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Environmental performance of blue foods

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Fish and other aquatic foods (blue foods) present an opportunity for more sustainable diets[1,2]. Yet comprehensive comparison has been limited due to sparse inclusion of blue foods in environmental impact studies[3,4] relative to the vast diversity of production[5]. We provide standardized estimates of greenhouse gas, nitrogen, phosphorus, freshwater, and land stressors for species groups covering nearly three quarters of global production. We find that across all blue foods, farmed bivalves and seaweeds generate the lowest stressors. Capture fisheries predominantly generate greenhouse gas emissions, with small pelagic fishes generating lower emissions than all fed aquaculture, but flatfish and crustaceans generating the highest. Among farmed finfish and crustaceans, silver and bighead carps have the lowest greenhouse gas, nitrogen, and phosphorus emissions, but highest water use, while farmed salmon and trout use the least land and water. Finally, we model intervention scenarios and find improving feed conversion ratios reduces stressors across all fed groups, increasing fish yield reduces land and water use by up to half, and optimizing gears reduces capture fishery emissions by more than half for some groups. Collectively, our analysis identifies high performing blue foods, highlights opportunities to improve environmental performance, advances data-poor environmental assessments, and informs sustainable diets.

MAIN TEXT

The food system is a major driver of environmental change, emitting a quarter of all greenhouse gas emissions, occupying half of all ice-free land, and responsible for three quarters of global consumptive water use and eutrophication[3,6]. Yet, it still fails to meet global nutrition needs[7], with 820 million people lacking sufficient food[8] and with one in three people globally overweight or obese[9]. As a critical source of nutrition[8,10] generating relatively low average environmental pressures[1,2,11,12], blue foods present an opportunity to improve nutrition with lower environmental burdens, in line with the Sustainable Development Goals to improve nutrition (Goal 2), ensure sustainable consumption and production (Goal 12), and sustainably use marine resources (Goal 14).

Blue foods, however, are underrepresented in food system environmental assessments[13] and the stressors considered are limited[4] such that we have some understanding of greenhouse gas emissions[14,15], but less of others such as land or freshwater use[16]. Where blue foods are included, they are typically represented by only one or a few broad categories (e.g., [3,17,18]), masking the vast diversity within blue food production. Finally, estimates combining results of published life cycle assessments undertaken for different purposes and consequently employing incompatible methodologies[19,20], cannot be compared reliably. It is therefore critical to examine the environmental performance across the diversity of blue foods in a robust, methodologically consistent manner to serve as a benchmark within the rapidly evolving sector as blue food demand increases[21], production shifts toward aquaculture and production technologies advance.

Here, we provide standardized estimates of greenhouse gas (GHG) emissions, consumptive freshwater use (water use), terrestrial land occupation (land use), and nitrogen (N) and phosphorus (P) emissions for blue foods, reported per tonne of edible weight. We identify a set of key life cycle inventory data (i.e., material and energy input and farm-level performance data) from published studies and datasets to which a harmonized methodology is applied. We draw on studies that collectively report data from over 1,690 farms and 1,000 unique fishery records around the world. The 23 species groups represented in our results cover over 70% of global blue food production. We then discuss environmental impacts not covered by the standard stressors, most notably biodiversity loss. Finally, we leverage our model to identify and quantify improvement opportunities and discuss public and private policy options to realize these improvements. In doing so, these results help identify current and future opportunities for blue foods within sustainable diets.

Blue food environmental stressors

Reducing food system GHG emissions is central to meeting global emission targets[8]. Fed aquaculture emissions result primarily from feeds[22], while fuel use drives capture fisheries emissions[11]. Across assessed blue foods, farmed seaweeds and bivalves generate the lowest emissions, followed by small pelagic capture fisheries, while flatfish and crustacean fisheries produce the highest (Fig 1). For fed aquaculture, feed production is responsible for >70% of emissions for most groups (Fig S6). Farmed bivalves and shrimp produce lower average emissions than their capture counterparts (bivalves: 1362 versus 11,400 kg CO_2-eq t^{-1}; shrimps: 9090 versus 11956 kg CO_2-eq t^{-1}; results expressed in terms of edible weight), while salmon/trout are similar whether farmed or fished (5173– 5379 versus 6881 kg CO_2-eq t^{-1}).

Land use, especially conversion of natural areas, results in a range of context-dependent biodiversity impacts and GHG emissions[23] and creates potential trade-offs with alternate uses, including production of other foods. On-farm land use is low (<1000 $m^2a\ t^{-1}$; <10%) for most systems and highest (3737–8689 $m^2a\ t^{-1}$) for extensive ponds (e.g., milkfish, shrimp, and silver/bighead carp). Generally, most land use is associated with feed production for fed systems and explains the overall rankings (Fig 1), though milkfish uses the highest amount of on- and off-farm land.

Freshwater increasingly constrains agriculture production but capture fisheries and unfed mariculture require little to no freshwater[24]. Although blue foods are produced in water, consumptive freshwater use is largely limited to feed production and on-farm evaporative losses for freshwater production[16], with feeds accounting for >80% for all groups apart from carps and catfish (Fig S6). High evaporative losses cause carps to have the highest total water use, while milkfish and miscellaneous marine and diadromous fishes have the highest feed-associated water use. Among fed aquaculture, trout and salmon have the lowest water use, in part attributable to lower crop utilization, highlighting a trade-off with fishmeal and fish oil.

Nitrogen and phosphorus emissions are responsible for marine and freshwater eutrophication and are highly correlated due to natural biomass N:P ratios (Table S4). For fed systems, the majority of N (>87%) and P (>94%) emissions occur on-farm. The highest total N and P emissions result from miscellaneous farmed marine and diadromous fishes, milkfish, and fed carp. Non-fed groups such as seaweeds and bivalves, as well as unfed and unfertilized finfish systems (e.g., silver/ bighead carp), represent extractive systems that remove more N and P than is emitted during production, resulting in negative emissions (Fig 1).

Across all blue foods, farmed seaweeds and bivalves generate the lowest stressors. However, these groups also highlight several assumptions and nuances. First, bivalve estimates change by nearly five-fold when expressed in terms of edible portion (Fig 1) compared to live weight (Fig S10) due to the shell weight. Second, some processes falling outside our system boundaries represent a potentially large fraction of life cycle emissions for these groups, even if still small in absolute value in some cases. For seaweeds, a large proportion of GHG emissions can occur at the drying stage[25] while for bivalves, CO_2 emissions during shell formation[26] and high emissions associated with live product from transport[27] can be important. Third, impacts on biogeochemical cycling and habitats are highly context dependent. For example, the systems represented here extract nitrogen and phosphorus, which could be problematic in nutrient poor environments. Additionally, ozone effects from volatile short-lived substances depend on the location and varies widely across species[28,29]. Fourth, sustainable diet recommendations based on these or similar results must account for differences in nutrition content and bioavailability, a particularly important consideration for seaweeds[30]. Finally, these systems are underrepresented in the literature, particularly for edible seaweeds (Fig S3). As recommendations point toward the potential of these groups, it is important to increase data on these systems, deepen understanding of the above nuances, and be mindful of the total impacts associated with large-scale production on coastal habitats.

Capture fisheries, with negligible land, water, N and P values also compare favourably, though groups fall at both the bottom and top of GHG rankings. Among farmed finfish and crustaceans, silver and bighead carps result in the lowest GHG, N, and P emissions, while salmon and trout use the least land and water. To compare with terrestrial foods, we estimated stressors for industrial chicken produced in the US and Europe and find it falls in the middle of farmed blue foods, with similar stressors as tilapia (Fig 1, S14). Because chicken typically has lower stressors than other livestock[3], it follows that many blue foods groups compare favourably to other animal-sourced foods. Notably, groups generating among the lowest stressors (e.g., bivalves and small pelagic fishes) also provide the greatest nutritional quality across all forms of aquatic foods[2,10].

Our results represent the most comprehensive and standardized blue food stressor estimates to date. Overall, data availability is correlated with global aquaculture production across these taxa groups, but there are still notable taxonomic and geographic gaps (Fig S3, S4). Critically, there are substantial data gaps for silver/bighead carp and aquatic plants given their level of production (Fig S3). Further, our capture fishery data primarily represents commercial marine fisheries[31]. However, subsistence marine and inland catches often utilize non-motorized or no vessels which likely generate few emissions, but there is insufficient data on fuel use across the diversity of small-scale fishing methods to reliably estimate emissions. These systems should be prioritized for additional research. Our estimates represent a snapshot of the knowledge of current production, but future work on emerging production technologies, feed innovations and growing sub-sectors is important for tracking changes against these benchmarks.

From stressors to ecosystem impacts

Emission and resource use stressors are valuable for comparing environmental performance across foods but cannot fully capture final ecosystem and biodiversity consequences (i.e., impacts). Estimating impacts stemming from blue food production requires considering additional stressors and accounting for local context.

While GHG, N, P, land, and water are important stressors commonly used to compare foods, other less studied stressors can be critical drivers of ecosystem impacts (Fig 2). Both aquaculture and fisheries may impose other stressors through toxic substance applications (e.g., antifouling, pesticides in agriculture) and physical disturbance (e.g., bottom trawling, on-bottom culture). Additional stressors include genetic pollution, invasive species introductions[32], application of antibiotics[33], and disease spread[34]. While capture fisheries have negligible N, P, water and land stressors, other stressors can dramatically alter ecosystems. Fisheries often shift size structure and abundance of targeted species (e.g.,[35,36]), alter the structure of food webs (e.g., [37]) and impact non-targeted fauna through bycatch[38].

Local context, such as ecosystem function, carrying/assimilating capacity, and species composition influence how stressors translate into environmental impacts[39,40]. Notably, land use impacts on biodiversity depend on the land use history and ecological context[41]. While all land used for food cultivation represents habitats converted at one point, avoiding additional agricultural expansion is important for preventing further habitat loss[42]. This is also true for on-farm land use by aquaculture, where conversion of ecologically valuable ecosystems, such as mangrove forests[23] that serve as critical carbon sinks[43] and nursery habitats, can generate severe impacts. Local species composition and management contexts are also important, including risks associated with marine mammal bycatch (Box 1). Individual stressors may also have nonlinear relationships with impacts or act interactively[44,45], such as climate change impacts compounding land use patterns that limit climate refuges or migration options[46] or resulting in more frequent disease outbreaks, that increase antibiotic use and risk of antibiotic resistance.

Capturing the full suite of environmental impacts will require more systematic data collection and methodological advancements. This is crucial for informing policy decisions and realizing the potential contributions of blue foods to sustainable diets while avoiding undesirable trade-offs. Combining local ecological risk and stressor estimates can reveal these important trade-offs, as well as potential synergies (Box 1). Instances of trade-offs complicates sustainability messaging. To this end, while there are no impact-free foods, highlighting synergies simplifies sustainability messaging and helps identify priority interventions.

Box 1 | Emissions and biodiversity risk: Stressors from life cycle assessments quantify fishery emissions but fail to capture local ecological risks. Combining stressors and impact assessments can illuminate potential sustainability trade-offs. Ecological risk assessments have been developed for capture fisheries to promote holistic assessment of local ecological risks. Integrating GHG emissions with marine mammal risk assessments reveals that some low-GHG emission gears are associated with higher marine mammal risks (e.g., gillnets and entangling nets; Fig 3), while bottom trawls show the opposite. Acknowledging ecological context is critical because risk from similar gears varies across regions. For example, traps and lift nets generally pose low risk to marine mammals (Fig. 3). However, North Atlantic right whales (*Eubalaena glacialis*) in the northwest Atlantic are at high risk from entanglements in American lobster (*Homarus americanus*) traps[47].

Levers for reducing environmental impacts

Variance in stressors indicates diversity across fishing/farming systems (Fig S7-S9) as well as potential “performance gaps.” High variability in milkfish and miscellaneous marine and diadromous fish stressors points to large potential performance gains per unit. This is promising given the interest in marine finfish expansion[48]. Meanwhile, smaller performance gains per unit for high production groups like carps likely generates larger total gains. While some variability within a taxa group is due to differences in on-farm practices, production technology is an important factor across stressors[49] as variability in stressors for a given species reared in different farming systems can be considerable (e.g., [50]).

We find feed conversion ratios (FCRs) represent the strongest lever, wherein a 10% reduction results in a 1–24% decrease in all stressors (Fig 4a). To evaluate potential shifts under current technology, we estimate the effect of moving each species to the 20th percentile FCR and find the largest reductions for silver and bighead carps (Fig 4b). However, lower FCRs generally come at the cost of larger pond area[33], suggesting a potential trade-off with land and water use.

Holding all else constant, a 10% fish production yield improvement (t ha^{-1}) reduces land and water use for freshwater pond systems by 1–9% (Fig 4a). Increasing yields to the 80th percentile reduces land use by 1–49% and water use by 13–51% (Fig 4b). Intensifying production, however, can require more energy for aeration and water pumping as well as increased disease risks with higher animal densities.

Feed composition represents another potential lever. Overall, shifting relative proportions of crop- and fish-derived inputs to feeds results in negligible changes in stressors (Fig 4a). Comparing changes in feed sourcing, we found switching to deforestation-free soy and crops reduced GHG emissions by 6–54% (Fig 4b). This could create a co-benefit of also reducing biodiversity impacts. However, as part of integrated global commodity markets, reductions by aquaculture producers will only help meet emissions targets if broader food sector commitments are made. Replacing fish meal and fish oil with fishery by-products has a relatively small effect (Fig 4b), but increased by-product utilization can improve system-wide performance when it directs potential wastes toward more favourable applications[51]. Finally, novel aquaculture feeds, including algal, microbe and insect meals, are increasingly available but currently account for a small fraction of feeds. While they likely hold potential to improve feed quality and reduce forage fish demand[52], their impacts at scale remain uncertain[53] and therefore could not be modeled here.

For capture fisheries, reducing fuel use represents the primary stressor improvement opportunity. Increasing stock biomass could reduce fuel use per tonne of fish landed[12,54], where a 13% catch increase with 56% of the effort[55] corresponds to a 50% reduction in GHG emissions. Alternatively, we find that prioritizing low fuel gears within each fishery can reduce GHG emissions by 4–61%, depending on the species (Fig S16). In some cases, this could create co-benefits for biodiversity impacts (Box 1). Another strategy is to transition fishing fleets to low emission technologies[8]. While some fleets have transitioned to electric, hydrogen fuel and sail-assisted vessels, general adoption necessitates transformations beyond traditional fishery management.

Realizing blue food’s environmental potential

Blue foods already have great potential for reducing food system environmental stressors. Unfed aquaculture results in negligible values for most considered stressors, and many fed aquaculture groups outperform industrial chicken, the most efficient major terrestrial animal-source food. Capture fisheries vary widely in their GHG emissions but are low impact with respect to the other stressors considered. This underscores the value of sustainably managing wild fisheries to avoid the environmental replacement cost that would be incurred under fish catch declines[24].

Our standardized estimates enhance the resolution of the potential role of blue foods within sustainable diets, highlighting opportunities to shift demand from relatively high- to low-stressor blue foods and from terrestrial animal-source foods to comparatively low-stressor blue foods. Shifting to non-animal alternatives remains an efficient lever but low-stressor blue foods may represent an appealing alternative for some consumers. Further, blue foods provide the highest nutrient richness across multiple micronutrients (e.g., iron, zinc), vitamins (e.g., B12), and long-chain polyunsaturated fatty acids (e.g., EPA and DHA) relative to terrestrial animal-source foods[10], which may provide greater incentive to shift demand since consumers generally prioritize seafood freshness, food safety, health, and taste over sustainability[56].

Major challenges remain for shifting demand, as well as meeting increased demand. While improved management offers potential opportunities for expanding some production from low stressor capture fisheries, uncertainty remains around the extent and feasibility of rebuilding many fisheries[48]. Additional research is needed to understand the total environmental impacts of large-scale expansion of low per unit stressor foods, especially for system-specific impacts (Box 1). Increasing production also requires creating appropriate incentives and reducing barriers for producers. Historical food system transitions required public investment technologies that could be scaled-up by the private sector and public policy leadership[57]. Overly strict regulations or lack of capital can prevent expansion of low stressor blue foods like offshore mussel farms (e.g., [58]). Facilitating low-stressor blue food expansion and novel production methods may require new and more adaptive policies and distribution of grants or other forms of start-up capital. Finally, policies can steer production and consumption through taxes and subsidies[59] as well as softer policies, like dietary advice considering environmental impacts[60].

Within the diversity of blue food production there are numerous opportunities to reduce environmental stressors. As a young and rapidly growing sector, there are many promising technological innovations in aquaculture (e.g., recirculating aquaculture systems, offshore farming and novel feeds). However, less charismatic interventions may represent greater potential for rapid and substantial impact reductions. These include policy or technological interventions that improve husbandry measures (especially reducing disease and mortality) and lower FCRs. Improved management in salmon aquaculture demonstrated considerable sustainability benefits through disease and area management plans[61] and improved stock management with precision aquaculture and automation[62]. Further, selective breeding, genetic improvements and high-quality feeds can all reduce FCRs (Table S8). While we looked at individual interventions, improvements will likely occur through a suit of interventions and the synergistic or antagonistic interactions of interventions represents an important area for future work. Unfortunately, many innovations are often beyond the reach of smallholder producers of low-value species. This highlights a need for public research and development as well as technology transfer to enable all farmers to adopt practices that reduce environmental stressors. For capture fisheries, continued management reforms together with incentives to utilize low fuel gears could substantially improve the performance of capture fisheries[11,48]. A range of actors will be important for stimulating a shift to more sustainable production methods and, for instance, nation states, civil society and the private sector all have important roles to play. Private sector pre-competitive collaborations, e.g. SeaBOS[63] and the Global Salmon Initiative can help stimulate production improvements at scale. Likewise, government-led initiatives helping small-holders improve their farming practices through e.g., access to high quality feeds, seed and broodstock, are crucial for closing the aquaculture performance gap[64–66]. Certification and improvement projects can help reduce ecosystem impacts[67], but have been criticised for passive exclusion of small-scale producers. Moving towards best practices like state-led, national certification schemes and area-based approaches will therefore be key[68]. Finally, the finance sector can help steer the sector towards sustainability through strategic investments[69].

The above findings do not suggest unlimited blue food growth is possible nor that expansion comes without environmental trade-offs. Further, without careful consideration for local contexts and inclusion of relevant stakeholders, environmentally focused interventions can generate social and economic trade-offs that undermine broader sustainability goals. Nevertheless, farmed blue food is among the fastest growing food sectors and the global community now faces a unique window of opportunity to steer expansion toward sustainability[70]. Our model and results provide blue food stressor benchmarks and enable data poor environmental stressor assessments. This serves as a critical foundation for understanding blue food environmental performance and to ensuring sustainable and healthy blue foods are available now and into the future.

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Fig. 1 | Stressor posterior distributions. Panels represent a) Aquaculture GHG emissions (kg CO_2-eq t^{-1}); b) Aquaculture N (kg N-eq t^{-1}); c) Aquaculture P (kg P-eq t^{-1}); d) Capture GHG emissions (kg CO2-eq t^{-1}); e) Aquaculture Water use (m3 t^{-1}); f) Aquaculture Land use (m^2a t^{-1}). Values represent tonnes of edible weight and use mass allocation. Dot indicates the median, colored regions show credible intervals (i.e., range of values that have a 95% (light), 80%, and 50% (dark) probability of containing the true parameter value). Taxa group names are abbreviated ISSCAAP names (See Table S3 for definitions). Beige bands represent estimated chicken minimum to maximum range. See Fig S10 for estimates expressed in terms of live weight.

Fig. 2 | Major stressors stemming from aquaculture and capture fisheries. Icons with magenta border are quantified in this study while the others are discussed qualitatively.

Fig. 3 | GHG emissions compared to marine mammal risk. Data represent fisheries in Europe (NE Atl) and Central America (C Am SSF) by gear type. Dot indicates the median estimate of the mean kg CO_2-eq t^{-1} and intervals show 95% (light), 80%, and 50% (dark) credible intervals. Risk index is the sum of the number of marine mammals at risk times 3, 2 or 1 for high, medium, and low risk, respectively.

Fig. 4 | Aquaculture stressor intervention opportunities a) Change (%) in each stressor associate with a 10% reduction in the parameter value (black cell indicates stressor change >20%); b) Change (%) in each stressor under four scenarios (defined in Table S8) relative to the current estimate. Arrows indicate changes greater than 50%. Additional aquaculture scenario results displayed in Fig S15 and capture scenario results in Fig S16.

Data and Code Availability

All data and code used to produce the results of our analysis are available in the supplementary information and on GitHub (https://github.com/jagephart/FishPrint), with the published version archived (DOI: 10.5281/zenodo.4768324).

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Author contributions

JAG, PJGH, RP and AS contributed equally to the study. JAG and CG organized the initial workshop. JAG, PJGH, RP, AS, GE, CDG, PT and MT conceived of the idea and designed the overall study. JAG, PJGH, RP, AS, KDG, SH, KM, MM, RN, WZ, and FZ compiled the data. JAG and KDG developed the model and analysed the data. All authors reviewed the results and contributed to and approved the final manuscript.

Additional information

Supplementary Information is available for this paper.

The authors declare the following competing interests: RWRP became employed by the Aquaculture Stewardship Council while this manuscript was under consideration.

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