

Does aquaculture add resilience to the global food system?

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Aquaculture is the fastest growing food sector and continues to expand alongside terrestrial crop and livestock production. Using portfolio theory as a conceptual framework, we explore how current interconnections between the aquaculture, crop, livestock, and fisheries sectors act as an impediment to, or an opportunity for, enhanced resilience in the global food system given increased resource scarcity and climate change. Aquaculture can potentially enhance resilience through improved resource use efficiencies and increased diversification of farmed species, locales of production, and feeding strategies. However, aquaculture's reliance on terrestrial crops and wild fish for feeds, its dependence on freshwater and land for culture sites, and its broad array of environmental impacts diminishes its ability to add resilience. Feeds for livestock and farmed fish that are fed rely largely on the same crops, although the fraction destined for aquaculture is presently small (~4%). As demand for high-value fed aquaculture products grows, competition for these crops will also rise, as will the demand for wild fish as feed inputs. Many of these crops and forage fish are also consumed directly by humans and provide essential nutrition for low-income households. Their rising use in aquafeeds has the potential to increase price levels and volatility, worsening food insecurity among the most vulnerable populations. Although the diversification of global food production systems that includes aquaculture offers promise for enhanced resilience, such promise will not be realized if government policies fail to provide adequate incentives for resource efficiency, equity, and environmental protection.

food portfolio management | crop resources | diversity | shocks | global change

Aquaculture's meteoric rise during the last two decades provokes both optimism and apprehension among scientists and policy analysts concerned with global food security. The cultivation of fish and shellfish ("fish") in terrestrial freshwater and marine systems grew at an annual rate of 7.8% worldwide between 1990 and 2010; a rate that substantially exceeded that of poultry (4.6%), pork (2.2%), dairy (1.4%), beef (1.0%), and grains (1.4%) over the same period (Fig. 1). Aquaculture currently provides roughly half of the fish consumed worldwide (1, 2), and its share is expected to increase in the future as wild fisheries reach or exceed their sustainable limits and as aquaculture technology and management continue to improve. Aquaculture is arguably the most vibrant sector of the global food system. In addition to rapid growth in volume and value, the sector is

characterized by substantial investment in many regions of the world and rapid innovation in the breeding of cultured species, feed practices, and rearing systems. Its future development trajectory is not guaranteed, however. Although aquaculture contributes significantly to the upward trend in per capita animal protein consumption on a global scale, it is increasingly dependent on terrestrial crops and wild fish for feeds, draws on freshwater and land resources for a large portion of its aggregate production, and can be damaging to aquatic ecosystems and fisheries (4–6). Aquaculture thus adds to—but can also diminish—resources that support food security at regional and global scales.

The increasingly tight interconnections between the aquaculture, crop, terrestrial livestock, and fisheries sectors present a critical question addressed in this paper: does

continued growth in aquaculture enhance or undermine the potential of the global food system to meet future food and nutrition security needs in the face of expected and unexpected socioeconomic trends, resource scarcity, and climate change? In answering this question, we examine the role of aquaculture in the global food portfolio and assess its contribution to food supplies and price

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do they simply amplify prior resource, environmental, and social stressors on the global food system?

Aquaculture's future growth and net contributions to resilience will depend on a number of key variables. Terrestrial aquaculture systems, just like agriculture, will be particularly vulnerable to projected shortages in freshwater availability in many regions resulting from human exploitation and climate change (10). Marine aquaculture, although not directly affected by freshwater constraints, will still be impacted indirectly through its dependence on crop-based feeds (11). Ocean acidification from elevated greenhouse gas emissions may threaten shellfish culture throughout the world (12), and over time, may also disrupt the overall function of marine food webs that support the provision of fishmeal and fish oil for aquaculture feeds. The thermal mass of water will likely dampen the acute effects of temperature on marine aquaculture systems from climate change, but freshwater systems are likely to experience rising water temperatures, declining dissolved oxygen levels, and increased toxicity of pollutants (13). For many species, even small temperature changes can have an impact on productivity and managing aquaculture for resilience will require close attention to all of these variables, as well as to evolving disease and parasite dynamics/pressures, heightened storminess (e.g., potential increase in frequency and strength of hurricanes and typhoons associated with climate change), and increased coastal pollution.

A Portfolio Perspective

Modern portfolio theory offers an intuitive framework for gauging the extent to which growth in aquaculture and the diversification of food production systems will enhance the resilience of the food system.[†] The aim of a portfolio approach, used mainly in financial markets, is to invest in a suite of assets (or in this case, food production activities) that collectively has lower risk relative to that of any individual asset. The return of a portfolio is a weighted combination of the assets' returns. Financial investments fundamentally involve a tradeoff between risk and returns (with risk defined as the SD of returns); investors can concentrate their asset bundle, diversify their assets, or substitute one asset for another to achieve their desired balance of risk and return. The degree of risk they face depends on the correlation between the assets' returns. When the returns to

individual assets are negatively correlated, as is the case with stocks and bonds, it is easy to see how a portfolio reduces the overall risk of investments, particularly in a volatile financial market. However, even when the assets are positively correlated—as long as they are not perfectly correlated—diversification can lower the risks for a targeted return.

In applying portfolio theory to developments in the global food system, one might think of the targeted return as the aggregate output of crops, livestock, and fish (wild capture and aquaculture) needed to meet human demands. Risks associated with food production systems involve not only temporary declines in productivity but also extensive or irreversible changes in the natural resource base that can undermine long-term productivity. The risk is captured by the variation and trend in food production and prices, because prices reflect fluctuations in supply and demand.[‡] The degree of food price volatility is indicative of the global food system's resilience to a wide range of stressors, such as pest and pathogen outbreaks, extreme weather events (droughts, floods, temperature extremes), climate variability [e.g., El Niño-Southern Oscillation (ENSO) events], and other market shocks related to changes in the energy and financial sectors or in macroeconomic conditions (7, 17). Over the longer run, price changes reflect the food system's resilience to slower-moving variables, such as freshwater and soil depletion, changes in mean climate conditions arising from elevated greenhouse gas concentrations, and population growth. A pattern of higher and more variable prices over time would suggest deteriorating resilience in world food supplies, whereas a pattern of stable prices would indicate a more robust and resilient system.

Volatility in aggregate food prices depends on variations in crop, livestock, and fish prices and on the correlations among these prices based on interactions in output and input (feed and fertilizer) markets. On the output side, crop, livestock, and fish systems are vulnerable to distinctive pest and pathogen stressors, and the sectors tend to be geographically dispersed. Although yields from individual sectors may be positively correlated in the face of climate change/variation and volatility in energy prices, they are not perfectly so, and yield variation resulting from pest and pathogen outbreaks are not typically correlated between sectors. Product markets are also linked via consumer choice:

a price increase in one commodity (e.g., meat) causes consumption of substitutes (e.g., fish) to rise. The correlates between food sectors are more complex when considering feed inputs for livestock and aquaculture. Given that a large share of livestock and aquaculture systems rely on grain and oil crops for feeds, a jump in these crop prices will lead to a corresponding rise in the cost of cultured fish or meat products, albeit to differing degrees.

Fig. 2 shows the relative fluctuations in price indices for individual food sectors and for food in the aggregate during the period 1990–2013 (18). Cereal and oilseed prices have shown much stronger variation than have price indices for meat, aquaculture, and capture fisheries. Lower volatility in the meat and fish sectors suggests a significant share of substitution possibilities between various animal protein products, as well as substitution of ingredients within the feed sector. Nonetheless, the correlations between the sectors are surprisingly high, ranging from 0.8 (meat and oils) to 0.97 (capture fish and aquaculture). The coefficient of variation for food in the aggregate is 0.33 over the entire period—substantially higher than that of aquaculture, fisheries, and meat (0.16–0.21) but below that of grains and oils (0.4).

What do the data in Fig. 2 suggest about the global food portfolio and the role of aquaculture in this portfolio? First, they show that aquaculture prices, on average, have been less variable than other food commodities and thus appear to add some degree of stability to the global food system. Second, the fact that prices of crops, livestock, and fish products move closely together indicates that the markets are highly integrated. The diversity and substitution among food products, as well as the reliance of the meat and fish sectors on crop-based feeds and also fishmeal and fish oil, will fundamentally determine the risks and returns to the world's food portfolio over the course of the century.

Diversity in Food Products

At the global scale, increasing the diversity of food production activities by adding a robust aquaculture sector can improve the resilience of the world's food system as long as it does not deplete resources or pollute the environment in ways that reduce yields in aquaculture or the productivity of other food sectors. A more diverse food system essentially increases the substitution possibilities in production and consumption, adding flexibility to the system that can help buffer price volatility and improve resource use efficiency. Diversity can be measured at varying levels of

[†]For further reference on portfolio theory, see refs 14–16.

[‡]This analogy would not hold for subsistence food systems or isolated agricultural regions that are not linked to markets.

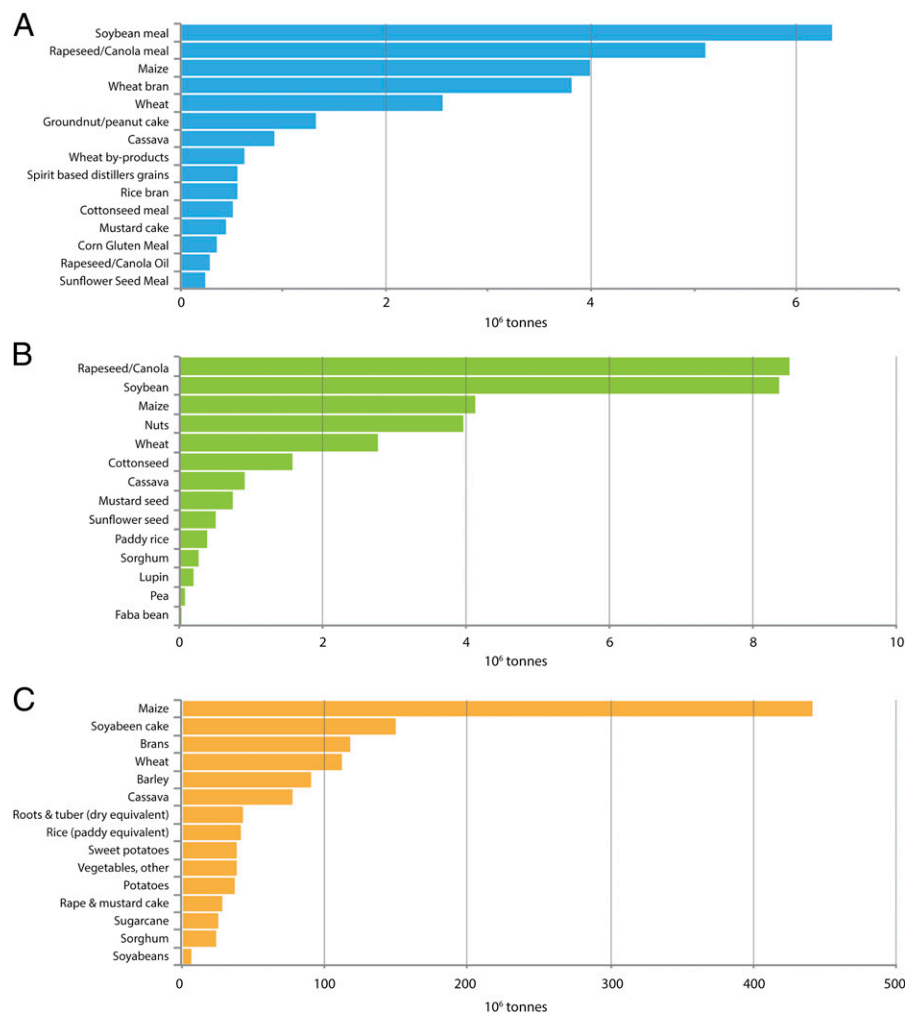


Fig. 3. Global amount of (A) major crop feed ingredients used in aquaculture in compound feeds for fed species, (B) their relative plant equivalents (estimates from ref. 21), and (C) major agriculture products used in all terrestrial animal feeds (3).

on a more limited number of species. Like the crop and meat sectors, the cultivation of fish and shellfish in aquaculture systems is now dominated by ~35 species that together account for 90% of total global production. Four species alone (grass carp, silver carp, indian carps, cupped oysters) account for ~30% of global aquaculture output by volume (2). It is unlikely that these particular species will dominate the aquaculture market in the future, however, especially given current trends in income growth and the rising demand for high-quality fish in emerging economies. Based on the diversity of aquaculture systems overall, price volatility will likely remain lower than that of staple crop systems, as shown in Fig. 2.

Dependence on Feeds

The share of aquatic species raised on supplemental feed inputs continues to rise over time and accounted for almost 70% of total aquaculture production in 2012 (8).

Aquaculture's dependence on feeds, derived from a wide variety of food-quality and human-inedible coproducts from crop, livestock, and fisheries sectors, has important implications for the resilience of the world's food system and aquaculture's contribution to it (Fig. 3). Utilization of diverse feed resources—especially when they differ from those used in terrestrial animal farming or those consumed directly by humans for food—can increase the net returns to the global food system and provide stability by allowing substitution in feed ingredients when supplies and prices dictate. Individual aquaculture species differ in their demand for feed and feed ingredients. For example, mollusk species such as mussels and oysters, which account for ~23% of global farmed seafood production (2), are not fed; instead, they use natural ecosystems for food (e.g., detritus, plankton) that otherwise are not directly exploitable by humans. These filter-feeding species also

help to reduce eutrophication and other threats to coastal ecosystems caused by nutrient enhancement. By contrast, in 2010, up to two-thirds of the world's farmed finfish and crustaceans were dependent on commercial pelleted diets (extrapolated from ref. 3). Because virtually all of farmed fish and shellfish species are cold blooded and physically supported by water, they are more efficient feed converters and have higher edible yields than most terrestrial animals (11, 20).

Energy, protein, and lipids in aquafeeds are currently derived from crops and crop byproducts, wild fisheries (i.e., forage fish) and fish processing byproducts, and livestock byproducts (11). Fig. 3 illustrates aquaculture's global demand for crops that form the basis of commercially produced compound feeds. Aquaculture uses both crop byproducts (coproducts) and food-quality crop products. A large overlap exists between resources used for feeding farmed fish and for feeding terrestrial livestock, with soybeans and maize playing a dominant role (Figs. 3 and 4). The amount of industrially produced feeds currently used by aquaculture is a small fraction (~4%) of global animal feed utilization.[§] The livestock industry is larger than the aquaculture industry and thus consumes a greater share of the world's feeds (poultry, 41.5%; pig, 30%; ruminant, 25% in 2009).[¶] In addition, a significant share of aquaculture production still relies on fertilizer inputs and farm-made feeds to enhance fish growth, particularly in developing countries.[¶] These patterns are expected to change in the future as demand for high-valued aquaculture products, which rely on commercial aquafeeds, continues to grow, and aquaculture production methods in general intensify to improve returns on land and other resources.

Aquaculture's net contribution to global food supplies will depend not only on its food-grade crop consumption and its ability to use agriculture residues, but also on its utilization of wild fish for feeds. The availability of small pelagic fish for aquafeeds—at prices that allow the feed industry to remain economically viable—is likely to decline in the future as many stocks are still overexploited and as more fish are consumed directly by humans for nutrition and pharmaceutical purposes. In addition,

[§]In 2009, the total global animal feed production was roughly estimated to 708 million tonnes (21).

[¶]The volume of farm-made feeds used in the global aquaculture sector is estimated to be in the range of 18–31 million tonnes (22) and is comprised of various locally produced crops, byproducts, and household food wastes. In addition to this are low-value fish/trash fish used as direct feed to aquaculture, estimated as 6–8 million tonnes in China alone in 2008 (21).

Challenges of Managing the Global Food Portfolio

A number of features of the global food system complicate policymaking at the national and international levels. Most important, there is no central decision maker in the global food system; national governments typically intervene heavily in their food and agricultural sectors, distorting international price signals and largely preventing global cooperation (28). Billions of individuals participate in crop and animal production worldwide, and major agribusiness companies influence the direction of production, consumption, trade, and policy within countries. It is virtually impossible to implement a single global strategy, such as reducing animal production/consumption (e.g., as suggested in ref. 29) or replacing inefficient livestock systems with more efficient aquaculture systems. A strategy for the latter needs to be implemented at the national level through market and regulatory incentives, and if done well, it will have minimal negative spillovers to the global food system.

The second challenge involves the responsiveness of food production systems to stressors, including both fast-moving variables such as market price volatility and pathogen outbreaks and slower-moving variables such as climate change. In global financial markets, price signals are almost instantaneous, and adjustments between assets occur quickly. In food systems, on the other hand, it is often difficult for producers to adjust their systems immediately to price signals due to fixed assets (machinery and natural capital) and agro-climatic conditions. In addition, lags may exist between the initial period of resource depletion and the emergence of price signals that flag a decline in crop, livestock, or fish supplies (30). The fundamental dependence of the food sector on natural resources can lead to slow or partial adjustments in the portfolio. Meeting the growing global demand for food by adding new production activities to the portfolio when natural resources are constrained could backfire unless technological innovation and adept management strategies prevail—and this process takes time and foresight.

Third, portfolio theory is largely indifferent to the question of externalities, which, as mentioned earlier, play an important role in all food systems. For example, applying more fertilizers to crops to meet rising feed demands by the aquaculture and livestock sectors is likely to lead to increased nutrient run-off and higher hypoxia rates in coastal ecosystems, thus damaging capture fisheries

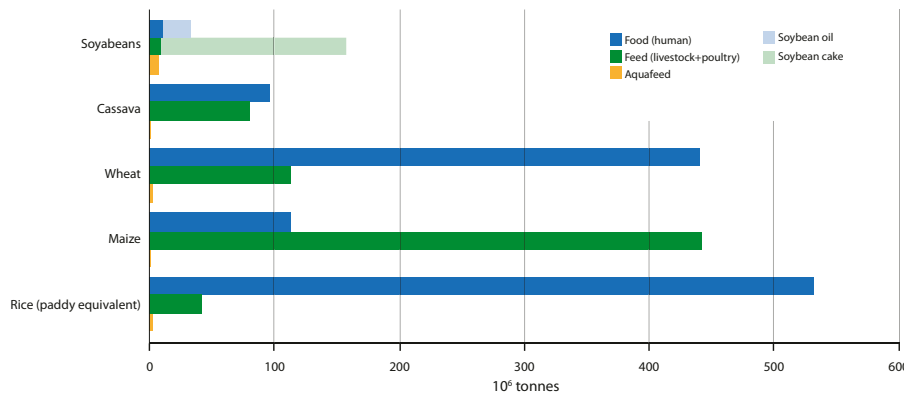


Fig. 4. Five major agriculture items used for animal feeds (for both terrestrial and aquatic culture) and human food according to FAO (1) for feed/food data and aquafeed-plant equivalents (21).

the exploitation of forage fish may be curbed by conservation efforts as awareness about the role and function of these fish in marine food webs continues to grow (5, 23). Meanwhile, as the volume of aquaculture output expands, the use of fish processing wastes for feeds is expected to become more prevalent (6, 11). The development of a feed industry that uses fish processing wastes as a prime ingredient will be a critical factor in augmenting net food supplies from aquaculture.

Overall, the aquaculture sector currently provides more opportunities for efficient transformation of agriculture and fisheries resources (including byproducts and co-products) for human protein consumption than does much of the terrestrial livestock sector (4, 11, 20). Moreover, many of the most pressing challenges associated with typical high-input terrestrial animal production systems are less severe in their aquatic analogs, as measured per unit protein produced (e.g., contributions to greenhouse gas and eutrophying emissions). In some instances, comparable threats do not arise at all (e.g., emergence of novel human disease threats such as bird flu), or if such pressures do arise, they are distributed differently across the globe (e.g., habitat degradation and loss) (4, 24). As a result, substituting terrestrial animal production with selected aquaculture species and systems that use feed and other resources efficiently would increase resilience to the global food portfolio, as long as the latter minimizes environmental impacts and negative spillovers to other food systems. Substitution between meat and farmed fish would depend, however, on consumer tastes and preferences, and at present, the very rapid growth of meat demand (far in excess of population growth) constitutes a challenge.

There currently exists a large diversity of farming systems, both on land and in water, with variable environmental performance and social consequences (4, 6, 25, 26). For example, raising large carnivorous fish species, such as salmon, tuna, and grouper, requires sizable inputs of fish resources, and even the carp-based mono- or polyculture systems in China use significant fish feed inputs (27). Reducing the share of wild fish in feeds is a major priority for the aquaculture industry (driven mainly by prices as other industries compete for supplies), and significant progress has been made in identifying alternative or modified feed ingredients, such as protein and lipid rich crops, yeasts, and microalgae (6, 11). In terms of social outcomes, expansion of aquaculture can offer increased opportunities for both small-holder and waged employment opportunities, particularly in the processing sector. These opportunities will become increasingly important as human settlements continue to crowd the coasts and urbanize. However, the emergence of a competitive aquaculture sector focused on, for example, salmon or cod might also reduce the incomes of local fishing communities targeting those same species. In all of these cases, appropriate government policies are needed to minimize externalities and thus to enhance social and biological resilience. The question is whether such policies can be coordinated across nations to improve food system resilience at the global scale because trade plays a large role in all major food commodity systems, especially the fisheries sector (8). Consequently, careful consideration of relative contributions to local and global-scale impacts will always be needed when forming policies that enable aquaculture expansion.

or aquaculture itself. The fact that most environmental externalities are not priced in the market—and producers therefore have no incentive to internalize the environmental costs of their activities—results in a set of crop and animal production activities that do not necessarily add resilience to global food supplies. The absence of viable markets for fresh water in almost all locations leads to a similar pattern of suboptimal outcomes with regards the resilience of world's food supplies. A portfolio approach provides an intuitive framework for balancing food production activities, increasing overall returns, and lowering risks, but it cannot become operational until these key market failures are addressed, which in turn will require proper institutions (31–33). Until that time occurs, the environmental impacts of aquaculture are likely to be additive—not offsetting—to the widespread environmental stresses arising from crop and livestock production, such as nutrient and chemical pollution, ecosystem destruction and biodiversity loss, greenhouse gas emissions, water depletion, and excessive energy use.

Finally, although not specifically addressed in this paper, it is important to acknowledge that the rapid growth of aquaculture may generate additional equity and distributional effects. Equity is an important social target and inequality effects need to be identified and addressed through appropriate policies and policy instruments, involving policies at both global and local/regional scales, the former being much harder to achieve.

Conclusions

The present diversity of aquaculture systems—characterized by a wide range of cultured species, feed ingredients, and feed practices—contributes important elements of stability to the world's food portfolio. Caution is warranted, however, in concluding that a more diverse food portfolio will enable the global food system to meet the rising demand for protein in the face of climate change, resource scarcity, and other economic and biophysical stresses. As the aquaculture sector develops and becomes more technologically sophisticated and potentially more reliant on fish/crop-based feeds, issues of social inequity are likely to develop in terms of income

generation and access to fish/crops for food (vs. feed). In addition, the ability of aquaculture to add resilience to world food supplies will depend on how the sector develops in terms of species composition, feed inputs, and system design and operation and whether such development can offset the negative externalities associated with existing terrestrial crop and livestock systems (e.g., nutrient loss and greenhouse gas emissions) and capture fisheries (e.g., overfishing). If not designed and managed to minimize environmental damages and social injustices, aquaculture is likely to make the global food system less—not more—resilient.

Nations encouraging aquaculture growth should thus focus on building flexible and heterogeneous production systems that

derive feeds from both food-grade and non-food-grade agricultural products as efficiently and equitably as possible. Such a strategy requires the development of a diversity of aquaculture species; the promotion of coproducts from the crop, live-stock, and fisheries sectors for feeds; the design of infrastructure that uses renewable energy; and the implementation of management practices that minimize wastes and environmental impacts. At the national scale, appropriate policy incentives, proper institutions, and sound industry support will be needed for a flexible and resilient global food portfolio. If the aquaculture industry seeks to dominate the global market for animal protein, it should take a leading role in promoting this strategy of resilience.

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