



Measuring the potential for sustainable intensification of aquaculture in Bangladesh using life cycle assessment

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Food production is a major driver of global environmental change and the overshoot of planetary sustainability boundaries. Greater affluence in developing nations and human population growth are also increasing demand for all foods, and for animal proteins in particular. Consequently, a growing body of literature calls for the sustainable intensification of food production, broadly defined as “producing more using less”. Most assessments of the potential for sustainable intensification rely on only one or two indicators, meaning that ecological trade-offs among impact categories that occur as production intensifies may remain unaccounted for. The present study addresses this limitation using life cycle assessment (LCA) to quantify six local and global environmental consequences of intensifying aquaculture production in Bangladesh. Production data are from a unique survey of 2,678 farms, and results show multidirectional associations between the intensification of aquaculture production and its environmental impacts. Intensification (measured in material and economic output per unit primary area farmed) is positively correlated with acidification, eutrophication, and ecotoxicological impacts in aquatic ecosystems; negatively correlated with freshwater consumption; and indifferent with regard to global warming and land occupation. As production intensifies, the geographical locations of greenhouse gas (GHG) emissions, acidifying emissions, freshwater consumption, and land occupation shift from the immediate vicinity of the farm to more geographically dispersed telecoupled locations across the globe. Simple changes in fish farming technology and management practices that could help make the global transition to more intensive forms of aquaculture be more sustainable are identified.

accountable to food production) (1, 12). Food production is also pushing the thresholds of climate change (25% accountable to food production), biosphere integrity, and land-system change. Farming also produces a large share of anthropogenic persistent and potentially toxic substances due to widespread use of pesticides and therapeutants (1). Thus, as demand for food grows, there is an urgent need to limit the environmental consequences of its production by producing more using less.

This concept is known as sustainable intensification (SI). A rapidly growing body of literature explores the application of SI to agricultural production strategies (13–17). The literature can be divided into two parts: First, publications conceptualizing SI (e.g., refs. 15 and 18); and second, empirical analyses of SI. The second group can be subdivided into (i) macro- and mesoscale studies (conducted at the global/regional and the country/river catchment/ecological zone scales, respectively); and (ii) micro-scale (farm-level) studies. Most macro/meso studies model the effects of hypothetical large-scale improvements in agricultural resource use efficiency (e.g., refs. 19 and 20). In contrast, most micro studies use empirical data on farm input use and yields to infer the contribution of specific technologies to SI (19–22). Irrespective of scale, SI is usually evaluated with reference to an individual metric or a few indicators.

sustainable intensification | aquaculture | life cycle assessment | seafood | fish

Global demand for animal protein is growing as the human population increases and diets in developing nations transform in response to rising incomes and urbanization (1). These trends are changing demand for food, driving a shift in consumption from traditional staple grains to diverse higher value alternatives, including fruit, vegetables, meat, dairy, and fish—a pattern referred to by economists as Bennett’s Law (2). As a result, since the turn of the millennium, meat production has increased by 35%, milk production by 32%, soybean feedstock production by 73%, and aquaculture (farmed fish) production by 142% (3, 4). Human population grew by 19% over the same period (5). Increasing per capita availability of higher quality food means that the global population is increasingly well fed.

However, increasing food production is linked to escalating environmental degradation. Production of food is a major contributor to global warming, freshwater depletion, land use and land-use change (LULUC), biotic resource use, biodiversity loss, disruption of global phosphorus and nitrogen cycles, and the overexploitation of wild fish stocks (6–11). Agriculture is the primary driver for exceeding planetary boundaries of freshwater consumption (70% accountable to food production) and biochemical flows (>99%

Significance

Aquaculture has only recently begun to make significant contributions to the global food system but is undergoing rapid growth and intensification. Identifying the most sustainable intensification options for aquaculture provides an opportunity to avoid some of the environmental pitfalls of agriculture and livestock production. Life cycle assessment is operationalized here as a tool to evaluate a range of environmental impacts resulting from the intensification of aquaculture production in Bangladesh and a subset of trade-offs among them. Intensifying aquaculture production results in multidirectional outcomes across different environmental impact categories. These findings are used to identify simple improvements in farm management practices that can make the intensification of aquaculture more sustainable.

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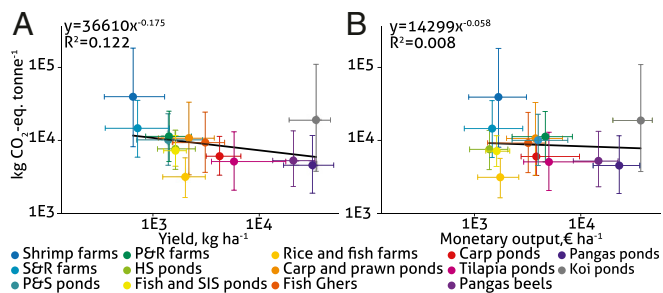


Fig. 1. Median global warming impacts per metric ton of fish over output in terms of volume per hectare (A) and monetary value (B), including 68% CIs.

There are several weaknesses in this body of work. First, the evaluation of individual metrics does not permit the weighing of trade-offs among different types and sources of impacts and, thus, cannot capture the full spectrum of environmental impacts associated with agricultural intensification. This is problematic because win-win situations in agriculture are scarce, while trade-offs among the use of different resources are abundant (23). Second, most studies only evaluate SI with respect to production practices on-farm, meaning that impacts occurring in other segments of the value chain (e.g., electricity generation, input manufacture, and transport) often go unaccounted for. Third, few studies use empirical data to analyze intensification as a dynamic meso-/macro-scale process, meaning that most research is limited to *ex ante* or *ex post* evaluation of the adoption of a specific technology. Fourth, the predominant focus of SI research has been on staple crops, with limited attention on nonstaples (such as farmed fish) that make up an increasing share of the global food basket (3, 4).

Life cycle assessment (LCA) is a standardized methodology (ISO 14040–14044) for assessing multiple environmental impact categories along whole production chains. Research on LCA often addresses the environmental trade-offs between production systems operating at different levels of intensity but is seldom framed explicitly in terms of SI. In the present paper, we use LCA to evaluate environmental consequences and trade-offs associated with the ongoing intensification of fish farming in Bangladesh. Using LCA as a framework for evaluating SI makes it possible to (i) quantify multiple environmental impacts from farming systems operating across a broad spectrum of intensity, (ii) identify environmental trade-offs between technologies and among impact categories, and (iii) pinpoint impact mitigation strategies. This approach provides the structure for the remainder of the paper. We limit our assessment to the production phase and do not attempt to quantify the social or economic consequences of intensification.

The central research question addressed is How does the intensification of aquaculture in Bangladesh affect the environmental sustainability of fish production? Opinion in the literature on the sustainability outcomes of intensification is divided. Many LCA studies conclude that livestock production under intensive conditions results in reduced environmental impacts compared with more extensive forms of production (24, 25). However, LCA studies of aquaculture are split between those that find low-intensity fish farming environmentally superior to intensive production (26, 27), and those that report that the land-sparing effects and efficiency gains of intensification minimize a variety of negative impacts (28, 29). For example, Cao et al. (26) concluded that semiintensive shrimp farming in China resulted in lower global warming, acidification, eutrophication impacts, and energy and biotic resource use than intensive production, on a point-value basis, whereas Henriksson et al. (30), found that the eutrophication and ecotoxicity impacts of semiintensive shrimp farming in Vietnam were greater than those of intensive shrimp farms. As a result, we hypothesize that

impacts of aquaculture intensification will be multidirectional and will involve trade-offs among different impact categories.

Intensifying Aquaculture

Over the past three decades, aquaculture has risen from relative obscurity to become a major component of the global food system. The sector now provides more than half of all fish destined for direct consumption by humans worldwide (4). In contrast, global capture fisheries landings have remained stagnant since the mid-1990s, and it is estimated that even under optimal management conditions, there is limited scope to raise the contribution of wild stocks to total fish supply by more than 10% (31). This scenario makes aquaculture the only means by which anticipated future demand for fish can be fulfilled (4, 31).

Technological change and intensification have been integral to aquaculture's rapid rise. Key technologies facilitating intensification include nutritionally complete pelleted feeds, fertilizers, improved animal strains, veterinary medicines, and mechanical aeration and water exchange. Use of these inputs has improved returns from land and other production factors and facilitated greater economic efficiency, with subsequent reduced market prices for farmed fish (32–34). Intensive aquaculture is highly dependent on inputs of externally sourced nutrients (feeds), leading to criticism that it is associated with depletion of wild fish stocks and deforestation owing to use of fishmeal, fish oil, and soybeans in feeds (33, 35, 36). The high stocking densities associated with intensification often entail increasing use of therapeutants to counter the elevated risk of pathogens and infectious diseases (35, 37). In contrast, extensive aqua-farming systems rely primarily on natural or managed *in situ* production of phytoplankton and zooplankton and are commonly portrayed as working in balance with ecosystem services (38) but can also result in significant LULUC.

Aquaculture in Bangladesh

Aquaculture is of particular importance to Bangladesh, where around 60% of dietary animal protein intake is derived from aquatic animals and where fish consumption plays an important role in reducing malnutrition (39–41). Aquaculture's contribution to fish supply in Bangladesh has increased dramatically over the past three decades, from 0.12 million metric tons (t) in 1985 to 1.95 million t in 2014, whereas capture fisheries' growth has already peaked (4). As a result, 55% of the fish produced in Bangladesh is now farmed, mirroring the global trend (4). Apart from the importance of aquaculture to its food security, Bangladesh was used as an example because of its particularly high diversity of fish farming technologies, with average yields ranging from 0.65 to 34 t ha⁻¹ (42). This wide spectrum of farming intensities made it possible to measure and compare the environmental impacts of multiple farming systems with varying resource demands and to identify options for more sustainable management.

The transition from an aquatic food system dominated by capture fisheries to one increasingly dominated by aquaculture has

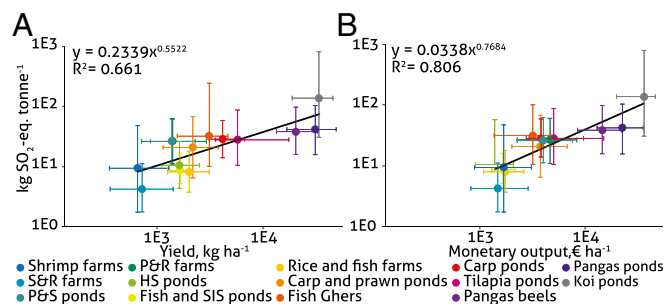


Fig. 2. Median acidification impacts per metric ton of fish over output in terms of volume per hectare (A) and monetary value (B), including 68% CIs.

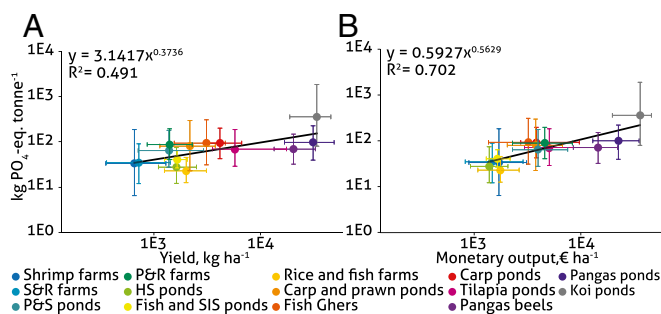


Fig. 3. Median eutrophication impacts per metric ton of fish over output in terms of volume per hectare (A) and monetary value (B), including 68% CIs.

been made possible by simultaneous horizontal expansion of pond area and achievement of progressively higher levels of productivity per unit area of land (intensification). The latter trend has been supported by the widespread adoption of commercially manufactured aqua feeds, similar to the increased use of feed supplements in the livestock industry. Bangladesh's production of pelleted feeds increased at an average rate of 24% per year over the period 2008–2015, to reach an estimated 1.6 million t in 2015 (43).

Bangladesh has a higher population density than any country in the world, excluding city-states (39). There are virtually no possibilities for further agricultural expansion, and arable lands are being lost to urbanization at an alarming rate (44). Ecosystem degradation and overexploitation of both marine and freshwater ecosystems further threaten future fish production from capture fisheries (40), meaning that aquaculture is destined to be the main source for any additional fish in the future. The intensification of aquaculture is, therefore, likely to be essential but must occur in a sustainable manner to avoid environmental impacts that compromise future food production.

LCA for Environmental Benchmarking

To compare the complete environmental impacts of aquaculture systems operating at different production intensities, it is necessary to account for environmental interactions along the value chain (e.g., resource extraction, fuel refining, agriculture, capture fisheries, feed production, hatcheries, grow-out, and the logistics linking them). When conducting an LCA, relevant elementary flows that enter and exit a production chain are modeled and aggregated into life cycle inventories (LCIs). These are then classified and characterized toward a selected set of impact categories. Here, relative ranges of impacts were estimated for six environmental impact categories commonly associated with food production, noted below.

Analysis was performed on production technologies of varying intensity, classified using a dataset of 2,678 aquaculture farms (to our knowledge, the largest in-depth aquaculture farm survey conducted anywhere in the world). Six environmental impacts were quantified using LCA: global warming, acidification, eutrophication, freshwater ecotoxicity, freshwater consumption, and land occupation. These impacts correspond closely to the main planetary boundaries for which food production is a major driver and, together, constitute a comprehensive, though not exhaustive, impact metric. Impacts in the six categories were plotted against total output per hectare (as a proxy for production intensity), measured in terms of both volume (t ha⁻¹) and monetary value (€ ha⁻¹) (a principal component analysis is shown in *SI Appendix*, Fig. S1).

Results

On-Farm Production Practices. Fourteen distinct fish production technologies were identified from farm survey data (*SI Appendix*, Tables S1–S26). The quantity of inputs used, outputs produced, and duration of production cycles differed greatly among them.

The products of these systems consisted of seven fish groups: carp (*Cyprinidae*), tilapia (*Oreochromis spp.*), pangasius catfish (*Pangasius hypophthalmus*), koi (*Anabas testudineus*), small indigenous fish species (SIS), freshwater prawn (*Macrobrachium rosenbergii*), and shrimps (*Penaeus monodon* and others). Koi was the most productive species in terms of both volume and monetary value per hectare, followed by pangasius. These systems were also most reliant on manufactured pelleted feeds.

Most farming systems used supplementary feeds and fertilizers. Supplementary feed materials included rice bran, broken rice, mustard oilcake (a by-product of oil milling), pulses, wheat flour, and snail meat. Three different types of pelleted feeds were used: farm-made feeds, commercial sinking feeds, and commercial floating feeds. Fertilizers used included manure, urea, diammonium phosphate, triple super phosphate, and potassium chloride.

Life Cycle Impacts. Global warming impacts (expressed as emissions of kilograms of CO₂-eq t⁻¹ fish output) showed no correlation (R^2 values below 0.3 were deemed irrelevant) when plotted against the volume of fish produced per hectare (kg ha⁻¹) (Fig. 1A) or monetary value generated per hectare (€ ha⁻¹) (Fig. 1B). Thus, intensification could not be said to influence the carbon emissions related to aquaculture products. However, the source of the greenhouse gases (GHGs) emitted differed with intensity, from emissions mainly related to methane emissions from ponds in extensive systems (up to 96% of the emissions), to emissions mainly related to the production of feeds in intensive systems (up to 87% of the emissions) (*SI Appendix*, Tables S29–S42). Extensive shrimp ghers resulted in the largest global warming impacts [68% confidence interval (CI), 8,200 to 186,000 kg CO₂-eq t⁻¹], followed by intensive koi farms (68% CI, 3,800 to 111,000 kg CO₂-eq t⁻¹).

In contrast, acidification impacts were strongly correlated with increasing farming intensity, in terms of both volume and value ($R^2 = 0.66$ and 0.81 , respectively) (Fig. 2). The major sources of emissions were nitrogen oxides (NO_x) (16% to 41% of overall acidifying emissions) and ammonia (NH₃) (13% to 33%) from agricultural fields. Transportation (including raw materials, feeds, etc.) accounted for up to 10% of the acidifying emissions—a larger contribution than for any other impact category. Intensive koi farming resulted in, by far, the largest acidifying emissions (68% CI, 106 to 666 kg SO₂-eq t⁻¹)—more than five times the median impact (19.8 kg SO₂-eq t⁻¹). Extensive shrimp and rice farms had the lowest acidifying impact (68% CI, 1.7 to 11 kg SO₂-eq t⁻¹), followed by rice and fish (68% CI, 3.7 to 18 kg SO₂-eq t⁻¹), fish and SIS (68% CI, 5.1 to 16 kg SO₂-eq t⁻¹), and shrimp ghers (68% CI, 1.7 to 47 kg SO₂-eq t⁻¹).

With regard to eutrophication, there was also a respective correlation ($R^2 = 0.49$ and 0.70) toward larger impacts in more intensive systems, defined in terms of both mass and value (Fig. 3). This was largely the result of nutrients in farm runoff water (47% to 92% of overall nutrient emissions), with higher

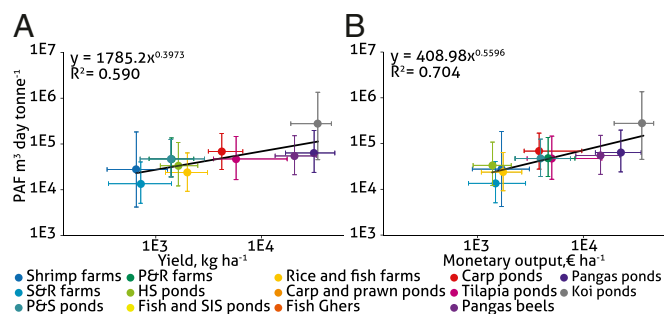


Fig. 4. Median freshwater ecotoxicity impacts per metric ton of fish over output in terms of volume per hectare (A) and monetary value (B), including 68% CIs.

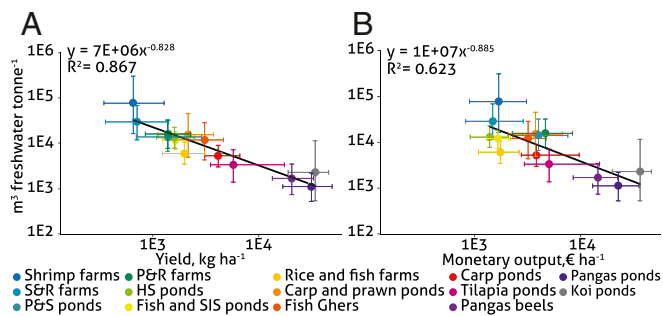


Fig. 5. Median freshwater consumption per metric ton of fish over output in terms of volume per hectare (A) and monetary value (B), including 68% CIs.

concentrations in farms using larger inputs of feed and fertilizers. Intensive koi farms again caused the largest emissions (68% CI, 80 to 1,869 kg PO₄-eq t⁻¹)—over three times higher than any other system.

Freshwater ecotoxicity impacts are expressed as potentially affected fractions (PAFs) of species integrated over time (days) and volume (cubic meters) per kilogram of chemical emitted (45). The level of impact also increased with farm intensity, with koi farming again resulting in the largest impacts (68% CI, 45,000 to 1,356,000 PAF m³ d t⁻¹ fish; Fig. 4). Over 90% of the impacts on intensive farms were related to pesticide use on agricultural fields for the production of feed ingredients such as rice, soybeans, and wheat. Standing out as especially hazardous among the many chemicals used were chlorpyrifos and carbofuran, both widely used in Bangladeshi agriculture (46). On-farm chemotherapeutant use only made substantial contributions to freshwater ecotoxicity in less-intensive shrimp and rice farming systems (65% of 14,000 PAF m³ d t⁻¹ fish) and in shrimp ghers (27% of 28,000 PAF m³ d t⁻¹ fish), relying on the use of methylene blue. Overall, all aquaculture systems had limited direct on-farm freshwater toxicity impacts (1,200 to 10,100 PAF m³ d t⁻¹ fish) compared with those caused by the products used in agriculture for the production of feed crops (e.g., Boro irrigated rice: 54,400 PAF m³ d t⁻¹ rice).

Freshwater consumption was inversely correlated with intensity, with less water consumed per unit output by farms (Fig. 5). This was largely due to lower evaporation rates per metric ton of product in the intensive farms, since the production per unit pond surface area was higher than in extensive farms and the grow-out period often shorter. Across all farming systems, freshwater evaporation from ponds was the major reason for freshwater consumption (64% to 100%), followed by agricultural irrigation for feed crop production (0% to 32%). Shrimp farming in ghers was the most water-demanding system, consuming roughly 34 times the amount of water consumed by pangasius farming in ponds, the least water-demanding system per unit of output.

Surprisingly, there was no correlation between land occupation and production intensity. However, the type of land used shifted from direct (aquaculture ponds) to indirect (agricultural land for the cultivation of feed crops) as intensity increased (Fig. 6). For the two least-intensive farming systems—shrimp ghers (68% CI, 349 to 1,293 kg ha⁻¹) and shrimp and rice farms (68% CI, 359 to 1,414 kg ha⁻¹)—pond area accounted for 97% to 98% of overall land use. Conversely, in systems with the highest stocking densities (koi and pangasius farms yielding 20 to 34 t ha⁻¹), a mere 2% to 9% of land occupation occurred at the farm site. In these systems, as much as 76% of the land needed to support production was located overseas, mostly under agricultural production.

Discussion

Our results show that the intensification of aquaculture in Bangladesh is positively correlated with acidification, eutrophication, and freshwater ecotoxicity impacts; negatively correlated with freshwater consumption; and indifferent with regard to GHG emissions and land occupation. This indicates that the intensification of aquaculture has not resulted in escalating consequences across all environmental impacts and may help to reduce certain impacts.

Feed provisioning was the main driver behind most impacts, with the exception of freshwater consumption, which was dominated by evaporation from ponds. Thus, “producing more fish using less feed” would result in some of the largest improvements in the environmental performance of most aquaculture systems. Similar conclusions have also been identified for other types of aquaculture, including salmon in net pens (47), tilapia in cages and ponds (29, 30), seabass in sea cages (48), and shrimp monoculture in ponds (26, 30).

Improvements in feeding efficiency can be achieved by a variety of means, including better feed formulation, use of appropriate feed servings (pellet size and structure), and better on-farm feed management practices (e.g., storage and feeding rates). Minimizing predation, maintenance of water quality within optimum parameters, effective disease diagnostics and access to veterinary advice, and improvements in overall farm management can contribute to improvements in fish survival and, thereby, in feeding efficiency. Adoption of a range of simple management practices that improve farm economic performance thus has the potential to contribute to SI.

Choice of species farmed is one of the most important factors influencing both feeding requirements and survival. Species choice and size also influences edible yield (the portion of harvested product that can be utilized for direct human consumption) and duration of the production cycle. Grow-out times, in turn, govern both methane emissions and water losses through evaporation (49). Aeration technologies promote aerobic digestion of organic material that can reduce methane emissions, but doing so will entail trade-offs with escalating energy demands from fuel for pumps, paddle wheels, and other aeration equipment, and so must be properly evaluated to determine impact (30). Genetically improved strains of fish and shrimp also have significant potential to improve feed conversion rates and overall environmental performance (49).

A general trend for all impact categories is that a proportionately larger share of the environmental impacts occurs outside the farm site as production intensifies, with the distance at which an impact occurs extending initially to other countries and then other continents. Moreover, the consequences of different impact categories materialize at different geographical scales. Global warming acts on a global scale; acidification on a continental scale; and eutrophication, freshwater ecotoxicity, freshwater consumption, and land occupation on a provincial scale.

These tendencies mean that the environmental trade-offs associated with SI often imply spatial burden shifting. Land-scarce countries such as Bangladesh, or ecologically sensitive areas, may be able to export some of their environmental footprints by

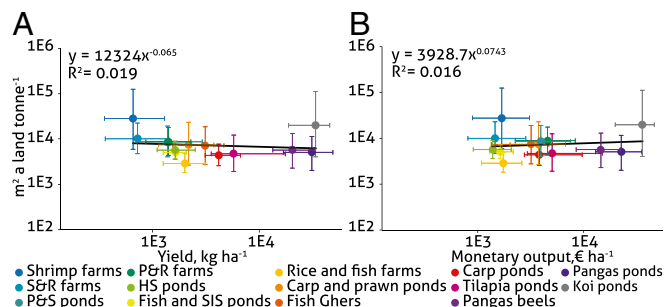


Fig. 6. Median land occupation per metric ton of fish over output in terms of volume per hectare (A) and monetary value (B), including 68% CIs.

intensifying aquaculture production. Ensuring that less ecologically sensitive regions are the recipients of the burden of exported externalities would therefore be an important attribute of SI. For example, it might prove better to raise Asian shrimp intensively on a diet high in soybeans produced in the United States than to farm extensively in coastal zones where ponds often are constructed on highly biodiverse ecosystems such as mangroves and wetlands (50). Noteworthy in this context, however, is that increasing dependency on globally traded inputs may also make food production more vulnerable to volatility in global commodity markets.

The spatial scales at which some intensification impacts occur mean that mitigation measures may have a role to play in achieving SI. For example, the localized consequences of eutrophication could be reduced by discharging effluents in less-sensitive receiving waters, over longer periods of time, or in areas where nutrients can be reabsorbed (e.g., agricultural land or algae farms). Similarly, forms of farming that result in high freshwater ecotoxicity impacts should be avoided in ecologically sensitive areas.

Across the diverse set of species and aquaculture production technologies explored in the present study, environmental impact trends remained consistent as both volume and value of output per unit pond area increased. However, the fate of different products farmed in Bangladesh differs greatly, with most finfish species being consumed locally, while most shrimps and freshwater prawn are exported. Processing and distribution can account for up to 70% of the overall GHG emissions for some exported seafood commodities, meaning that impacts from farm to consumer can differ greatly (30). Moreover, food waste in the distribution, retail, and consumption stages can be particularly high for seafood (51). Food waste differs among species and markets, depending on infrastructure, fillet yield, cultural food preferences, and cuisines. Consumer preferences also influence intensification, as stocking densities and rates of feed application are closely related to the choice of species farmed. For example, if demand for koi or pangasius in Bangladesh increases further, producers are likely to respond by shifting toward more intensive production systems, with implications for the environmental impact profile of the sector.

Consideration of environmental impacts up to and including the point of consumption, therefore, remains an important area for future research. Evaluating individual products at the point of consumption would influence outcomes, especially if alternative LCA methodologies were used. For example, using economic allocation would mean that (high-value) shrimp tails are assigned a much larger environmental burden than (low-value) carp heads. However, although using economic allocation reduced the absolute environmental impacts of carps in our study by between 3% and 75%, depending on the farming system, the relative ranking of the systems changed little (*SI Appendix, Table S28*).

Finally, fish farming has the potential to contribute to the SI of global food systems as a whole, given that many aquatic animals convert agricultural and livestock by-products into edible fish protein more efficiently than terrestrial animals (33). This suggests the need for future research on SI of aquaculture to adopt a more holistic food systems approach that pays greater attention to interactions among the fish, livestock, and agricultural sectors. Moreover, results point to the need to consider the consequences of multiple stressors in order to promote more resilient ecosystems and food production systems. Ideally, this would also include consideration of the social and economic implications of SI.

Materials and Methods

The unit used for scaling when horizontally averaging data influences the dispersions around flows as well as ultimate conclusions (52). For the purpose of the present study, we averaged farm data at one hectare of production in

order to equally reflect the impacts of different species, and used a functional unit of 1 t of whole wet-weight live animal at farm gate.

Primary data for the current manuscript were collected by WorldFish Bangladesh, under the US Agency for International Development (USAID)-funded Cereal Systems Initiative for South Asia in Bangladesh (CSISA-BD) project. A total of 2,678 farmers were selected at random from a farm census covering 15 of Bangladesh's 64 districts, in which the country's highest concentrations of fish farms are located. Farm data were collected between November 2011 and June 2012 using structured questionnaires (*SI Appendix, Tables S1–S9*). A total of 14 production systems were identified during the survey, as described in detail by Jahan et al. (42). A description of the chemical use data (i.e., water and soil treatment compounds, disinfectants, antibiotics, pesticides, feed additives, probiotics, and fertilizers) has been published by Ali et al. (53). No data were available, however, on therapeutic use in tilapia ponds, fish ghers, prawn ponds, and SIS ponds. These systems were excluded from the freshwater ecotoxicity correlation. Data on energy use on-farm were unavailable. This could have resulted in the underestimation of some impacts. Previous research has shown that these emissions can account for between 5% and 22% of global warming impacts at the farm gate in Bangladeshi shrimp and prawn farms (30).

Feed data were collected in 2012 from a survey of 19 commercial manufacturers of formulated pelleted feeds operating across a range of scales, and 10 small "semiauto" mills manufacturing farm-made feeds (43). LCI data for feed resources, electricity production, transportation, and hatcheries were sourced from Henriksson et al. (30), supported by the ecoinvent v2.2 LCI database. Integrated rice production area and inputs were not included in the analysis.

The fate of pond nutrients and sediments was modeled based on nutrient budgets, as described by Henriksson et al. (30), and methane emissions were assumed to be $533 \text{ kg ha}^{-1} \text{ y}^{-1}$ (coefficient of variation, 0.4; lognormal distribution) (54). This estimate is similar to the default Intergovernmental Panel on Climate Change (IPCC) methane emission from rice paddies ($475 \text{ kg ha}^{-1} \text{ y}^{-1}$) (55). Methane emissions and freshwater evaporation rates from aquaculture ponds are, however, strongly influenced by site-specific factors such as temperature, wind, sun exposure, and pond chemistry. None of the production systems in the present study, for example, uses mechanical aeration, something that surely would influence both methane formation and freshwater evaporation from ponds.

Emissions from agricultural fields were consistently modeled in line with the ecoinvent v3.0 guidelines (56) using the Excel template provided as supporting material by Henriksson et al. (30); these calculations build on the IPCC model for dinitrogen monoxide (N_2O) emissions from managed soils (57), the Agrammon model (<https://www.agrammon.ch>) for NH_3 emissions (58), and Nemecek and Schnetzer (56) for NO_x (as NO_2) emissions and phosphorus leaching. Water consumption for agricultural crops was defined by their "blue water footprint" (59, 60).

Global warming potentials were sourced from Myhre et al. (61), eutrophication and acidification potentials from the updated Handbook on Life Cycle Assessment (CML-IA) baseline (62), and freshwater ecotoxicity potentials from USEtox (30, 45). Land occupation was simply quantified as square meters occupied annually (m^2a), and freshwater consumptive use as cubic meters made unavailable for alternative uses (49, 60). Consequently, emissions related to LULUC were not considered.

Given the different characteristics of polycultured aquaculture species, the allocation factor (the fraction used for dividing environmental burdens across coproduced products) exerts a strong influence on the results. In the present study, allocation was solved consistently for all unit processes not part of the ecoinvent v2.2 database (<https://www.ecoinvent.org/>) using mass allocation. This results in each unit of output from a system having identical environmental impact, thereby allowing for comparisons across systems. Results based on economic allocation are presented in *SI Appendix, Table S28*.

Overall dispersions were calculated using a "protocol for horizontal averaging of unit process data" (63). The protocol recognizes three sources of overall dispersions: inherent uncertainty (inaccuracies in measurements and models), spread (variability resulting from averaging), and unrepresentativeness (mismatch between representativeness and use of data) (63). The final life cycle impact assessment results were later propagated over 1,000 Monte Carlo simulations using CMLCA v5.2 (www.cmlca.eu).

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