



OPINION OPEN ACCESS

No Free Lunch: Sustainable Aquaculture Requires Recognizing Past Science, Improvements, and Comparative Assessment

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1 | Introduction

Aquaculture has become an established part of the global food system and plays a key role in supporting food security and livelihoods [1–3]. Indeed, aquaculture growth is critical for ensuring future sustainable, healthy, and equitable food systems [3]. Not all aquaculture is created equal, however, posing both sustainability opportunities and challenges [4, 5]. A unifying feature of any food production sector is that it will have an environmental impact, and aquaculture is no exception [6, 7].

Given this current reality, the goal of research should arguably be to improve aquaculture where it can be improved, seek equity in its development to address food security, and recognize that other management levers in agriculture and wild capture fisheries will be necessary to address “aquaculture’s footprint.” The science on aquaculture, while diverse and expanding, needs to acknowledge and build on past advances rather than downplay or ignore the benefits of those improvements. Full respect and understanding of these advances will ensure that proposed solutions reflect the real complexities and variability of aquaculture systems—a unique industry that spans land, sea, and freshwater spaces. From our collective perspective, several

pernicious critiques of aquaculture continue to resurface (e.g., *Science Advances* “Aquaculture” special issue) that we address here in hopes of refocusing future research in more constructive directions. Specifically, we respond to four major themes from the special issue and central to aquaculture debate within the literature: (1) interactions and dependencies between aquaculture and wild capture fisheries, particularly feed; (2) aquaculture’s role in food security; (3) the social-ecological complexity concerning the morality of aquatic farming; and (4) constructing a path, not just demand for better data.

2 | Aquaculture and Wild Fisheries Feedbacks

The potential for aquaculture to reduce demand for wild fisheries was part of early general interest in farmed aquatic foods. Several studies have revealed, however, that aquaculture has not necessarily relieved pressure on wild capture counterparts [8–10]—though the counterfactual (i.e., state of fisheries in the absence of aquaculture) is hard to test. Instead, fisheries management has consistently shown to be the most effective strategy to date to recover and manage wild stocks [11]. As aquaculture continues to grow, a focus on *how* to

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integrate wild fisheries and aquatic farming (i.e., ecosystem-based approach) to achieve management, conservation, and sustainable resource use objectives is a needed line of study and application (e.g., [8]).

Feed represents a direct way in which fed aquaculture (e.g., finfish and crustaceans) interacts with capture fisheries, and therefore has been studied for decades [12–15]. As aquaculture has expanded, feed composition has shifted from the use of wild caught inputs (fishmeal and oil) to more cost-effective alternatives, including land-based crops (Figure 1a,b). Such efforts have prompted numerous synthesis, policy, and modeling papers [18–21]. These studies have challenged what we mean by “sustainable” production, as aquaculture has grown while reducing fishmeal and oil input per fed organism [22, 23]. Indeed, aquaculture is also criticized for using crops, which require more water and land [4, 24] and can contribute to terrestrial biodiversity loss (e.g., from soy produced on recently deforested land)—although impacts are comparatively less than from its use in livestock and poultry industries [21]. In addition, many feed ingredients are food-grade products that could theoretically be directly consumed by humans instead [25, 26]. Yet, the goal of having aquaculture, or any food sector for that matter, produce *zero* impact on the environment is simply impossible. Instead, reducing possible harms (e.g., through an Ecosystem Approach to Aquaculture [EAA]) [27–29] and assessing aquaculture relative to other nutritionally comparable food options (e.g., Life Cycle Assessment, Cumulative Pressure Assessment) [4, 6, 30–31] is a more balanced approach [5, 23, 32]. Aquaculture is part of the global food system and ignoring the diversity and efficiencies of different production practices will not help address the social-ecological problems surrounding how and where we produce food [33].

Because of the global scale of aquaculture and the nutritional value of fishmeal and fish oil as feed for fed species, aquaculture has been the main consumer of forage fish (i.e., small pelagic fish: anchovies, sardine, menhaden, etc.) since the 2000s

(Figure 1c)—the bulk source of marine-based ingredients [22]. Yet, even with the global rise of (fed) aquaculture over the past 40 years, forage fish landings have remained relatively stable over this same period (Figure 2a), indicating use has not resulted in sweeping collapses. Ultimately, this seeming disconnect between aquaculture growth and feed components has been possible because of improvements in feed efficiencies (i.e., feed conversion ratios (FCR), Figure 2b), market shifts that re-allocated forage fish from livestock feed to aquaculture feed (Figure 1c), shifts to terrestrial feed resources (Figure 1a,b), and greater incorporation of seafood byproducts [5, 20]. All these aspects contribute to how much forage fish go into feed and how much aquaculture biomass is produced, that is, fish in: fish out (FIFO) ratio [5, 34].

One of the most persistent critiques of “feeding fish to fish” is based on FIFO (e.g., [35]) (Figure 3). Yet how one estimates FIFO depends on numerous model assumptions and data quality, including accounting for or ignoring improvements to the sector over time. For instance, Roberts et al.’s [35] most extreme results stem from estimates published between 2008 and 2011 and thus collected in the early 2000s when efficiencies and percent inclusion were higher [14, 36, 37]. Older estimates will thus result in higher economic FIFO (eFIFO). In fact, the average eFIFO across taxa from the International Fishmeal and Fish Oil Organization (IFFO) (2000 and 2010 mean $\pm$ SD = 1.2 ± 1.1) versus the Roberts et al. values from across the four studies/reports (1.1 ± 0.5) generally align when time is considered (Figure 3). Another issue is “double counting” of fishmeal and fish oil (i.e., residual content). Rendering of forage fish simultaneously creates meal and oil from the same fish, and if this redundancy is not accounted for, it will increase the estimate of wild fish used [22, 34]. The recent research that calculates FIFO with byproducts (also known as trimmings) and “spillage” (better known as handling mortality, incidental mortality, or discard mortality) [35] is arguably misleading. Byproducts—parts of an organism not typically consumed by humans—are an increasing and, we argue, positive addition to the feed arsenal to compensate for the reduction of wild forage fish species [38]. In fact, the

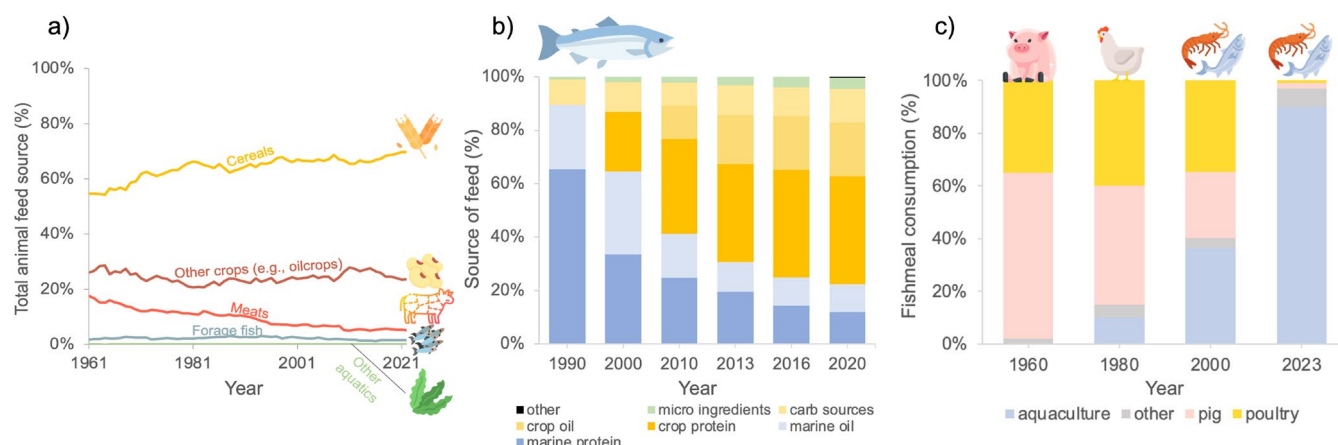


FIGURE 1 | (a) Percent of total global animal feed source from cereals (yellow), other terrestrial crops like oilcrops (e.g., soy; burnt orange), meat products (including eggs and milk; red), and other aquatic products, such as seaweeds [3]. (b) Source and change of feed ingredients of Norwegian Atlantic salmon *Salmo salar* over time, including marine-based (blues), crop-based (yellows), micro (vitamins and minerals; green), and other (insect meal, single cell protein, fermented products, and microalgae; black) [16]; (c) Percent fishmeal consumption by aquaculture (blue), pig (pink), poultry (yellow), and other (gray), with the dominant consumer depicted at the top [17].

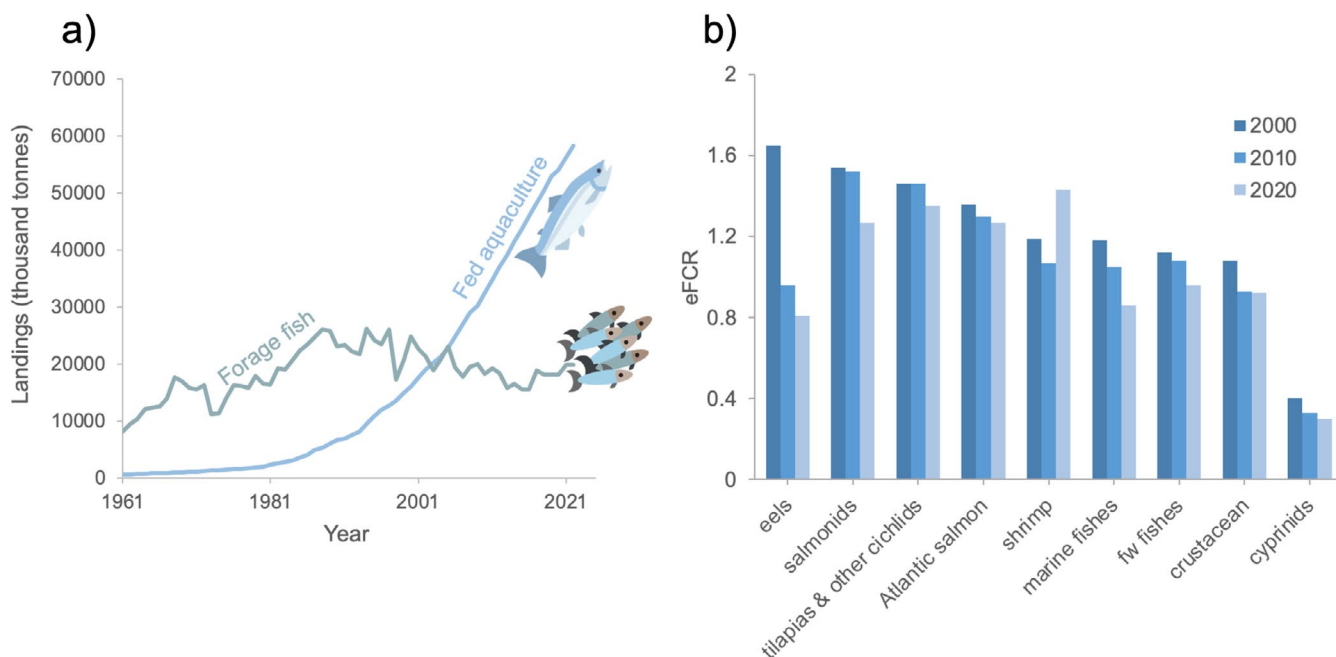


FIGURE 2 | (a) Total global landings (1000t) from 1961 to 2022 of forage fish used for feed (FAOSTAT 2024) and total fed aquaculture production ([3] finfish and crustaceans, excluding extensive silver, bighead, catla, roho labeo, and mrigal carp). (b) IFFO reported economic feed conversion (eFCR) ratio (i.e., feed efficiency) of main aquaculture taxonomic groups or species for the years 2000, 2010, and 2020 [17].

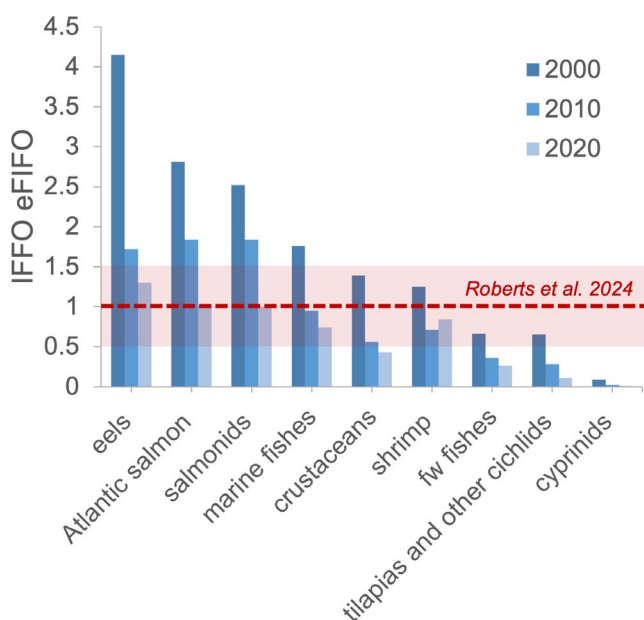


FIGURE 3 | Reported by IFFO, the economic fish in: fish out (eFIFO) ratio of major farmed groups across three decades with mean and standard deviation of [35] (from Figure 2) estimate (mean $\pm$ SD) shown in red [17, 35].

use of byproducts is advocated as a solution toward achieving better *nutritional* FIFO (nFIFO) [39]. Trimmings from fishes processed for human consumption are estimated to represent ca. 40% of fishmeal and fish oil production—a doubling of use since 2000 [17, 40–41]. Similar to the redundancy of meal and oil due to processing, including trimmings as a “fish use” penalty seems counterproductive. The original intent of FIFO was to understand how much fed aquaculture drives consumption of wild species, which would be reduced by using byproducts and

support a more circular economy. Similarly, the intent of FIFO is feed, not total mortality caused by fisheries.

Forage fish can be sustainably fished by using existing fisheries management tools calibrated to account for their life history and ecological role [42, 43]. Precisely measuring incidental mortality, however, is challenging [44] and not explicitly accounted for in most models. Yet, unobserved mortality occurs in most fisheries, and fishery stock assessments and management procedures are often robust to the additional mortality [45–47]. Modifications could technically be made to harvest control rules, but even so, adopting these changes would likely have little effect on long-term average catches from any given stock/fishery because of the naturally high population variability of small pelagic species [20, 48]. Regardless, the key factor is fisheries governance, not aquaculture management. Reduction fishery supply chains have long existed before aquaculture [22], even if aquaculture is the main user now (~90% of landings) [3] (Figure 1b). Other sectors, including livestock, pets, fertilizers, and pharmaceuticals, have and continue to use fishmeal and oil, a situation that would likely persist in the absence of aquaculture. This reality underscores the need for governance, not just markets, to influence if/how forage fish are used (i.e., considering equity and food security dimensions through different mechanisms, such as regulations, certification, etc.).

Governance has resulted in the restriction and removal of finfish aquaculture in some regions, including British Columbia, Canada [49]. If and how salmon pathogens impact wild salmon populations has a long and contentious past. Evidence of negative to neutral impacts has been repeatedly presented over the decades [50–53], creating enough uncertainty—especially among the public and policymakers—to phase out Atlantic salmon *Salmo salar* in Canadian waters. Yet, trade-offs persist,

as farmed salmon is continually imported from other countries for North American consumption [54].

3 | Aquaculture and Food Security

Ignoring aquaculture's contribution and potential in food security is shortsighted. Aquaculture can directly and indirectly contribute to food security, but how, where, and whether it does depends on context and distribution of nutritional and economic benefits [1, 7, 33, 55]. Direct food security benefits of aquaculture relate to situations where farmed products supply nutritious and affordable food that supports the nutritional needs of either local or distant populations. Currently, the majority of inland (93%) and marine (80%) aquaculture production is retained domestically, though there is greater variability at the species level [56]. While questions remain about the subnational distribution of aquaculture benefits across contexts, evidence from Bangladesh indicates that rapid aquaculture development led to a decline in real fish prices and an increase in per capita consumption of fish by the poorest households [57]. Even when farmed products are not directly consumed by those with the highest nutritional needs, aquaculture can indirectly benefit food security by supporting local income and employment (e.g., [58]). However, net welfare gains from aquatic foods are not guaranteed and must be coupled with broader rights and representation to realize an equitable and just distribution of benefits [33, 59–60].

An additional layer of food security considerations for aquaculture relates, once again, to the utilization of feedstuffs, including fishmeal and fish oil, compared to the potential food security benefits of direct human consumption. First, as a key component of a circular economy, utilization of processing by-products in feeds should be viewed as a positive trend from a food security and environmental perspective as these byproducts are not otherwise currently consumed directly by humans and they reduce reliance on direct wild-sourced ingredients. Second, when and whether reduction fisheries harm local food security is highly dependent on the local demand profile, which relates to cultural preferences and current policies. For example, there is no clear evidence that the South American market could absorb any significant portion of the Peruvian anchoveta *Engraulis ringens* landings, but there is growing concern around sardinella catch in West Africa where the species represents an important traditional food source, especially for the poor [61]. Third, the food security issues surrounding feed-based resources highlight the need to consider the food system from an integrated perspective. For instance, decreasing aquaculture's fishmeal demand may achieve little in reducing overall demand for reduction fisheries products, as the pig and poultry industry would likely absorb the supply at a reduced cost [22] (Figure 1a,c). And as we noted above, lower fishmeal inclusion rates come at the expense of increasing inclusion of soy meal and other terrestrial products, with other alternative ingredients in development (e.g., insect meal, single cell protein, fermented products, microalgae) and beginning to be incorporated into fed aquaculture diets, including Norwegian Atlantic salmon (Figure 1b) [13, 16, 18, 62–63]. It is thus worth reemphasizing that when it comes to food and

the environment, there is no free lunch. Indeed, all animals must eat.

4 | The Moral Dilemma

Trade-offs are not only relegated to environmental considerations, but also moral questions of food production itself. The seemingly simple baseline of how fish and invertebrates perceive pain is hotly debated and thus influences what and how it is accounted for (or not) in aquaculture and fisheries [64, 65]. Decades of research point to some synergies across animal welfare and ethics, but agreements are sparse [66] and trade-offs are ignored. For instance, octopus sentience is well documented and recognized in science and the public, but farming a commonly fished species, *Octopus vulgaris*, is being explored in Spain [67]. As a result, some regions (e.g., California and Washington, USA) have imposed outright bans on octopus farming before it happens, alongside articles advocating for such actions [68]. However, the bans are in regions where consumption is already low and do nothing to address octopus wild capture. For example, California state law (AB 3162) still permits 35 octopuses to be fished a day per person.

Avoiding all aquaculture for the sake of wild fish (e.g., [69]) must be weighed against the moral imperative of improving nutrition and livelihoods for low-income people, as well as improving sustainability in the global food system overall. Who decides what is ethical is moving beyond sustainability into a realm of cultural significance and social dimensions that will vary depending on community, identity, and positionality (e.g., [59]). Nevertheless, we agree that *who* benefits from aquaculture should be central to its use and development (e.g., Social Carrying Capacity) [70] and is not always the case [71], but the societal context and comparison to existing practices matters.

5 | A Path to “More Data”

High-quality and widely available data are fundamental for improved accounting of social and environmental considerations. Aquaculture is generally more data-limited than agriculture and wild capture fisheries; though data improvement needs exist across food sectors [72]. Such data limitations, including around subsidies, can constrain full accounting of a variety of measures around the world. Importantly, it limits our ability to compare the relative impact of aquaculture to other systems, which is essential for grounding and addressing the real issues. The path for data improvement, once again, runs through governance. Whether that be funding and government support to collect and house public data (e.g., [73]) or increase transparency of feed supply chains through mandates and/or certification programs (e.g., Aquaculture Stewardship Council). We strongly agree better data are essential to improve aquaculture environmentally and socially. But the argument is not whether we *need* better data, but *how* to get better data, which continues to be overlooked [72]. For example, a recent study synthesized global industry subsidies [74], providing critical and comparative insights into “costs” of such subsidies. Aquaculture was so comparatively small it

was lumped into wild capture values. Regardless, the point is it is not enough to simply demand more data; we need to find the transdisciplinary, collaborative, and synthesis paths to do so.

6 | Conclusion

We acknowledge people hold different moral views when it comes to food. Animal-sourced food consumption is indeed driving major sustainability challenges, and large dietary shifts would help. However, an all-or-nothing mentality can be polarizing, and complete shifts and disadoptions of foods are exceedingly rare, especially in seafood [75, 76]. Yet, these tensions around food production do not mean change is moot. Aquaculture has made significant progress toward reducing impacts on wild species while feeding a growing population, supported by decades of science and efforts aligned with EAA [77] and OneHealth [78]. We also encourage comparative assessments when it comes to understanding aquaculture sustainability. In fact, in the United States, aquaculture is more regulated than any other food sector to date, by orders of magnitude [79, 80]. This is not to say sustainability has been achieved and we can move on. Sustainability is a moving target and will always need updates and support—especially when it comes to more and better data. Given this context, we implore others to build on the significant past research, recognizing the complexity of a system that spans aquatic and terrestrial spaces and the outsized role policy plays in addressing the many concerns surrounding aquaculture. Ignoring the substantial influence of fisheries and agricultural management in influencing the sustainability of aquaculture oversimplifies the problem.

Author Contributions

H.E.F. conceived the idea, wrote the initial draft, collected and analyzed data, created figures, and revised the draft. J.A.G. conceived the idea, wrote the initial draft, and revised the draft. G.C. collected data, conceived idea, wrote initial draft, and revised draft. J.L.B. wrote the initial draft, revised the draft. T.E.E. wrote the initial draft and revised the draft. C.D.G. wrote the initial draft and revised the draft. B.S.H. wrote the initial draft and revised the draft. R.W.H. provided data, wrote initial draft. R.L.N. provided data, wrote initial draft, revised draft. M.T. provided data, wrote initial draft, revised draft.

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Conflicts of Interest

H.E.F.: sits on the scientific board of Actea, currently a member of the US Aquaculture Society of America Strategic Planning Committee and sits on the editorial board of Reviews in Aquaculture. J.A.G.: science advisor for Oceana. G.C.: Australian Research Council grant which includes Biomar Global as an industry partner. J.L.B.: Australian Research Council grant which includes Biomar Global as an industry partner. C.D.G.: science advisor for Oceana. B.S.H.: Australian Research Council grant which includes Biomar Global as an industry partner. R.W.H.: past Director of the Aquaculture Research Institute at the University of Idaho, USA. R.L.N.: sits on the Supervisory Board of Aqua-Spark and founded the Center on Food Security and the Environment at Stanford

University. In addition, there is forthcoming World Economic Forum consultancy work. M.T.: lead scientist in SeaBOS (Seafood Business for Ocean Stewardship). The other author declares no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new datasets were generated.

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