

Commentary

Environmental and nutritional double bottom lines in aquaculture

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Aquaculture has been viewed as a potential pathway to healthy and sustainable diets by increasing global nutrient-rich food production while minimizing environmental impacts. Here, we explore environmental and nutritional synergies, trade-offs, and constraints that illuminate the role of aquaculture to deliver on this double bottom line.

Meeting global nutritional needs without overwhelming environmental limits represents a major challenge for global food systems. Multiple forms of malnutrition, comprising both undernourishment and overnourishment and their associated impacts, continue to plague all corners of the Earth. Nearly one in five children is affected by stunting, indicating an environment of chronic undernourishment, and more than one in three adults are overweight or obese.¹ Globally, inadequate supplies of micronutrients (e.g., iron, zinc, calcium, and vitamin B₁₂) have highlighted the risks of inadequate intakes and potential deficiencies, with significant burdens in sub-Saharan Africa and South and Southeast Asia,² and an estimated one in three people has a micronutrient deficiency.¹

At the same time, food systems already represent a significant environmental burden in that they are responsible for over a quarter of all greenhouse gas emissions, half of global ice-free land use, and three-quarters of eutrophication and consumptive water use.³ These pressures, among others such as pesticide application and plastic pollution, affect ecosystems and can drive biodiversity loss. In order to halt and reverse these damages while improving nutrition security, a major overhaul of global food systems is urgently needed.

Aquatic foods currently make up 17% of the total animal-source protein consumption, and demand is projected to nearly double by mid-century; the majority of this growth is expected to come

from aquaculture.⁴ Aquaculture has been increasingly looked to as an opportunity to meet human nutritional demands with a lower environmental burden for some pressures, such as water use and greenhouse gas emissions. However, there are also risks for aquaculture expansion to exacerbate other environmental pressures and increase risks related to food safety while failing to feed those most vulnerable to malnutrition.

Potential challenges from aquaculture expansion

The aquaculture sector has long been criticized for its environmental impacts, including its reliance on wild fisheries for feed, habitat conversion, risks to wild populations, and coastal pollution from effluent. Fishmeal and fish oil sourced from wild fisheries have declined since 2000 despite increased aquaculture production as a result of growing demand for omnivorous species, improved feed conversion ratios, and the inclusion of alternative ingredients and processing byproducts.⁵ Nevertheless, an increasing share of global fishmeal and fish oil supply is destined for aquaculture,⁵ highlighting its continued importance for high-quality aquaculture feeds and pointing to a potential constraint for future aquaculture growth. Mangrove habitat conversion for aquaculture ponds, which results in a loss of ecosystem services such as coastal protection from storm surges and nursery habitat for wild fish populations, has also declined in recent de-

cares,⁵ but competition for coastal space can still represent a constraint for aquaculture expansion. Another major challenge for aquaculture will be managing the risks that genetic pollution, introductions of invasive species, application of antibiotics, and disease spread pose to wild populations.⁶ Water pollution from effluent and processing waste also remains a concern for local environments, particularly when it leads to eutrophication and increases harmful algal bloom risk. These resource constraints and water-quality concerns threaten not only ecosystems but also continued aquaculture growth.

Degraded water quality, both from aquaculture and from other sources, also poses risks for aquaculture food safety. Aquatic foods are consistently exposed to both chemical and pathogen water-borne hazards throughout their production cycle, which could present significant constraints to their broad adoption for safe consumption.⁷ Pathogens can originate from both animal and human sources; chemicals range from natural (e.g., biotoxins) to anthropogenic (e.g., plastics and pharmaceuticals) to mixed sources (e.g., heavy metals such as mercury).⁷ All of these hazards can have significant impacts on production and safe consumption. Annually, it is estimated that 31 different pathogens cause roughly 600 million people to contract a food-borne illness, which leads to more than 400,000 deaths, primarily as a result of bacterial pathogens across the food system.⁸ Ciguatera is

one of the most impactful non-bacterial pathogens that has been found in more than 400 aquatic food species; it causes morbidity in more than 50,000 people per year.⁹ Meanwhile, mercury is ranked as the third most toxic element to human health in that it affects more than 19 million people annually.¹⁰ Mercury is a neurotoxin, and high levels of exposure through diet can lead to severe health impacts, including impaired vision, speech, hearing, and motor coordination and even death. In general, the Food and Drug Administration has set 1 ppm of methylmercury in seafood as a threshold that should be observed for safe consumption. Most aquatic food species fall far below that, but there is variation between species (e.g., mercury biomagnifies, so carnivorous species have higher levels) and in particular regions (e.g., tilefish in the Gulf of Mexico have 10-fold higher mercury than tilefish in the Atlantic as a result of pollution, exceeding safe consumption limits). Not all of these statistics (with the exception of those for ciguatera) are estimating impacts from aquatic food consumption alone because diagnosis and attribution are so challenging, and more datasets about aquatic foods in general, and those coming from aquaculture in particular, are needed if we are to fully evaluate the size of potential challenges for human health from their consumption. Yet, these are just a handful of the many important health threats that could arise from the consumption of aquatic food, emphasizing the tremendous need for social responsibility in the aquaculture sector.

These risks can often be managed through proper farm siting, improved husbandry, continued feed innovation, waste management, and food safety screening, although the specific management needs differ across different aquaculture production systems. It is not the aim of this article to describe the most suitable approaches to minimizing risks in specific systems, but a body of research increasingly points toward an unrealized potential for aquaculture, if managed properly, to help meet multiple aspects of the nutrition-environment bottom line. To identify opportunities to steer aquaculture toward improving human nutrition and reducing environmental impacts, we

must look across the diversity of aquaculture production for nutrient-environment synergies.

Nutritional and environmental benefits from aquaculture

Recent research has shown ways that aquatic foods can substantially contribute to global human nutritional challenges, harnessing the rapid increases in aquatic food production to provide for growing nutritional demand.¹¹ Aquatic foods appear to provide at least two major nutritional benefits: (1) they directly supply micronutrients to deficient populations, and (2) they displace the consumption of unhealthier animal-source foods (e.g., red and processed meats). In this first role, the nutrient density of aquatic animal-source foods is superior to that of terrestrial animal-source foods; small and large pelagics, bivalves, salmonids, carps, and cephalopods all nutritionally outperform even the most nutrient-dense terrestrial animal-source food.¹¹ This high density and diversity of nutrients has enormous potential in meeting growing nutritional demands. In a future scenario of intensive aquaculture production, models have shown that hundreds of millions of inadequate micronutrient intakes could be averted,¹¹ and additional benefits could be accrued from reduced cases of heart disease and cancers attributed to consumption of unhealthy animal-source food.¹²

Although environmental impacts vary widely across the vast diversity of aquaculture systems, some are well positioned to reduce environmental pressures. Systems that are unfed or have high feed efficiencies and limited on-farm land and water use outperform chicken across land and water use, as well as in greenhouse gas, nitrogen, and phosphorus emissions.⁶ Unfed mariculture, such as oysters and mussels, generate very low emissions and use negligible land and water resources, and low-feed silver and bighead carp systems still generate few greenhouse gas, nitrogen, and phosphorus emissions.⁶ The high feed efficiencies for farmed salmon and trout drive their high performance among fed species, which in combination with being farmed in the ocean results in limited land and freshwater use.⁶ Frameworks that crucially analyze the tradeoffs between human health and the environment

will enable the sector to optimize its potential for sustainable and healthy food-system benefits.

The nutrient-environment double bottom line

A key question that remains is which forms of aquaculture perform best across nutrient and environmental dimensions. Bringing together new standardized data on environmental pressure (greenhouse gas emissions, nitrogen emissions, land use, and freshwater use⁶) and nutrient content (fatty acids, vitamin B₁₂, calcium, iron, and zinc¹¹) reveals opportunities for aquaculture to contribute to the double bottom line (Figure 1). First, nearly all aquaculture groups outperform chicken, the most efficient terrestrial animal-source food, across these environmental and nutrient metrics (Figure 1). Ranking the groups according to the total environmental and nutrient scores (which we standardized by dividing by the max of each variable) shows that bivalves perform best, followed by silver and bighead carp, trout, and salmon.

However, there is also significant heterogeneity in performance across both environmental performance and nutrient content, such that nearly every blue food group ranks highest in at least one metric. This gives rise to potential tradeoffs. For example, although bivalves rank highly in nearly every metric, they fall below many other groups for calcium and fatty acid content. In situations where fatty acid supply is of greatest concern, salmon or trout might be considered to perform best despite their lower zinc and iron content. On the environmental side, whereas silver and bighead carp perform relatively well in terms of land use, nitrogen emissions, and greenhouse gas emissions, they rank the lowest for freshwater use. This tradeoff arises because these carp are often raised in extensive systems that have limited feed inputs but occupy large areas that experience evaporative losses. This suggests a need for tailored approaches to local production systems.

To explore the relative performance of aquaculture for the range of environmental and nutrient dimensions, we standardized values to a maximum of 1. However, this should not imply that each

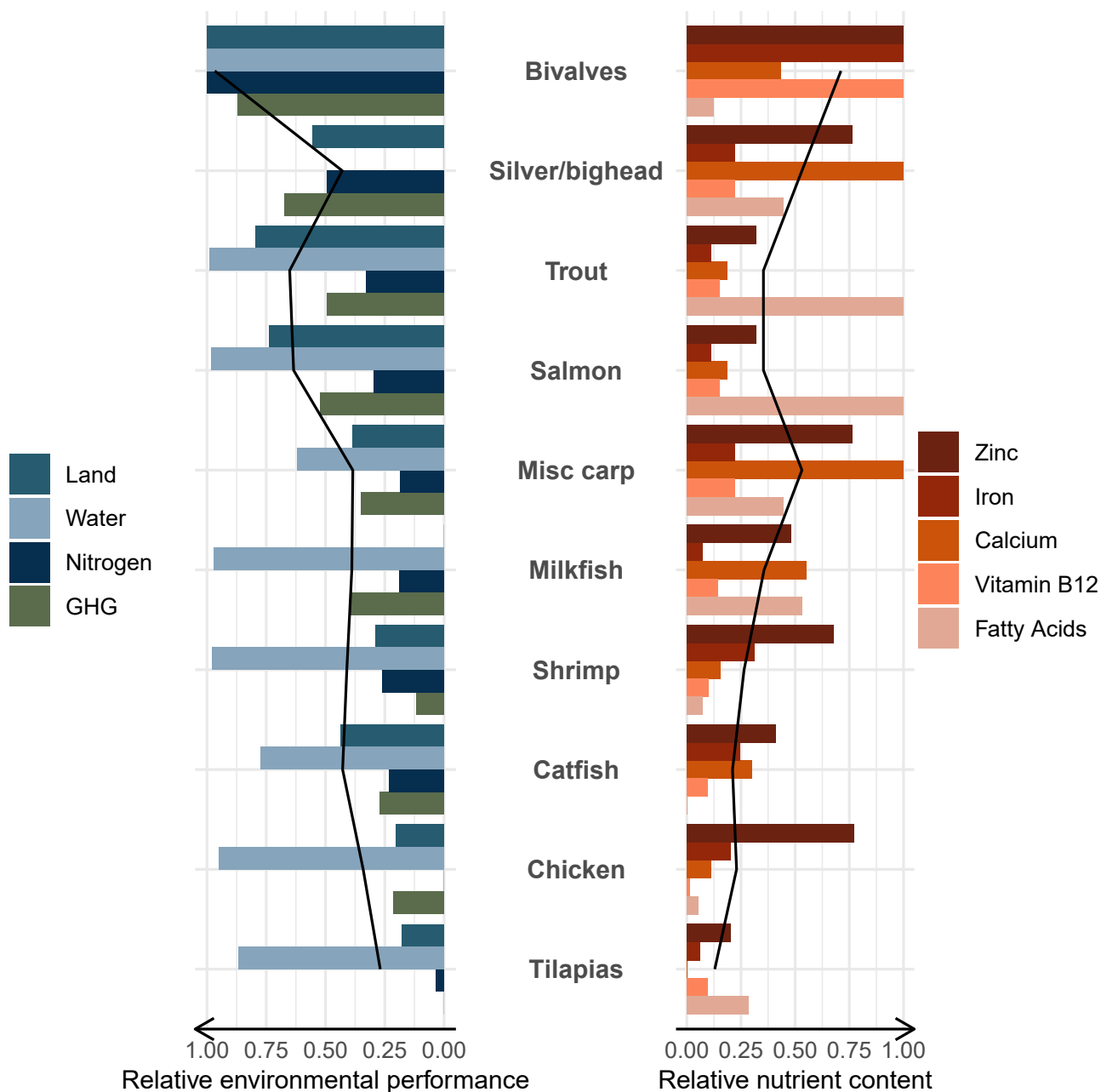


Figure 1. Relative environmental performance and nutrient content for aquaculture groups

The black lines indicate the mean score across the environmental and nutrient variables. Data on environmental performance are from Gephart et al.,⁶ and data on nutrient content are from Golden et al.¹¹ We standardized values to 1 by dividing each variable by the maximum value. Note that environmental performance scores increase from right to left on the x axis, whereas nutrient scores increase from left to right. Species groups are ordered by the total score across all environmental and nutrient variables.

indicator is equally important. The impact of nitrogen emissions, land use, and freshwater use must be evaluated within the local environmental contexts. Local conditions, such as freshwater scarcity or prevalent eutrophication, could lead managers to weigh those dimensions more heavily in decision making. Simi-

larly, countries face different nutrient demands based on demographics and food environments. Shepon et al.¹³ evaluated the potential for aquaculture production in Indonesia to be reoriented to meet national nutrient deficiencies while reducing environmental pressures. Optimized aquaculture scenarios increased

nutrient densities by more than 100% and reduced environmental pressures to 25% that of a business-as-usual scenario; however, no single system completely satisfied the nutrient-environment double bottom line.¹³ Each environmental and nutrient measure must therefore be weighted according to local priorities.

At the same time, aquaculture production and consumption occur within the broader global food system. Fishery products and their inputs are highly traded, and as a result, their environmental burden and nutritional benefits can occur in locations distant from production. On the environmental side, most greenhouse gas emissions and land use are associated with feed production for nearly all aquaculture species.⁶ Although feed production sometimes occurs on farm, many feeds are imported or include imported ingredients, thus displacing the environmental pressures to distant locations. Meeting global environmental goals, most notably global emission goals, requires managing these exported environmental impacts. Environmental standards for trade, such as excluding soy from recently deforested lands from feeds or instituting emission-based border taxes, can contribute to this goal. However, it remains important to provide protections for small-scale producers that are often excluded from the market when high regulatory costs are imposed.

On the nutrition side, exported aquaculture diverts these nutrient-dense products to foreign consumers, which may or may not align with nutrient needs.¹⁴ Among the most highly traded aquatic foods are high-value ones, including salmon and shrimp, which also have a high proportion of production from aquaculture¹⁵ and are unlikely to be destined for undernourished consumers. However, increases in aquaculture production are positively associated with increases in national aquatic food supply, which aligns with case studies showing that consumption of farmed fish among the poor increases as aquaculture expands as a result of decreased prices.¹⁶ Additionally, aquaculture production can generate indirect benefits for local communities by increasing incomes. In Myanmar, aquaculture was observed to generate more income and larger spillovers to the local economy than agriculture, pointing to opportunities for aquaculture to contribute to rural development.¹⁷ Equitable distribution of benefits is central to realizing this potential given that the “blue justice” literature has pointed to the “blue growth” promises of economic development as creating social harms for coastal commu-

nities without sharing the economic benefits.¹⁸

As we look across the diversity of aquaculture, there are multiple paths for the sector to contribute to the nutrient-environment double bottom line. Relative to other animal-source foods, farmed aquatic species perform well on a range of key environmental and nutrient dimensions, and unfed or low-feed groups rank at the top. However, no group is a silver bullet—there are tradeoffs among both the considered indicators and those not included, and not all environmental and nutrient dimensions merit equal weighting. Decisions must therefore be made in line with local priorities. Whether aquaculture development is oriented toward domestic or foreign markets, realizing the potential for aquaculture to contribute to healthy people and a healthy planet depends upon managing environmental threats from and to aquaculture production and ensuring that its nutrients benefit those who need them most. Furthermore, a critical lynchpin for the success of the aquaculture sector is the monitoring and management of water quality to minimize damage to both environments and human health. If these risks are properly managed, aquaculture can provide a nutrient-dense food source and support pathways to healthy and sustainable diets.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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