nature sustainability

PERSPECTIVE

https://doi.org/10.1038/s41893-020-0540-7

Sustainable commoditization of seafood

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Debates on seafood in the Global South tend to prioritize food security, whereas debates on seafood in the Global North emphasize sustainability. We track the evolution of both debates and propose the concept of 'sustainable commoditization' to reconcile them. We identify three pillars of action that are necessary for sustainable commoditization of seafood in the Global South, namely: (1) sustainable intensification; (2) supply chain transformation; and (3) supporting policy and regulation. We believe that the concept of 'sustainable commoditization' is applicable well beyond the seafood sector and is especially relevant for agriculture and forestry more generally.

Development of seafood (fish and other edible aquatic animals) supply chains and product cycles has occurred at different rates in the Global North and Global South. The literature reflects the lagged pattern of development across the two regions. Broadly, debates on role of seafood in the Global South tend to emphasize food security[1–3], whereas debates on seafood consumed in the Global North—where adequate food security in an aggregate sense has already been reached—tend to give more weight (compared to the South) to sustainability concerns[4–6]. Recently, there has been a partial convergence of these debates around the theme of sustainable intensification[7–9].

The sustainable intensification literature has a strongly productivist focus, centred on identifying more efficient forms of production. We contend that sustainable intensification is a necessary but not sufficient condition for the development of food systems that sustainably address Southern food security. These cannot emerge without the co-development of supply chains and public and private regulation that create and transmit demand for safe and sustainable seafood, deliver inputs and technology to producers, and move product to consumers. We propose the concept of 'sustainable commoditization' to capture this dynamic.

Our sustainable commoditization perspective is based on three premises: (1) food systems in the Global South will continue for some decades to focus on commoditizing food (making it more abundant and cheaper) to meet rapidly growing demand; (2) growth will create sustainability challenges in the form of negative externalities that undermine future food production; and (3) it will be necessary to address a dilemma; the need to combine rapid increases in production with the development of supply chains to deliver food to consumers in urban and rural areas, while addressing sustainability challenges.

We use the seafood product cycle and supply chain to illustrate the dilemma of sustainable commoditization. The product cycle is the movement over time of a product category from niche, to commodity (cheap and in bulk, standardized), to differentiated (with distinctions over levels of quality, safety and sustainability)[10]. Supply chain evolution follows a path from traditional (local, fragmented, with extensive production systems), to transitional (longer spatially but fragmented and with production in each segment of the supply chain technologically intensifying), to modern (consolidated, coordinated and intensified)[11].

Seafood supply chains and product cycles have undergone particularly rapid and profound change from the 1900s (Global North) and 1960s (Global South). The speed and visibility of these transformations and their environmental impacts have given rise to lively popular, scientific and policy debates in the North around the environmental impacts of seafood production.

Northern debates about seafood sustainability have arisen in a context of 'post-commoditization'. Many Northern supply chains are 'modern'—that is, consolidated, technologically advanced and with high levels of traceability and regulatory institutions. This stage of development corresponds with a point in the demand side of the product cycle focused on differentiated products that embody food safety and environmental sustainability characteristics. In contrast, most Southern seafood supply chains are at a transitional stage of development, characterized by a fragmented structure, technology in flux from extensive to intensive, and absent or nascent public regulatory standards and enforcement. Southern seafood product cycles tend to be dominated by commoditization: the drive to produce more fish at lower cost for the rapidly expanding markets in Southern cities where most seafood is consumed[12].

In keeping with these patterns of development, debates around seafood sustainability have centred primarily on sustainability attributes demanded by actors in the Global North, and the institutions and technology required to supply them[13]. Emphasis in the South has been primarily around sustaining productivity and volume growth toward commoditization—often referred to in terms of a 'blue revolution'[14]. The North's environmental sustainability concerns have been a comparative sidelight in Southern policy debates, except where they threaten producer access to Northern markets[15].

In the first half of this Perspective we track the evolution of the seafood sustainability debate through the lens of staggered product cycles and supply chain transformations in capture fisheries and aquaculture in the Global North and the Global South. In the second part, we contend that, under certain conditions, supply chain and product cycle development can support sustainable commoditization in the South's seafood sector. We emphasize three pillars that are necessary for this to occur, namely: (1) sustainable intensification; (2) supply chain transformation; and (3) supporting policy and regulation.

Seafood sector evolution in the North and the South

The following subsections address the historical march of the seafood product cycle and the debate in the Global North and South.

Commoditizing fisheries in the North and South. Marine capture fisheries underwent a phased process of supply chain

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industrialization and product cycle commoditization over the course of the twentieth century, beginning at the turn of the century in the Global North. Similar processes played out later, and over a more compressed timeframe in the South, starting with North–South technology transfer post-World War II (WWII).

First, in the North, industrialization began with the introduction of steam-powered fishing vessels from the late nineteenth century, and diesel-powered vessels from the 1930s. Subsequent technological innovations—including better boat and net designs, mechanical winches, fishing gears made with synthetic fibres, radar, sonar and global positioning systems—extended the distance and duration of fishing trips and enhanced the efficiency with which fish could be located and caught[16,17].

Concurrent improvements in canning, freezing and refrigeration, and transport and logistics improved fish preservation and extended the distance over which chilled or frozen products could be traded, contributing to the globalization of seafood markets[16,18]. These developments gave rise to new commoditized product forms (for example, canned tuna, readymade 'TV dinners' and frozen fish fillets)[19]. In the food service industry, technological change (for example, pressure oil cookers) and product innovation (for example, breaded fish sticks) contributed to the rise of a mass market for fish[20].

Industrialization and commoditization of fisheries in the Global North were hastened by government policies promoting fisheries as a vehicle for national food security, trade and economic development[21]. Increases in fishing efficacy and effort led to the overexploitation of successive Northern stocks (for example, Californian sardines in the 1940s; North Sea herring in the 1960s; Northwest Atlantic cod in the 1980s and early 1990s), pushing the frontier of marine fisheries progressively further outward, from coastal areas, to offshore, to the high seas[16,17].

Second, in the South, Northern fishing technologies were transferred to newly independent nations after WWII through development assistance programs, and Southern governments promoted fisheries development for domestic food security and international trade[22]. This resulted in industrialization, commoditization, spatial expansion and biological overexploitation of Southern fisheries, similar to that experienced in the North, but occurring on a compressed timescale due to the transfer of existing technology[17].

Third, a confluence of factors contributed to demand for increasingly commoditized forms of seafood, beginning in the North over the first half of the twentieth century, and accelerating from post-WWII to the 1970s, and in the South from the 1980s–1990s onwards. These drivers included urbanization, increasing affluence and Bennett's Law (that is, a statistical regularity that the share of food expenditures on non-staple foods grows disproportionately with income, leading to diet diversification). The entry of growing numbers of women into the workforce also increased women's opportunity cost of time, creating demand for convenience foods such as frozen 'fish fingers', paralleling the rise of other mass-produced convenience foods such as the hotdog[20].

Northern demand for Southern commoditization. In the North, concerns about the sustainability of marine fisheries' commoditization and demand for fisheries regulation and management grew from the 1970s, as successive stocks became fully exploited or collapsed. Growing awareness of impacts on charismatic megafauna such as dolphins, albatrosses and sea turtles also spurred Northern demand for marine conservation[23]. Research has continued to draw attention to the detrimental impacts of industrial overfishing since this time[24–27], contributing to the development of increasingly sophisticated fisheries management and conservation strategies[28].

The rise of large processors, food service chains and supermarkets in the North from the 1970s led to the transformation of seafood supply chains from transitional to modern, and concentration in midstream and downstream segments, paralleling changes in the broader food system[29]. These changes occurred at the same time as biological limits to the expansion of Northern capture fisheries were being reached or exceeded, prompting two sets of supply responses.

First, fishing activities were outsourced to the Global South by licensing fishing rights in the exclusive economic zones of Southern countries to Northern industrial fleets[30,31], and intensifying imports of fish from transitional capture fisheries supply chains in the South[32]. Second, aquaculture developed as an alternative source of commoditized seafood in some Northern countries (for example, Atlantic salmon in Norway, channel catfish in the United States), transforming former 'niche' products sourced from capture fisheries in relatively limited and seasonal volumes into commodities available year round[33].

Northern demand for shrimp arose during this period as a response to excess demand, and as a further phase in the product cycle toward product differentiation. Demand for shrimp induced a supply response in the fisheries of the Global South, where fishing of shrimp for export intensified. Simultaneously, technological breakthroughs enabled the take-off of farmed shrimp production in Taiwan during the 1980s[34]. Shrimp production was subsequently outsourced to Southeast Asia, where demand from a rapidly growing Japanese economy propelled a farmed shrimp boom[35] and prompted the emergence of transitional supply chains.

Southern commoditization and aquaculture's rise. The closing frontier of capture fisheries expansion during the 1980s in countries such as Thailand, China and Indonesia coincided with increasing domestic seafood demand, prompting concerns about seafood security. As in the North decades earlier, Southern demand growth was driven by the confluence of urbanization, rising incomes, changing opportunity costs of time and Bennett's Law. Pressure to raise volumes and lower costs of seafood supply was again achieved, where possible, by further intensification of capture fisheries exploitation (including geographic expansion of fishing effort to the waters of less-developed Southern nations), and promotion of aquaculture.

A mix of indigenous Southern innovation, technology transfer through overseas development assistance, and foreign direct investment, drove rapid technological change in Southern aquaculture from the 1980s onwards[36]. Uptake of formulated feeds and the translocation of hardy, fast-growing fish and shrimp species around the globe contributed to the intensification and expansion of production.

Farm-level innovations and nascent commoditization were matched by transformation in the off-farm segments of Southern supply chains; from traditional, to transitional and, latterly, to emerging modern stages. This transition resulted in a 'quiet revolution', characterized by proliferation of non-farm enterprises providing inputs, logistics, trade, other services and associated innovations, contributing to the lengthening of value chains upstream and downstream of the farm[37,38]. Simultaneous changes in Southern food service and retail diversified the product forms (for example, frozen, prepared and precooked) and food environments (for example, informal vendors, restaurants, supermarkets and convenience stores) in which seafood was purchased and consumed, contributing to the commoditization of demand[39].

Contrary to conventional wisdom[2], growth in the supply of seafood for Southern domestic consumption has dwarfed Southern seafood production for export. For instance, in ten of the most important Southern seafood-producing nations, responsible collectively for 87% of total global aquaculture output, domestic markets utilize 89% of seafood originating from aquaculture and 78% of seafood originating from capture fisheries[12].

Northern concerns for seafood sustainability. Northern demand for seafood with traits including quality, variety, safety and sustainability emerged following the fulfilment of demand for cheap and

plentiful 'bulk' seafood by domestic commoditization and outsourcing production to the South. This development represented both a reaction to negative environmental externalities (costs of production not fully internalized by producers) associated with the first waves of commoditization, and a progression of the product cycle toward differentiation as a means to stimulate further demand. Over time, Northern environmental concerns have evolved from their initial focus on the sustainability of seafood produced in the North to encompass seafood originating from the South, creating pressure for Southern exporters to produce seafood differentiated along sustainability lines.

Environmental movements began to induce regulation as early as the 1970s, giving rise to increasing state-led regulation of Northern fisheries based on stock assessments and management instruments such as total allowable catches. These approaches were later augmented by 'rights-based' mechanisms such as individual transferable quotas, claimed to provide economic incentives for better stock management[33]. These efforts have yielded mixed results and have been criticized for driving industrial concentration and the exclusion of small-scale fishers. Successful rebuilding or maintenance of stocks at or above maximum sustainable yields has occurred in certain fisheries, particularly in the United States, Australia and New Zealand[28]. Considerable management failures also exist however, notably in the European Union (EU), where short-run political objectives have often resulted in setting harvests at unsustainable levels[40,41]. However, the EU has used trade rules to combat illegal, unreported and unregulated fishing among Southern trading partners[42]. These regulations have also been used to leverage improvements in working conditions in fisheries supply chains[43].

Aquaculture supplying Northern markets has attracted close scrutiny. Research and non-governmental organization (NGO) campaigns from the 1990s onward have highlighted a host of negative environmental externalities, pertaining particularly to (mainly Northern) salmon and (Southern) shrimp. These include: exploitation of marine forage fish to produce feeds[44,45]; mangrove destruction[46]; transfer of parasites and disease from farmed to wild fish[47,48], escapees and invasive species[49,50]; antimicrobial use[51]; and water pollution[52].

Particularly in the North, these concerns have stimulated state-led regulation (for example, zoning, restrictions on farm siting, water quality standards and food safety standards), though these efforts have not always been successful in preventing events such as fish escapes or sea-lice outbreaks[48]. Northern sustainability concerns have also encouraged the search for technological solutions, such as substituting novel feed ingredients such as insect meal or microalgae for fishmeal in feeds[53] and moving fish farms offshore to mitigate point source pollution[54].

Third-party standards and certification, supported by coalitions of NGOs, retailers and the seafood industry, emerged as an alternative mode of sustainability governance for fisheries and aquaculture in the 2000s and 2010s[55]. Sustainability certification has expanded considerably since this time, but is limited mainly to Northern markets, where most demand for products differentiated along sustainability lines is concentrated, and has proven hard to implement in the context of fragmented transitional production and supply chains in the South[55–57]. Recent estimates suggest that just 6% of global seafood production is certified[58].

Emerging Southern sustainability concerns. The Global North consumes only 30% of the world's fish[32]. Global seafood supply is predicted to double by 2050[59], and the Southern share of global consumption is set to increase further, with almost all the additional supply coming from aquaculture. Market signals from the South are still mainly for the commoditization stage of the product cycle, meaning that most demand is for low-cost seafood, delivered in bulk, all year round. A central issue for the sustainability of global seafood supply over coming decades is therefore whether, and how quickly, Southern commoditization can become sustainable.

Some convergence is already occurring between the Global North and upper-middle-income Southern countries (for example, Thailand and China), where demand for products differentiated along food safety lines is emerging, and increasingly supplied through modernizing supply chains[60]. State-led environmental regulation in these same countries is beginning to address some of aquaculture's environmental externalities, such as point source pollution from farms[61,62].

However, just as the North 'exported' much of the environmental burden of seafood commoditization to the South, upper-middle-income countries are beginning to outsource parts of their production to lower-income countries. This may result in foreign direct investment from higher- to lower-middle-income Southern countries, aimed at accelerating the latter's move from niche to commodity stage, and allowing the former to import cheap commodity fish, much as has already taken place through earlier rounds of North–South investment and technology transfer.

The three pillars of sustainable commoditization

In the previous section, we contend that the centre of gravity of the seafood sector is in the Global South, and that the great majority of its production is in the commoditization phase of the product cycle and is expanding rapidly. Total fish supply is predicted to increase from 154 Mt in 2011 to 186 Mt in 2030, with the largest expansion expected in India, Latin America and the Caribbean, and Southeast Asia[63]. Africa sits at the early part of an S-shaped curve for diffusion of aquaculture and will probably see substantial growth if predictions of the emergence of a large middle-class driving demand for animal source foods prove correct[64]. This phase of development brings with it the risk that unsustainability will grow over time[41], replicating crises already experienced in the North and parts of the South. However, growing affluence in the Global South may also increase demand for sustainability and reduction of externalities, impelled by the logic of the Environmental Kuznets Curve (a hypothesized relationship under which some forms of environmental degradation first rise, and then fall with increasing income per capita[65]), and the march of the product cycle.

In order to fulfil its own food security needs and meet growing food safety and sustainability demands (from the North and, increasingly, from its own modernizing markets), the South will need to enter a phase of sustainable commoditization. We propose three pillars of action to support sustainable commoditization in the South. These are illustrated in Fig. 1.

We conceptualize sustainable commoditization as a pyramid comprised of three linked components or triangles: (1) sustainable intensification; (2) supply chain transformation; and (3) policy and regulation. The goal of sustainable intensification is to increase output and production efficiencies simultaneously, while reducing negative externalities. Both policy and regulation and supply chain transformation are necessary to create the conditions under which sustainable intensification can occur. Policy is required to deliver public goods such as education and infrastructure, while regulation provides the basis for environmental, worker and anti-trust protections. Effective policy and regulation create requirements and foster innovations that support sustainable intensification and supply chain transformation. Supply chain transformation reduces transaction costs and risks, facilitating the development and application of technical and institutional innovations that increase efficiencies and output, thereby lowering consumer prices. Supply chain growth is essential for inclusion, creating employment and opportunities for seafood producers and supporting enterprises, and linking them to consumers to ensure food security. In the following subsections, we elaborate the characteristics of each triangle in relation to the current and future supply of seafood.

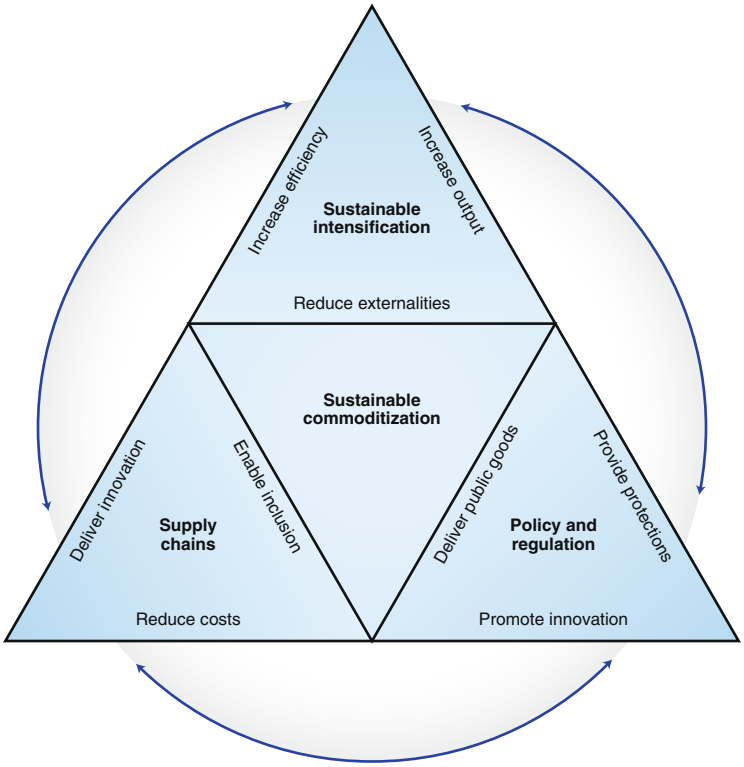

Fig. 1 | The triangle of sustainable commoditization. The triangle is formed of three pillars required for sustainable commoditization: sustainable intensification, supply chains, and policy and regulation.

Sustainable intensification. We address sustainable intensification in capture fisheries and aquaculture separately in recognition that, broadly speaking, wild fish are naturally reproducing common pool resources and farmed fish are artificially propagated private property, necessitating different institutional and technical strategies. We further differentiate between capital-intensive and small-scale fisheries.

Sustainable intensification in capital-intensive (large-scale) Southern fisheries will require enhanced regulation and management of stocks that are already highly commoditized, such as tunas and Peruvian anchoveta, to ensure that sustainable levels of fishing can be maintained over the long run, and to induce improvements in labour standards[66]. Technological advances have potential to increase the efficacy of fisheries monitoring, control and surveillance (MCS) systems, which have historically been weak in most Southern countries[67]. Better MCS can also reduce illegal fishing by foreign vessels in the exclusive economic zones of Southern nations. Recent advances in the species selectivity of fishing gears deployed in Northern fisheries aimed at reducing bycatch may also have applications in the South[68]. However, implementation of such technical solutions is heavily dependent on the effectiveness of governance structures, which are often weak.

Small-scale capture fisheries employ 90% of the world's fishers and are overwhelmingly located in the Global South, where they serve important welfare and food and nutrition security functions[69]. Intensification and/or commoditization in small-scale fisheries runs the risk of creating socially and ecologically undesirable outcomes (indeed, many sustainability challenges in fisheries are the outcome of increased scale and intensification of fishing effort). Nevertheless, small-scale fisheries account for approximately half of the world's fish landings[69], meaning that they have the potential to create externalities that are large in aggregate. Moreover, excluding small-scale fisheries from sustainability debates risks marginalizing them by locating industrial fleets at the centre of sustainability discussions.

The principle challenge for sustainable commoditization in small-scale fisheries is to enable what we term 'inclusive upgrading'. This will require institutional innovations that allow for improved practices, environmental performance and collective economies of scale, without causing consolidation and dominance by large firms. Modernization of some segments of small-scale fisheries supply chains (for example, processing and logistics) may help to improve food safety and reduce food losses[69]. Integration of sustainable management with marketing that emphasizes the unique nature of small-scale fisheries products may present opportunities for 'leapfrogging' from niche to differentiated production in certain cases, with precedents in some high-value small-scale fisheries in the Global North[70].

We take as a given that fish demand will continue to grow for decades in the Global South, and that future expansion of seafood supply will rest primarily on aquaculture[63]. Existing configurations of aquaculture will be inadequate to meet that additional demand sustainably, due to the increasing burden of resource use entailed. If growth is to occur sustainably, negative externalities will need to be reduced at the same time as production is intensified and scaled-up to meet demand for fish from Southern consumers at affordable prices.

Environmental externalities experienced in the immediate vicinity of farms (for example, mangrove conversion and water pollution) are the main targets of most state-led environmental regulation and private standards for aquaculture. Although these externalities are important, Life Cycle Assessment (LCA) studies consistently find that feed provisioning is the main driver of environmental impact across most impact categories and most production technologies, due to dependence on tele-coupled ecosystem space and services[71]. This means that innovations that enhance feed-use efficiency will result in the largest improvements in environmental performance in most aquaculture systems[8]. Enhancing resource-use efficiency in

aquaculture while enabling output gains will require research and development (R&D) of new technologies that reduce, optimize or change the nature of external input use. We outline some of the most important of these in the following text of this subsection.

Genetic improvement, via domestication, selective breeding or genome editing, will play a key role. Only 30% of the 250 species of fish currently farmed worldwide have undergone basic domestication, and only 12% have been the subject of any type of selective breeding program[72]. Aquaculture lags far behind agriculture and animal husbandry in using selective breeding to improve the biological efficiency of production. Fish selected for faster growth by selective breeding often display improved feed conversion and higher survival, leading to more efficient utilization of feed inputs[73]. Genome editing using CRISPR-Cas9 (clustered regularly interspaced short palindromic repeats—CRISPR associated protein 9) is a rapidly developing field that opens a range of further possibilities for genetic improvement, for traits including growth, disease resistance and production of 100% sterile fish to prevent interbreeding with wild stocks[74].

Improved fish feed formulations have the potential to improve feeding efficiency and radically alter dependence on raw material inputs. Novel feed ingredients including insects, algae and seaweeds are recognized as potential substitutes for conventional marine (fish meal and fish oil) and terrestrial feed ingredients, may be produced with substantially lower environmental impacts than conventional ingredients, and are an important area for ongoing R&D[75]. Innovations in feed formulation have already enabled major improvements in the efficiency of marine ingredient use for farmed salmon[76]. However, substitution of terrestrial for marine feed ingredients can generate other environmental burdens, including increasing demand for freshwater, land and phosphorus[77].

Improved farm management can enhance feed utilization efficiency. 'Precision aquaculture' is an emerging field that combines sensors, artificial intelligence and automation to increase productivity, yield and environmental sustainability while improving fish health and welfare[78]. Sensors can be used to continuously monitor biological and environmental parameters, generating data that can be interpreted using artificial intelligence or predictive models to support decision making, while automation (for example, of vaccinations, feeding, sampling, grading or harvesting) can increase accuracy and reduce stress experienced by fish.

Supply chain transformation. Technological innovation is necessary but not sufficient for sustainable commoditization to occur. Supply chains transmit signals demanding, or providing incentives for, farmers, fishers and other supply chain actors to make technological investments needed for sustainability and to deliver seafood to low- and middle-income consumers in the South at affordable prices. Supply chain transformation is required to: (1) create new livelihood and business opportunities for producers and enterprises; (2) develop and supply sustainability-enhancing technologies at scale and at affordable cost; and (3) reduce transaction and production costs to offset the costs of internalizing externalities and ensuring traceability.

There are two branches of this development of seafood supply chains in the Global South. On the one hand, there has been a proliferation of small and medium enterprises (SMEs) providing goods and services such as feed, equipment, hatcheries and nurseries, ice, wholesale trading, logistics, processing and retail, as documented in countries including Bangladesh[38], Myanmar[79] and Nigeria[80]. This quiet revolution in the 'hidden middle' of seafood supply chains (evident in both capture fisheries and aquaculture) is massive in terms of the aggregate scale of investments, and essential to driving the expansion of seafood production and distribution to consumers, but is largely overlooked, particularly with respect to its sustainability implications[81]. The enabling environment for the development of these enterprises, which link fishers and farmers to input and output markets, increasing ease of market entry and lowering transaction costs, is crucial for commoditization.

On the other hand, while SMEs are the mainstay of transitional supply chains connecting rural areas in the South to cities, they lack the organization and institutional impetus, coordination and R&D capacity needed to drive major sustainability gains in supply chain, fishing and farming practices. The scale of these investments and the nature of the coordination challenges involved will require the engagement of large companies in modern supply chains undertaking activities such as breeding programs, feed milling and processing and distribution. For example, investments by Charoen Pokphand in Thailand in selective breeding of white-legged shrimp, feed development, and research on pond design and management, have allowed the company to deliver and maintain consistently high yields despite disease epidemics, while reducing use of marine ingredients in feeds[7].

Large enterprises have buyer leverage in supply chains to require, via private standards and contracts, the adoption of sustainability and safe handling practices by farmers and intermediaries. For example, by committing to use only sustainably sourced fish, 'lead firms' such as Walmart and McDonald's have created demand for certified fisheries products in the United States[82,83]. A Southern company, Thai Union, the world's largest producer of canned tuna[84], has recently made similar commitments[85]. Large enterprises, including those in the South, have the capacity to make investments in post-harvest handling and processing, with food safety, energy efficiency, and cost competitiveness relative to traditional supply chains. The challenge accompanying the supply chain-changing leverage of large firms and imposition of stringent private standards is the eventual concentration that may result[86]. This would imply a shift away from the inclusive patterns of supply chain transformation associated with the quiet revolution, and the distribution of gains from small producers to consumers.

Policy and regulation. Delivering sustainable commoditization will require a mix of public and private sector actions and investments that support innovation and development of supply chains capable of signalling requirements for, and delivering, sustainability and food safety, and efficiently marketing seafood commodities to assure food security. The following elements are essential.

First, policies needed for sustainable intensification. Environmental regulation to protect the environment and maintain a sustainable stock of natural resources is a *sine qua non*. Well-enforced government legislation (for example, protection for biodiversity hotspots, water quality standards and regulation of antibiotic use) is the first line of defence against unstainable practices, and already makes important contributions to environmental protection and food safety in aquaculture in the Global North. Stringent environmental regulation can also act as spur for private sustainability innovation[87]. For capture fisheries, catch documentation systems to ensure traceability at every stage in the supply chain, such as those required by the EU, are recognized as essential tools for reducing illegal, unreported and unregulated fishing (a primary goal of many fisheries management efforts)[88].

Private standards offer a complementary means of delivering food safety and sustainability, but will only affect a small part of the market in the early stages of commoditization when the share of large firms is small. Public standards, such as the Thai Quality Shrimp program and the Vietnamese Good Aquaculture Practices (VietGAP) program can provide an important intermediate step for producers seeking to obtain more rigorous third-party certification, especially if they become de facto mandatory[89].

Second, policies that enable commoditization by building capacity and incentives to invest in technology and supply chain development. These include government investments in public goods in

terms of provision of new knowledge and research, and technology transfer from the public to private sector to introduce innovations that lead to sustainable intensification. Institutionalized transfer of knowledge and expertise between universities and companies—the 'education-industrial complex'—can facilitate development and application of technologies that enhance sustainability and scaling-up through private investments in supply chains[90]. For instance, in Norway, the environmental performance of the salmon industry has been improved with the help of government-sponsored research on disease[91]. Investments in hard infrastructure (roads, electrification, wholesale markets, and ports) are also an essential part of the enabling environment that allows businesses in supply chains to thrive.

At the same time, there is a need for policy to balance risks and benefits in avoiding regulation that can constrain technology transfer or prevent investments and innovations that could provide food security and sustainability gains. Examples include the EU's decision to regulate organisms modified by CRISPR-Cas9 in the same way as conventionally genetically modified organisms[92], and restrictions on the reuse of seafood processing co-product in animal feeds[93].

Third, policies are needed to ensure that sustainable commoditization is inclusive and that terms of incorporation into supply chains are beneficial for workers as well as businesses. Although consolidated supply chains may accelerate the uptake of innovation and simplify sustainability governance, they are likely to exclude smaller actors. Regulation of competition, institutional innovations and effective delivery of support services to small farms, fishers and SMEs are needed to limit exclusion from modern supply chains. 'Beyond farm' governance that integrates area-based approaches to management of aquaculture with collective action and risk assurance to lower the transaction costs associated with smallholder certification and incorporation into modernized supply chains provides a promising starting point[58]. A recent series of scandals highlighting the extreme exploitation experienced by workers in some seafood supply chains[43] also underlines the need to ensure that the right to decent work is a central principle of sustainability governance.

Conclusion

Using seafood as an example, we tracked the lagged historical pattern of supply chain and product cycle development across the Global North and Global South. Debates in the literature have mirrored this pattern, lending greater weight to food security concerns in the South and sustainability concerns in the North. Drawing together these threads, ensuring food security sustainably in the Global South emerged as a key challenge. This question is increasingly addressed through the rubric of sustainable intensification—a strongly productivist concept that elides attention to other facets of the food system.

We introduce the concept of sustainable commoditization, comprised of three triangles united in a pyramid—sustainable intensification, supply chain transformation, and policy and regulation—as a framework for conceptualizing and resolving these contradictions. A confluence of all three components is required and any one is necessary but not sufficient to achieve food security with sustainability. The interdependence of the three components and the dynamic feedbacks between them mean that they must continually coevolve. Adaptive policy and regulation serves as an entry point for creating conditions under which supply chains grow and transform to transmit demand for products differentiated along safety and sustainability lines, and supply innovations needed to produce and distribute them in ways that reduce environmental externalities and costs to consumers. As the examples provided in this Perspective indicate, this concept has broad applicability, but lends itself more easily to application in aquaculture than capture fisheries.

The close parallels between aquaculture and other forms of agricultural production mean that the concept of sustainable commoditization presented here is applicable to agriculture and forestry and, more generally, to the food sector, and to the bio-economy. For example, since WWII, the poultry sector has gone through a revolution where niche production was modernized, initially in the North and more recently globally, by increasing efficiency through genetic improvement, improved nutrition and optimized supply chains, which led to the introduction of new differentiated value-added products[94], subject to increasingly strict environmental, health and animal welfare requirements. Sustainable commodification is also a challenge facing the forestry sector, where growing demand for diverse forest products combined with a growing preference to stop and even reverse deforestation, is leading to the emergence of advanced technologies for harvesting, monitoring supply chains, and stricter certification and regulations[95].

Received: 14 March 2019; Accepted: 16 April 2020;
Published online: 18 May 2020

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Author contributions

B.B., T.R. and D.Z. designed the research. B.B. and T.R. performed the research. B.B., T.R. and D.Z. wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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