on a global scale, with minimal ecological, social, and climate impacts ("IFFO's Estimates", 2024; Free et al., 2022). Food waste by-products, plant-based, insect, and single cell proteins and oils, will all need to play a role. Further support of promising aquaculture feed ingredients and innovations, like those identified in this paper, must be advanced to set informed sustainability regulatory standards for aquaculture in the United States. Given the need to conserve finite marine resources, even partial adoption of novel ingredients could support aquaculture growth and may provide food security benefits (Cottrell et al., 2020).

Because fish meal, fish oil, and soy protein are utilized in many industries, their replacement with novel ingredients may ultimately reduce dependence on wild-caught marine and unsustainable terrestrial agriculture ingredients from *the aquaculture sector* but is not likely to benefit forage fish stocks or land conservation unless there are regional and ecosystem-based conservation and management measures adopted and enforced (Froehlich et al., 2018).

To meet this need for sustainable and equitable aquafeed ingredients necessary to fulfill the rising demand for seafood from aquaculture, continued *innovations in manufacturing* and *improvements in resource use efficiency* are required, as is continued *investment* in scaling such technologies. *Collaboration* between conventional and novel ingredient producers and other stakeholders may speed up research, development, and production to support the potential for continued growth as a source of sustainable aquaculture feed. Policy interventions and regulations will be necessary to incentivize feed industries to develop and innovate solutions for the increased use of sustainable innovative ingredients (Sandström et al, 2022).

We are in the early stages of ensuring that this expanded range of aquaculture feed solutions is incorporated to improve diets for finfish without sacrificing human nutrition and improve the overall sustainability of aquaculture food systems.  Ninety percent of retailers in the United States have sustainability commitments, and voluntary certification standards exist.[3] Consumers are more willing to pay a premium for responsible seafood (Smetana et al., 2022). Effective enabling policies and standards demonstrating a strong commitment to sustainability in aquaculture feed will provide exciting opportunities for all stakeholders seeking to grow a sustainable aquaculture food system in the United States. The success in high-income countries such as the United States could be replicated in low-income countries as sustainable aquaculture feed becomes more economical and policies are widely adopted to support the growth of new technologies, thus improving the sustainability of global seafood (Free et al., 2022).

[3] See ASC Aquafeed Standard

## Appendix 1. Glossary of Terms

**Aquaculture:** Aquaculture is the breeding, rearing, and harvesting fish, shellfish, algae, and other organisms in all water environments ("What is Aquaculture?", 2019).

**Aquaculture Feed**: Nutritional formulations given to aquatic farmed animals that meet the species' requirements for protein, fatty acids, and vitamins/minerals with additives to optimize growth and immune function and increase performance.

**Circularity/Circular Economy**: An economic system based on the reuse and regeneration of materials or products, especially to continue production in a sustainable or environmentally friendly way (Oxford Languages).

**Fatty acids**: EPA and DHA are the predominant healthy fats contained in oily fish as a result of consumption of wild fish, or in the case of farmed fish, fatty acids added to aquaculture feed formulations.

**Feed Conversion Ratio (FCR)**: The ratio of the dried weight of feed administered and the weight gained by harvested fish. A crude metric was used to estimate the efficiency of feed conversion to fish. A *smaller* FCR indicates *higher* efficiency.

**Fish In: Fish Out (FIFO)**: A metric first adopted in the early 2000s to account for the amount of fish products it took to grow 1 kg of farmed fish to compare the performance of various aquaculture operations. This relatively simple metric was used to quantify the environmental impact and typically does not account for the contributions of fisheries and aquaculture by-products to FMFO or the nutritional contributions of various ingredients; the fish meal is nutritionally superior to most other aquaculture feed ingredients ("Fish-In:Fish Out Ratios", n.d.). When FIFO *accounts* for the wild-caught marine ingredients only (not by-products), this metric is synonymous with the forage fish dependency ratio (FFDR), a preferred metric.

**Fish Meal:** Fish meal is a nutrient-dense, highly palatable feed ingredient made from processed fish proteins (IFFO).

**Fish Oil**: Fish oil is a lipid (fat) source made from processing fish fats, notable for containing high levels of the essential omega-3 fatty acids (IFFO). FMFO are marine ingredients used in aquaculture feed that result from processing raw materials such as wild-caught fish and the by-products of fisheries and aquaculture processing.

**Forage Fish Dependency Ratio (FFDR):** Used to calculate the quantity of wild (forage) fish used in feeds in relation to the quantity of fed animal production.

**Functional Feed Ingredients**: Ingredients may be included in small amounts in aquaculture feed formulations to benefit fish health or performance.

**Genomics/Genetics**: A field of study that aims to evaluate the genetic basis of performance and other production traits in farmed fish. This information is utilized in selective breeding supportive technologies and gene editing for genetic enhancement to increase efficiency.

**Illegal, Unreported, and Unregulated (IUU) Fishing:** A global problem that threatens ocean ecosystems and sustainable fisheries (NOAA, n.d.).

**Life Cycle Assessment (LCA):** An ISO-standardized analytical tool developed to evaluate environmental performance of products and processes. It constitutes a compilation and evaluation of a product system's inputs, outputs, and potential environmental impacts throughout its life cycle; the term may refer to either a procedural method or a specific study (Henriksson et al., 2013).

**Novel Ingredients**: Novel ingredients are unconventional feed ingredients from plants, animals, or inorganic origins (not traditionally used by feed manufacturers) that, after extensive research and scaling, can replace conventional ingredients in commercially relevant quantities. Examples include, but are not limited to: microbial and insect-based proteins, single cell proteins, using waste streams as resources, oil of non-conventional materials, and algal oils. Novel ingredients like new vegetable protein concentrates may also be traditionally developed to optimize their contributions to nutrition. They can include by-products from existing food production processes (Skretting, n.d.).

**Precision nutrition**: Nutrient levels in the feed that are required for optimal production performance of the fish and to simultaneously minimize waste (Zhang et al., 2020).

**Single Cell Proteins (SCP)**: Flours based on single-celled microbes or algae biomass. These SCP ingredients can be sustainably cultured using waste from other industries such as agriculture or food (Pereira et al., 2022).

**Traceability**: Traceability is the ability to follow materials from the beginning of the supply chain to the customer who purchases a product. With this data and information, traceability plays two roles that support sustainability. It provides visibility on inputs and processes across the value chain, and it provides the source information for provenance and sustainability certifications (Saenz et al., 2023).

# Appendix 2. Measuring Efficiency in Aquaculture

Multiple metrics are currently used to assess feed efficiency, complicating study comparisons. Many of these metrics were developed to focus on using marine raw materials, once considered the largest barrier to improved systemic environmental performance. However, We are unaware of a standardized method of comparing environmental impacts for standardized nutrition across ingredients. Such a method would be useful in considering the most sustainable way forward.

The feed conversion ratio (FCR) metric has been used extensively in the past: when the amount of protein in the feed increases, the weight gain of the fish increases, and the FCR decreases. The lower the FCR, the more efficient the conversion from feed to fish. FCR is generally lower for aquatic animals than terrestrial livestock.

While the FCR is a suitable basic metric used for assessing the economic value of operations, the FCR metric does not account for the nutritional value of the fish being raised and consumed, the nutrition contained in the feed formulation itself, or how much weight of the fish is "wasted" in processing. In aquaculture operations, fish processing waste is often recycled back into fish meal/oil in the aquaculture feed processing cycle. Due to the limitations of FCR, especially in light of new feed formulations, scientists have pursued alternative methodologies (Fry et al., 2018).

"Fish In:Fish Out" (FIFO) ratio estimates the efficiency of aquaculture systems based on their reliance on marine aquaculture feed ingredients and the subsequent production of net fish weight gain (Jackson, 2010). This is a suitable metric for appropriating fish from ecosystems (or fish that eat forage fish) or from human populations that eat forage fish. However, the FIFO does not consider the increased use of plant-based or fish-processing by-products in the feed, the net human edible protein produced, or that the current demand for fish oil exceeds that for fish meal in feed formulations (Skretting, 2024; Kok et al., 2020; (Chary et al., 2023). Furthermore, the FIFO metric does not consider overfishing or other environmental or climate impacts related to feed (including terrestrial impacts to land and water), or impacts from aquaculture food systems more broadly, including food-feed competition (Konar et al., 2019).

Fish In Fish Out (FIFO) has been widely used to evaluate the efficiency of fish use in aquaculture feeds, and these assessments generally indicate that efficiency is increasing (*FIFO is decreasing*) based on this metric across all species groups. This trend is largely the result of more targeted use of FMFO (i.e., replacement with plant-based ingredients where possible ("Fish in: Fish Out

Calculation", n.d.; "Species categories explained", n.d.). For marine finfish species, the FIFO declined from 2.21 in 2000 to 0.75 in 2020 ("Fish in: Fish Out Calculation", n.d.). However, there are some issues with applying this metric, and new metrics are evolving. For example, research based on a concept called "eFIFO," which "discounts" fish processing by-products now widely included in FMFO, has shown that global fed-aquaculture produces 3-4 times as much fish as it consumes; most species are net producers of fish (salmon and trout are net neutral) (Kok et al., 2020).

A more commonly used metric is FFDR, which is calculated using the weight of forage fish products (not by-products) and their yield ratio. Industry data indicates that 0.13 kg of forage fish are used for each kg of fed aquaculture product produced and that efficiency has improved fourfold from 2000 to 2020 (Holmyard, 2022).

The Life Cycle Assessment (LCA) is a complex, "cradle-to-grave" approach that considers multiple impacts from throughout a system or process, including feed ingredients and their processing, farm activities, distribution, consumption, and waste recovery and can effectively evaluate resource efficiency from feeds, in the context of global warming potential and water and land use. However, outcomes of LCA are dependent on location, inputs, species, etc., which makes comparisons between feed ingredients and across systems difficult (Cargill, 2022, p. 35). Here's what we know:

- Despite extensive analysis of marine and terrestrial *conventional ingredients*, **data gaps exist**, especially related to fish oil purification, the conduct of Asian wild-caught fisheries, and land use/habitat impacts from agriculture (Newton et al., 2023; Fletcher, 2022). This complicates comparisons between and within traditional and novel ingredients, particularly for sourcing ingredients with widely varying carbon footprints.
- Marine ingredients generally have lower LCA climate change impacts than terrestrial ones; both are variable in their impact (Newton et al., 2023). A shift from marine ingredients to plant-based also puts pressure on agricultural resources such as water, land, and phosphorus. Broader ecosystem impacts remain unknown and require additions to a formulation (Kok et al., 2020). Soy ingredients continue to have the highest emissions (Skretting, 2022, p. 20).

- Certain novel plant-based proteins (barley protein concentrate, corn fermented protein) compete well against other protein ingredients in categories of climate change, water consumption, and land occupation (Hatch Blue, 2024). Different methodologies (e.g., economic vs mass allocation) present varying results. Novel ingredients tend to use more energy in production, and efficiency may be lower due to processing (Cottrell et al., 2020). Shifting to renewable energy sources would be useful. Formulations that include multiple ingredients tend to have more complicated effects on environmental sustainability than previously thought (McKuin et al., 2022).
- Increasing the use of human food system by-products may help to reduce feed: food competition, increase resource conversion efficiency, and improve circularity in the aquaculture feed system (Sandström et al, 2022). It can also be cost-effective and reduce greenhouse gas emissions.
- As a result of the inclusion of fish processing by-products, the impacts of aquaculture feeds on wild-caught fisheries have declined, but like all aquaculture feed ingredients, by-products are not created equally and some may lack the nutritional “punch” of others (Newton et al., 2023; Kok et al., 2020)
- Innovations to reduce the use of fish oil are likely to yield dividends in the sustainability of feed profiles. More fish are needed to yield a ton of fish oil than a ton of fish meal therefore reducing fish oil in feeds is more efficient at reducing overall forage fish demand than reducing fish meal (Cottrell et al., 2020).

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