

AQUACULTURE

Why aquaculture may not conserve wild fish

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We review literature on the displacement paradox and the Jevons paradox, with consideration of their implications for the potential effects of aquaculture on wild fisheries. The Jevons paradox refers to circumstances where improvements in the efficiency of resource use lead to growth in consumption and therefore undermine conservation. The displacement paradox refers to circumstances where increasing use of a potential substitute for a resource (e.g., farmed fish) does not lead to proportionate reduction in consumption of the other resource (e.g., wild fish). The literature on the displacement paradox and the Jevons paradox suggests that there may be unanticipated consequences from the rise of aquaculture that may be detrimental for fisheries conservation. Here, we present theoretical explanations, drawing on the tragedy of the commodity, for understanding the tendencies for these technological paradoxes to occur and emphasize their relevance for concerns associated with fisheries and aquaculture systems.

INTRODUCTION

From a marginal position in the global food system a few decades ago, aquaculture production has become the fastest growing food production sector (1). This considerable ascent has brought aquaculture technology center stage on a variety of socioecological concerns including food security, economic development, and sustainability. There have been many social benefits associated with aquaculture systems and the “blue revolution” (2–5). Yet, there is ongoing debate about the consequences and implications of modern aquaculture systems and the capacity of these systems to produce food in a sustainable and equitable manner.

One important debate centers on whether aquaculture helps reduce overfishing and stresses on the populations of fish and other aquatic organisms. Modern aquaculture production is sometimes promoted as an effective way to decrease pressure on wild fisheries by providing an alternative source of (sea) food, thereby potentially aiding in conservation and advancing marine sustainability while increasing food supply (6–9). As fish populations are stressed by modern capture fishing efforts, industrial aquaculture systems have the potential, at least in principle, to expand food availability for a growing global population while addressing the problem of overfishing of finite fish stocks (10). Fish provide valuable sources of protein and nutrients that are often difficult to obtain elsewhere and are the largest source of protein in many countries in the Global South (2).

Most recently, much attention has been given to novel aquaculture technologies including land-based and offshore systems for advancing sustainable production (11, 12). Corporate actors and environmental organizations with whom they work suggest, for example, that “well-managed offshore aquaculture can help conserve wild ocean resources and provide healthful seafood for a growing global population” (13). Other corporate actors promote the ecological benefits of the technologies that “can lessen fishing pressure” (14). Innovative breeding programs for bluefin tuna are publicized as having potential to “dramatically” increase production through aquaculture “without affecting the wild stocks” (15).

However, similar to many modern food production technologies, aquaculture has a mixed environmental record and concerns abound regarding the way this technology contributes to advancing sustainable food systems (16). Some aquaculture systems have large environmental impacts including high energy use, pollution, overuse of antibiotics, and detrimental effects on local ecosystems and wild fish stocks (17, 18). Most modern industrial aquaculture production is done using fed (rather than passive, unfed) systems (19). The use of wild fish as feed in aquaculture systems has been a long-standing concern (20).

A critical tradition of research has examined the unanticipated consequences of changes in technological, economic, and social systems (21–23). A large body of this research has shown that changes in technological systems can lead to paradoxical outcomes due to the political, economic, and cultural forces that shape their application. In the 19th century, William Stanley Jevons observed that improvements in the efficiency of steam engines led to an increase in coal consumption, identifying what is now referred to as the Jevons paradox (24). Building on this work, York (25–27) identified the displacement paradox based on the observation that potential substitutes for a resource, such as renewable energy for fossil fuels, often do not suppress the consumption of that established resource. This research tradition suggests that we should consider whether aquaculture systems head-off environmental concerns. Aquaculture may, paradoxically, have the opposite effect.

Here, after a brief discussion of the state of fisheries and aquacultural systems, we review the literature of the displacement paradox and the Jevons paradox with consideration of the implications of these paradoxes for the potential of aquaculture to aid in marine conservation, particularly wild fisheries. As part of this review, we present theoretical reasons—drawing on “the tragedy of the commodity” framework (28)—to consider the conservation potential of aquaculture in the context of the current global economic order. The addition of the tragedy of the commodity expands the analytical insights for explaining how and why these paradoxes emerge or persist and thus adds to the capacity to better address them.

AQUACULTURE AND FISHERIES

Fish and other aquatic organisms (hereafter simply “fish”) are playing an increasingly substantial role in the modern global food system

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(29). They are among the most highly traded food commodities, increasing at an average rate of almost 7% per year since the mid-1970s (1, 30). Since the early 1960s, global fish consumption has grown at rate of about 3% annually, which has exceeded human population growth (about 1.6% annually) (1). Total human consumption of fish has almost doubled since 1990, with a 10-fold increase in total economic value. At the same time, according to the Food and Agriculture Organization (FAO) of the United Nations, global fish captures have effectively plateaued since the early 1990s. Some assessments suggest that global fish captures may be in decline (31).

Along with capturing fish, the rearing of aquatic animals in aquaculture systems to produce food has been practiced for millennia (32). In the modern era, aquaculture systems have taken on a variety of production forms. Some are very similar to the earliest methods, while in recent decades, others have developed to use modern technologies. Modern industrialized systems are one form of aquaculture that has an outsized role in the production and trade of aquatic species in today's global food system (5). Accounting for less than 6% of fish production in 1970, production from aquaculture systems (excluding plants) are now equivalent to fisheries captures. If we consider only fish for human consumption, then aquaculture produces more fish than capture fisheries (33). These modern industrial aquaculture systems are often in focus in policy discussions about increasing food production and environmental questions around sustainable development (10, 34).

The received wisdom in the fisheries management literature is that scientifically informed assessments together with sound, well-enforced policy lead toward sustainability in production (35, 36). However, stock assessments, while often very valuable for developing policy and management, have serious limitations, and examples of failures are well-known (31, 37). Further, the Global North/South divide and historical world-system dynamics influence the sustainability potential of global food production and consumption systems (38, 39).

The plateau of global fish captures may (misleadingly) suggest that, in recent decades, pressure and overfishing have been reduced and—coupled with the massive growth of aquaculture production—could be a result of rational management, in part, and the displacement of wild fish by farmed fish. Regulations on fishing together with the promotion of aquaculture—including expanding markets for farmed fish—may advance sustainability. That is, this picture could be seen as “win-win,” where additional technologies are providing the potential for economic growth and fish conservation because of the sustainable modernization of food systems. However, this assessment should be examined further, as the relationship between farmed and wild fish is not so uncomplicated.

Many wild capture fisheries around the world have been under high pressure for decades. According to the FAO, in 2019, more than 35% of assessed global fish stocks were fished at unsustainable levels, i.e., overfished, and only about 7% of fish stocks were “underfished” (1). The largest percentage of fish stocks assessed, about 57%, fell into the category of “maximally sustainably fished.” Fish stocks that are fished at maximum sustainable yield (MSY) are calculated to produce captures that are likely at their limit, above which they could begin to tip into the overfished category. Therefore, they are considered by many policy makers, scientists, and fisheries agencies to be fished to their most economically effective capacity (40).

There is a large body of evidence that marine ecosystems have been substantially damaged by modern fishing (41). There has been

a notable depletion of large predatory fish populations worldwide, and overfishing has led to the collapse of coastal ecosystems (42, 43). Pauly and colleagues showed over 25 years ago that one of the main reasons fish captures could be maintained was by “fishing down marine food webs,” i.e., relying on captures of aquatic organisms from lower trophic levels because higher trophic level species were so depleted (44). Research by Thurstan and colleagues (45) provides an important example of the consequences of this in their analysis of 118 years of bottom trawl fisheries in the United Kingdom. They found that landings per unit of fishing power declined 17-fold over the period examined. That is to say, over time, more and more effort by the fishing industry was required to catch the same amount of fish, a fact that highlights the extent to which the abundance of fish has declined over the industrial era.

That almost all global fisheries are fished at MSY or overfished and that there is robust evidence demonstrating that the depletion of fish communities worldwide indicates that the plateau in wild captures stems from the fact that wild production is quite likely at its ecological limits. That is, this outcome is not primarily driven by the reduction of quotas, better management, or reduction in capture effort (31, 46, 47). When considering the effects of aquaculture on wild fish captures, it should be recognized that substitutability is a complex social dynamic, and even sanguine economists on this issue suggest that there are a “wide range of cases” where the question is “real, interesting, and not foreclosed” (48). Open questions regarding specific cases and the efficacy of efficiency and substitutability for sustainability are good reasons to continue to interrogate technologically focused solutions to multifaceted socioecological problems.

REVIEW

As noted, because of the complex nature of social and ecological systems, the consequences of changes in technologies of production often have wide ranging and unanticipated consequences. In addition, it is important to recognize that the corporations that control industries and production processes have a primary concern with profits, not conservation (49). Thus, technological shifts, such as those associated with the rise of aquaculture, do not necessarily serve to protect ecosystems. Substantial bodies of research have examined the tensions among industries, technologies, and conservation. A large share of this research has focused on energy use, although there are a few studies directly relevant to food production and the aquaculture-fisheries question. Here, we review key aspects from the literature on the Jevons paradox and the more recently identified displacement paradox to highlight insights about potential consequences of the rise of modern aquaculture technologies for marine conservation and sustainable food systems.

The Jevons paradox

The Jevons paradox is one the best-known examples of unanticipated consequences from processes that could, in principle, aid in conservation, but in effect do not. The Jevons paradox is based on the observation that the improving energy efficiency of production processes is often associated with rising energy consumption, which may in part occur because improvements in efficiency make production more profitable and spur further growth (50). The paradox is named for William Stanley Jevons, who, in his analysis of coal use in the United Kingdom, observed that over the course of the industrial

era while steam engines had become continuously more efficient in their use of coal, producing more output per unit of energy, total coal use dramatically increased (24, 50). He argued that this occurred because the rising efficiency of steam engines made them more desirable (more profitable) to industrialists who used them to replace other productive sources, including human and animal labor, and thus dramatically expanded the use of coal powered machines.

The Jevons paradox is part of the more general phenomena of “rebound effects,” which are widely recognized in economics (51). A rebound effect occurs when an improvement in efficiency does not lead to a proportional decline in resource (e.g., energy) consumption. For example, if the fuel efficiency of cars improves by 10% but fuel use declines by only 8%, then there has been a rebound effect. Only when an extreme rebound occurs—where a decline in efficiency leads to an increase in resource consumption—is it a case of the Jevons paradox (sometimes called a “backfire”). There is a vast literature on rebound effects and the Jevons paradox and a number of insightful reviews of this literature (51–58). Hence, we will not attempt a complete review of this literature here, but rather highlight key theoretical insights that may have bearing on the aquaculture-fisheries question. In brief, a large amount of empirical work at multiple scales, from efficiency at the household or factory level to the efficiency of national economies, has shown that rising efficiency is often—paradoxically—associated with rising energy consumption (59). The key question is why this counterintuitive outcome frequently prevails.

The reasons for rebounds can be roughly placed into three categories: direct effects, indirect effects, and economy-wide effects (51, 53, 59). Direct effects refer to the straightforward effect where efficiency improvements reduce costs per unit of consumption and therefore spur consumption (e.g., people may drive longer distances if the cost per kilometer travelled declines due to improvements in efficiency). Indirect effects occur when the money saved from improvements in efficiency is spent on other goods and services (e.g., at the household level, where money saved from driving a more fuel-efficient car is used to help fund a vacation, which includes air travel), which require resources for their production and distribution. Direct and indirect effects are predicted outcomes from neo-classical economic theory and are, therefore, expected. In general, it is assumed that direct and indirect effects explain modest rebounds, but they are not sufficient to explain increasing energy use from efficiency improvements (i.e., the Jevons paradox). Economy-wide effects, a broad category, refer to the variety of ways improvements in efficiency can influence production processes (as with Jevons original example of the steam engine replacing human and animal labor), the development of new industries, and shifts in trade networks and consumer preferences, among other circumstances (57, 60–62). By affecting the types of goods that are produced, the manner and scale of production, the market structure, and consumption patterns, efficiency improvements of technologies can transform economies (as did refinements of the steam engine in the 19th century), expand markets, and entrench high resource consumption industries and lifestyles.

The key lesson from research on the rebound effect and the Jevons paradox that is relevant to considerations of the aquaculture-fisheries question is that technologies transforming production processes, as is done in the rise of aquaculture, have far-reaching and difficult-to-predict consequences, which can be counter to initial expectations. By helping to maintain and expand markets for fish

and other aquatic foods, aquaculture will not inevitably benefit wild fisheries and marine systems. This is a matter of historically specific processes that emerge not only out of economic but also political and cultural conditions and dynamics.

The displacement paradox

Did petroleum save the whales? Following the discovery of petroleum in Titusville, Pennsylvania in 1859, many people assumed that whaling would decline because petroleum could replace whale oil as fuel and industrial lubricant (27). However, global whaling accelerated in the fossil fuel era, partly because fossil fuels powered faster ships and other technologies that made it easier to capture whales and allowed for the development of new production processes and consumer goods that could use whale products (27). Industrial whaling only (mostly) came to an end in the 1980s after many whale species had been so depleted that whaling was typically not economically viable (63). The unanticipated failure of petroleum production to suppress whaling, although it provided a substitute for whale oil, is a prime example of the “displacement paradox”—a circumstance where one resource could in principle be replaced by another but in practice is not (27). The concept was developed out of a political-economic tradition that identified socioecological contradictions in modern economies (25, 27).

The displacement paradox is similar to, but distinct from, the Jevons paradox. The Jevons paradox is about the degree to which efficiency (i.e., resource use per unit of production) reduces overall resource use, whereas the displacement paradox is about the extent to which one resource or system is substituted for (i.e., helps to replace) another one. This paradox was initially named the “paperless office paradox” based on the observation that the rise in electronic storage mediums had not suppressed paper consumption and, in some contexts, was associated with rising paper consumption (25). The displacement paradox has been most explored in the realm of energy consumption. An analysis of time-series, cross-national data found that the use of non-fossil fuel energy only had a minimal effect on national fossil fuel consumption, where it typically required between 4 and 13 units of non-fossil fuel energy to displace one unit of fossil fuel energy (26). A more recent analysis found that since 1990s, there is a trend to rising displacement of fossil fuels by renewables, but the level of displacement remains low (64). Similar cross-national research showed that natural gas does not effectively displace coal consumption (65). A key lesson of this research is that energy sources do not necessarily compete in a simple manner with one another in aggregate and that increasing production of one source may serve to expand energy consumption rather than displace other sources.

Energy analysts Wilson and Zimmerman (66) provide a relevant and illustrative observation about the complexities of energy use in the United States. They note that in 2023, “the nationwide forecast of electricity demand shot up from 2.6% to 4.7% growth over the next five years...and grid planners nearly doubled the 5-year load growth forecast”. This has led some utilities to scrap plans for closing coal-fired plants and propose building more natural gas plants. A central source of the increases in energy demand stems from the growth in data centers, electric cars, and factories producing (paradoxically) materials for solar energy and batteries (67). The broader economic growth imperative tends to have an overriding effect on conservation outcomes and energy transitions. Thus, while alternative energy technologies are increasing, traditional energy supplies are often used to fuel their growth.

While most of the research on the displacement paradox has focused on energy systems, there has been work on food production and consumption. Analysis of time-series, cross-national data on different food sources found that growth in consumption of fish and aquatic invertebrates has not suppressed the consumption of land-based meat. Likewise, the rise in chicken production in recent decades has not appreciably suppressed the consumption of other land-based meat sources (68). There is also evidence of a displacement paradox in organic agricultural production (69, 70).

The research of food consumption and energy use suggests that aquaculture production may not necessarily provide the environmental benefits that some observers expect. To our knowledge, there is only one global-level study that directly assessed whether farmed fish have displaced catches from wild fisheries. Longo *et al.* (71), analyzing cross-national time-series data, estimated the extent to which rising aquaculture production suppressed wild fish captures. Along with fisheries captures and aquaculture production values, the models in the study were specified to hold constant or “control” for factors influencing demand for seafood within nations, such as population and gross domestic product, and statistical methods used to control for temporally invariant factors, such as geography.

Longo *et al.* (71) note that there are challenges with the statistical modeling, partly because wild captures and aquacultural production have wide variation across nations, residuals from the models are not normally distributed, and there are numerous outliers in the residuals. The statistical models they estimated typically had poor fits, unless leverage cases and those with outliers were removed. Of the nine models they present, only one found significant displacement of wild captures by aquaculture and that model fits the data poorly because it did not address outliers or leverage cases. Eight of the nine models, including the ones the authors consider the most appropriately specified, found no significant displacement. They concluded that there is no clear indication that aquaculture had displaced wild captures. More research needs to be done to assess whether aquaculture helps suppress wild captures, but based on these findings, there are good reasons to suspect that there has not been substantial displacement. The use of wild fish as feed in aquacultural system is one obvious reason that displacement may be limited (20, 72). Further, there are social systemic drivers that are shaping production and consumption processes. These processes affect numerous aspects of food and non-food systems, creating dynamics that tend to drive production and consumption upward (73).

A straightforward analysis of FAO data suggests that wild captures and aquacultural production are not closely tied, which lends support to the suggestion that the rise of aquaculture has not significantly suppressed captures (74). We calculated the Pearson's r correlation between the annual change (i.e., first difference, a transformation that allows for focusing on the association between the factors independent from overall trending) in aggregate global tons of aquacultural production (excluding plants) and tons of wild fish captures. If there was a significant negative correlation, then it would suggest that aquaculture may be helping to displace captures. The correlation for 1951–2021 is a nonsignificant -0.192 ($P = 0.108$, $N = 71$). For 1990–2021, the era during which captures (dynamically) plateaued, the correlation is a nonsignificant, $+0.179$ ($P = 0.335$, $N = 31$). Although this is only a simple analysis, it suggests that changes in aquacultural production and captures, at least at the aggregate global level, are socially differentiated processes.

The tragedy of the commodity

The technological paradoxes discussed above have been examined and understood from various perspective including mainstream neoclassical economic explanations to more critical social science perspectives. We further these debates by drawing on a sociological framework called the tragedy of the commodity to offer insights into the social structural processes that influence or shape environmentally paradoxical outcomes. The tragedy of the commodity framework is particularly apt for considering the implications of aquaculture because it was initially developed to understand contradictions in fisheries conservation.

The approach was formulated (75) as a critical response to Garrett Hardin's well-known tragedy of the commons model (76). The tragedy of the commons famously depicted hypothetical herders despoiling commonly held grazing land and has been long considered a useful model to understand and explain the social processes and problems of overfishing. The basic premise of Hardin's model was that users of resources held in common, not owned, would tend to individualize the benefits and socialize the costs. Hardin argued that overpopulation and the propensity toward self-interest will result in the exploitation of commons without regard for the social or ecological impacts. The tragedy of the commons thesis has generated much research and debate over the past several decades, and the controversies are ongoing (77–83).

Alternatively, the tragedy of the commodity emphasizes processes of commodification as fundamental driving forces for understanding and explaining various ecological “tragedies,” including those associated with fish and aquatic systems (28). A notable analytical aspect of the approach lies in lifting the veil of reification (or naturalization) of markets and commodities. In doing so, the analysis can help illuminate some socioecological implications of commodity systems and open distinct interpretations of environmental problems and solutions. A critical analytical shift that the tragedy of the commodity approach provides is to zoom out to a higher level of analysis. Rather than the resource users and other stakeholders—including the governing body or the state—as the central focus of study, the analytical emphasis becomes the historically specific social relations of production and consumption as well as related social structural processes.

Drawing on the tragedy of the commodity framework brings clarity to the reasons behind technological paradoxes by recognizing that larger social structural forces—e.g., political-economic power—are key factors shaping outcomes. For example, the logic of substitution appears quite reasonable and economically rational. To better conserve a resource or aim to stop using a resource (e.g., fossil fuels), it seems sensible to find and produce alternatives as replacements. However, structural drivers associated with commodification processes can subvert expected outcomes. For example, the profit motive and dynamics of market competition and capital accumulation often compel actors and stakeholders to adhere to institutionalized practices that emphasize growth of production and capital returns. That is, there is a powerful and underlying economic growth imperative strongly affecting viable options, decisions, and outcomes (73, 84). Commodification and economic growth are interdependent and reinforcing processes. Considering these social dynamics can help us to better understand the economy-wide effects and the Jevons paradox (57, 62). Efficiency gains can have broad influences on production and consumption, including what is produced and how, the scale of production and markets, and consumer behaviors.

Commodities are goods and services that are sold on a market. Once commodified, the service, object, or organism becomes regulated by the rules and logic of markets. It is well-known that these institutional rules tend to produce a drive toward expanding returns on investments and accumulating capital for further investments, in a cycle of expansion. It is essentially a continuous process of capital speculation, growth, and accumulation, creating a potent political-economic dynamic for growth. In this institutional context, technological systems, such as aquaculture, become first and foremost means for producing commodities. Clearly, the fish they produce are not only commodities. They may have important cultural and personal relevance, and, of course, they are sources of material sustenance for many. However, whether in relation to fish or any other commodity, the primary goal of commodity production is to exchange them on a market and grow and accumulate capital. This distinction is a key factor in this analysis. The drive for accumulation is an essential feature of modern commodity production. Accumulation is not a by-product. It is at the center of the process. Here, the systemic logic that generally guides decision-making, governance, and practice is foremost the logic of commodity production and not typically the logic of conservation or sustainability. The ongoing decline in the percentage of fish populations that are deemed “underexploited” is a broad sign of this logic in practice (1). The very concept of “underfishing” or “underexploited” betrays an assumption that all things, living or otherwise, exist to be commodified.

Because of profit seeking in markets, wild fisheries are fished to the maximum of what is considered sustainably profitable, written into the logic of MSY or maximum economic yield. MSY, which has been guiding fisheries management for many decades, is based on bioeconomic models (40). The concept contends that the maximization of captures produces environmentally and economically efficient outcomes, where lower captures tend to underuse the economic resource and too high captures overexploit, thus potentially reducing its long-term maximum production outputs. The FAO suggests that the stocks in maximum sustainably fished category are “sustainably managed” (1). Yet, these estimates can be interpreted in various ways. For example, populations determined to be fished at the level of MSY are substantially depressed from “natural” levels. Hence, at least some of the populations in this large percentage of global fish populations assessed as sustainably managed could be interpreted as teetering close to a brink, and following this strategy can potentially have long-term negative outcomes for sustainability (85, 86). Since the FAO began assessing these data in the early 1970s, the global percentage of so-called underfished populations has substantially decreased, while the percentage of globally overfished populations has increased.

Ongoing analysis suggests that numerous populations of global fish stocks are in a precarious state (41). Heavy fishing pressure is only one aspect of this concern, albeit a very important one. For example, pollution, climate change, habitat loss, and ocean acidification are also affecting marine systems in ways that threaten fish populations (17, 87, 88). Therefore, the promise of aquaculture production filling the gap, providing a relief valve for fishing pressure and environmental changes, and supplying sustainable aquatic food for a growing global population is, without question, notable and appealing to those concerned about sustainability and marine systems.

As research on the displacement paradox suggests, there are reasons that renewable energy use does not simply displace fossil fuel use or that aquaculture does not straightforwardly suppress fisheries captures. We suggest that this is, in part, directly linked to the fact

that these technologies are essential aspects of systems of commodification. The employment of aquaculture, such as the use of various energy sources or technologies, tends toward adding to the growth of production and supply. This can contribute to the sustainability problems associated with overexploitation or pollution, as the pace of growth outstrips the ecological benefits of efficiency or substitutions. Aquaculture is not tending toward replacing or conserving wild fish globally, but rather adding to the food supplied from marine systems. This may be deemed a positive outcome, i.e., increasing food supply, but that is not the same as sustaining healthy fish populations and marine ecosystems (2, 29).

Commodification of fish, food, and feed

In relation to aquaculture, there are surely also ongoing technical issues that are on the sustainability agenda of many producers, such as those relating to fish-in fish-out ratios (FIFOs), pollution, disease and the use of antimicrobials, and other ecosystem effects. Without question, methods of production, technologies, and substitutions are occurring, which in some instances have improved production efficiencies and limited ecological impacts, as partly suggested by trends in FIFO (89). Nonetheless, there are serious debates and controversies over using the FIFO measure as an indicator of sustainability, so some of the developments should be thoughtfully assessed (90, 91). These improvements are generally motivated by the logic of commodity production, such as reducing costs and losses, and increasing marketability through declarations of sustainable production. For example, an essential motive for substitutions in fish feed—and lower FIFO—is “driven by economic incentives,” i.e., limited supplies of fishmeal and fish oil and increasing costs to producers, along with the growth imperative of the industry (92). Yet, terrestrially based substitutions in feed have resulted in increasing use of plant and land animal sources of protein and lipids that come with their own set of environmental and health concerns, including for the fish themselves (92–94).

Structurally, sustainability goals are systematically secondary, at best, in a commodity system. Note that animal welfare goals seldom fit into this agenda at all, particularly in the realm of fish (95). The institutional dynamic forces of commodification shape the social context, where conservation or sustainability ambitions are structurally overshadowed by profitability, growth, and accumulation of capital, often by large enterprises. Consequently, the ecologically desirable outcomes may or may not be achieved. The tragedy of the commodity framework suggests that there are systematic tendencies toward the latter results, such as the displacement paradox.

Salmon aquaculture is a prime example for illustrating the concerns we discuss. While there have been technological developments in increasing the efficiency of salmon aquaculture, for example, in terms of FIFO, there are important ongoing questions and concerns that can be better understood and explained drawing on the tragedy of the commodity framework. The value of *Salmonidea* production increased fivefold between the years 2000 and 2021 (74). The massive growth of production of this family of carnivorous species is led by the farming of Atlantic salmon (*Salmo salar*). There is vast literature and debate on the costs and benefits of salmon aquaculture (28, 89, 96–99). Industrial aquaculture systems have been essential to making salmon a more common source of protein for many dinner plates, particularly in the Global North. Nevertheless, there is nothing to suggest that salmon aquaculture has had any benefits for the conservation of wild salmon, and there is much evidence and concern

regarding the negative impacts that these aquaculture systems have had on wild salmon populations, including from the spread of disease and genetic mixing of domesticated species with wild populations (100–102). There are also serious concerns about the growth and spread of sea lice in intensive salmon aquaculture, which decimated some salmon farms in recent years, necessitated delousing that can include the use of chemical pesticides (103), and negatively affected wild salmon (104).

From the tragedy of the commodity perspective, we should consider the political-economic forces associated with commodification (marketing, sales targets, profits, corporate subsidies, etc.) in shaping outcomes and how these interact and may contribute to technological paradoxes (28). The productivity growth of salmon and the profitability and capital accumulation for some of the largest seafood corporations in the world have been influential in these processes (96, 105, 106). The modern salmon industry is highly concentrated, capital intensive, and vertically integrated, with a few large companies owning numerous aspects of production and distribution (107, 108). Some of the biggest firms own hatcheries, farms, processing plants, and distributors (107). In Norway, the largest global producer of salmon, the industry has seen substantial consolidation over the past several decades, with a notable reduction in the number of companies along with considerable growth in production (105, 109). The developments in industrial technologies, markets, and infrastructure led by salmon aquaculture systems have been broadly influential in the growth of global aquaculture production and seafood consumption (96, 109, 110).

Promoting production and consumption of salmon from aquaculture has had economy-wide effects (96). For example, detailed analyses of advertising campaigns for salmon targeted in Japan and France concluded that the campaigns directly and indirectly increased consumption of salmon in each market (111, 112). The distinctions between wild, farmed, or eco-labeled sustainable salmon have added another element of commodification, opening additional markets and value premiums. Further, the added availability, through greater production, of salmon in groceries and restaurants has increased the affordability and consumption of salmon, adding to growth (106, 111, 113). Surely, the marked escalation in salmon consumption could not have been met through captures of wild salmon alone. That is, the salmon aquaculture industry has also driven an increase in demand for salmon, rather than having simply met a pre-existing demand.

The fact that these species, and others, are actively fed and reared on diets that contain fishmeal and fish oil remains a major concern. Recent estimates indicate that 11% of wild captured fish are used as feed in aquacultural systems (with an additional 5% going to land-based meat production) (89). Commodified aquafeeds containing captured fish can undermine efforts to reduce the impacts on existing wild fish populations (33). These essential feed inputs originate from whole fish and fish processing by-products. Major sources of fishmeal and fish oil include species of anchovy, mackerel, and sardines, among others. Fish used in feed can often be referred to as “forage fish” and sometimes “trash fish,” the latter term used to describe nontargeted captures that are not easily commodified as food (114, 115). However, fish feed—while sometimes containing various inedible by-products—can contain fish that otherwise could be directed for human consumption (20, 116). Already, so-called trash fish can be a source of food for humans (114). Diverting fish from intensive aquaculture systems, for example, to feed salmon, toward

human consumption could have benefits not only for human nutrition but for marine sustainability (117, 118).

There are ongoing debates about the benefits of aquaculture in the Global South regarding economic development, employment, and as supplying an important source of nutrition (9, 119–121). We suggest that the relationship between farmed fish and wild fish can play out in a manner not unlike other global environmental concerns, more often benefiting wealthy nations in the Global North and adversely affecting poorer and middle-income nations in the Global South (38). Global commodification of fish and the patterns of “unequal ecological exchange” that have emerged have challenged mainstream economic assumptions regarding the benefits of global trade for the marine environment and poorer populations in lower income nations (38, 122, 123). For example, the top producers of fishmeal globally are Peru, Chile, and Thailand, which—depending on the year—can make up about half the total global production (115, 118). In the largest seafood market, the United States, the top three species sold by volume and value are shrimp, salmon, and tuna, the majority of which are imported (113). Most of the shrimp and salmon consumed in the United States originates from aquaculture production and are reared on a diet that contains fishmeal and fish oil. Marine resources are often drawn from the Global South to supply the wealthiest markets (30), which sometime involves turning so-called forage or trash fish into high-value commodities.

The global food market dynamics that have been dominated by wealthy nations and large corporate actors have resulted in numerous tragedies of the commodity, including marine ecological degradation and severe labor exploitation (122, 124, 125). In the Global South, aquaculture production's contribution to domestic fish consumption is still “relatively insignificant” (126). Much industrial-scale aquaculture in the Global South tends to produce high-value species that are either destined for export to wealthy countries or affluent urban populations within the Global South (120, 127). When we consider the effects of the broader social relations of production, it is unlikely that increasing commodification of fish through aquaculture production (or other means) serves to increase availability of fish for poorer populations, particularly if low-value fish continues to be diverted into aquaculture production, and industrial fishing operations continue to deplete fisheries in the Global South.

Technological paradoxes and marine sustainability

We examined the scholarly literature on the paradoxes of technological changes, explaining the Jevons paradox and the displacement paradox, to help better understand the implications of aquaculture for marine sustainability. Central to our review is a concern with providing theoretical insight into why technologies often have unanticipated consequences. We offered the tragedy of the commodity framework as a way to highlight processes in the seafood sector that led to overexploitation. We provided a brief overview of research on the Jevons paradox, where improvements in efficiency can lead to rising resource consumption, and the displacement paradox, where a newly developed or deployed resource or technology (e.g., renewable energy or farmed fish) that could in principle replace an ecologically problematic source (e.g., fossil fuels or captured fish) does not in practice suppress consumption of it. The tragedy of the commodity framework elucidates why there is a tendency toward the lack of displacement, since it highlights structural dynamics; for example, how commodification is interconnected with processes of growth and capital accumulation.

Of course, technological paradoxes are not inevitable and, no doubt, not universal. Rather, they occur as a result of and in relation to existing social (particularly economic) structures. One important avenue for future research is to assess the contexts in which displacement is more or less pronounced. From a sustainability perspective, it is useful to examine how various existing and potential policy options can be deployed to help facilitate higher rates of displacement. A key lesson from this area of research is that we cannot simply rely on developing innovative methods of production or “green” commodities to lead to conservation or sustainable outcomes through market-based logic. It is essential to actively work on different societal levels—including outside of commodification systems—to directly suppress ecologically harmful practices (e.g., burning fossil fuels and overfishing).

Aquaculture systems will play an important role in developing sustainable food systems. The ways in which they will and the forms that they will take are not clear cut or predetermined. The discussed technological paradoxes and the tragedy of the commodity approach underscore that it is necessary to identify powerful background social structural forces that create the contextual conditions of production and consumption along with the potential for sustainable aquaculture systems. This assessment suggests that—along with sustainability management, governance, and innovations—social movements and civil society organizations that play a role in de-commodifying food systems, through for example emphasizing the human right to food and environmental justice, are useful avenues for addressing the types of problems we have discussed here. Therefore, rather than concentrating on technological improvements, efficiencies, and markets, efforts to promote sustainable aquaculture should first directly focus on ecosystem health and contributing to the well-being of food-insecure and poorer communities, especially in the Global South.

MATERIALS AND METHODS

The FishStatJ: Universal software from FAO Fisheries Division, Statistics and Information Branch for fishery statistical time series (2024; www.fao.org/fishery/en/statistics/software/fishstatj) was used.

Supplementary Materials

This PDF file includes:

Table S1

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