*Reviews in Aquaculture*

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# The Local Turn in a Global Sea: Identifying Sustainability Trade-Offs in Regionalized Marine Aquaculture Systems

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## ABSTRACT

Marine aquaculture, like the broader seafood industry, relies heavily on international trade and global supply chains for both production and sales. Recent global disruptions, including the COVID-19 pandemic, the Russian invasion of Ukraine, the conflicts in the Middle East, and trade tensions, have exposed the social and economic vulnerabilities inherent in a globalized production system. In response, these events have sparked growing interest in transitioning to localized and regional supply chain models. Calls to "buy national" and support domestic economies highlight this trend toward regionalization. This study explores the sustainability implications of regionalizing marine aquaculture by examining the four key segments of the supply chain. These are (1) upstream inputs and resources (2) aquaculture production (3) downstream added value-processing and (4) distribution–transportation. Potential benefits of regional production models include increased resilience to disruptions, lower transportation-related carbon emissions, and support for local economies. However, such models may also introduce trade-offs, including reduced production efficiency, supply and sales limitations, and implications for social, cultural, and governance

structures. Our analysis reveals that the sustainability outcomes of regionalization are complex and context-dependent. It is influenced by the specific characteristics of existing supply chains and the regional contexts in which they operate. While regionalization may offer advantages in certain contexts, it does not guarantee improved sustainability. Thus, it is crucial to critically assess the assumption that regionalization inherently leads to improved sustainability outcomes. Proactive evaluation of these dynamics is essential to develop strategies that maximize benefits while addressing potential trade-offs.

## 1 | Introduction

Recent geopolitical, environmental, societal, and economic events have exposed the vulnerabilities of a globalized economy, highlighting the systemic fragility of interconnected supply chains [1, 2]. These events have revealed previously overlooked social-ecological interactions and cascading repercussions [3, 4]. In response, countries worldwide are reassessing strategies to enhance resilience in food security and food systems, following the unprecedented disruptions caused by recent global shocks such as the COVID-19 pandemic, the Russian invasion of Ukraine, the tensions in the Middle East, and escalating tariffs and counter tariffs. Extreme climate-related events, such as heatwaves, uncontrollable wildfires, and flash floods, have further reinforced the susceptibility of transnational production chains to sudden disruptions with far-reaching economic and social consequences, particularly in critical sectors like healthcare, energy, and food systems [5, 6]. One commonly proposed approach to enhancing supply chain resilience is, for example, illustrated by the German National Circular Economy Strategy (NCES), adopted in 2024 [7]. This strategy emphasizes increasing the use of secondary raw materials and optimizing resource efficiency through a life-cycle approach, assessing the environmental, social, and economic impacts across all stages of the value creation process [7].

In food production systems, circularity is strongly associated with the concept of regionalization, defined as a process of refocusing and shortening production chains within a specific geographical and rule-making system [8]. Regionalization has long been a topic of discussion as a response to systemic social-ecological crises [9–11]. Recent geopolitical crises have provided tangible evidence that cross-border trade and supply chains can be quickly disrupted, intensifying discussions on the need for regionalizing value chains [12–14]. As a result, regionalization is increasingly viewed as a strategy for enhancing the resilience of value chains by reducing external dependencies and fostering self-sufficiency [7, 15]. Escalating exchange or tariffs and counter-tariffs is reinforcing the economic attractiveness of regional/local supply chains. It also addresses region-specific challenges [16–18], thus driving the formation of regional economic alliances, such as the Pacific Alliance that seeks to revitalize open regionalism in Latin America [19].

This article critically examines the sustainability implications of regionalizing marine food production systems, focusing on economic, social, environmental, governance, and cultural dimensions—the latter of which in particular has rarely been addressed but is of high relevance in food systems [20]. We focus on marine aquaculture, given its growing prominence as a strategy for addressing global food and nutrition security challenges, particularly in alignment with the United Nations Sustainable Development Goals (SDGs), that is, zero hunger (Goal 2) and sustainable consumption (Goal 12) [21]. However, marine aquaculture production, especially in finfish species like salmon, often operates under economies of scale that require large production volumes, frequently surpassing regional consumption capacities, and thus necessitating globalized trade arrangements [22]. Hence, marine aquaculture is particularly relevant for rethinking regionalization effects. Alongside capture fisheries, marine aquaculture constitutes a globally interconnected set of marine food production systems that supports food and nutritional security, employment, and economic livelihoods [23, 24]. In 2022 and for the first time in history, aquaculture surpassed capture fisheries as the main producer of aquatic animals [25]. Global aquaculture production reached an unprecedented 130.9 million tonnes, of which 94.4 million tonnes are aquatic animals, 51% of the total aquatic animal production [25]. Its success, particularly in finfish aquaculture, depends on highly globalized value chains [26–28]. In many cases, the production spans multiple countries or even continents and multiple sectors, from feed production to processing and distribution [25, 29]. Moreover, marine finfish aquaculture is the most growing aquaculture segment in high-income countries such as Europe and Northern America, since farmers have more control of the production process allowing for more efficiency improvements, together with high value productions (Garlock et al., 2025; Guillen et al., 2025 [30, 31]). Relatedly, marine aquaculture consists of companies, some of which operate a vertically integrated supply chain (i.e., the process whereby companies control multiple stages of the supply chain, from production to distribution), which can reduce costs and improve efficiencies [32]; (see [33] in the case of salmon aquaculture in Norway). Understanding the ramifications of regionalization in this context is critical for ensuring informed decision-making that balances resilience with sustainability objectives while considering regional culture. By examining the various sustainability outcomes across the value chain, we evaluate the extent to which transitioning to regional production pathways might yield benefits or unintended consequences.

Using the marine aquaculture value chain as an example, this review explores the complexities of assessing the impacts of regionalization on the different dimensions of sustainability. Although regionalization is often associated with positive "small is beautiful" narratives [34], this perspective risks oversimplifying the intricate trade-offs and systemic risks involved in reconfiguring production networks. Indeed, local aspects are nodes within global networks without which they would not exist, resulting in the global–local paradox. We argue that failing to account for these complexities may result in unintended negative sustainability consequences. Indeed, to accurately assess these potential impacts across different dimensions of sustainability and the potential benefits of regionalization, a thorough understanding of the entire production chain and their social-ecological connections is needed [35].

## 2 | Objective and Methodology

We aim to highlight the impact of regionalization on the sustainability performance of marine aquaculture value chains by building on the integrative framework developed by Krause et al. [36]. Our analysis focuses on four segments in the value chain: (1) upstream inputs—resources and inputs needed to initiate and sustain aquaculture operations; (2) aquaculture production—the farming of the aquatic species; (3) downstream added value-processing and enhancing the value of farmed products; and (4) distribution–transportation, marketing, and sale of the final product (Figure 1). This framework acknowledges that societal interests, priorities, and consumer perspectives influence all four segments.

Similar to the European Union's "farm-to-fork" agenda [37], we adopt a value chain perspective to analyse the influence of regionalization on the sustainability performance of marine aquaculture. We explicitly acknowledge that we apply a "Global North" lens, as the trend toward regionalization is most pronounced in Western countries, although there are strong, recent trends in Global South countries like Indonesia as well in the context of food and energy sovereignty and self-sufficiency (e.g., increasing agriculture and forestry areas, expanding mariculture and fisheries, and drawing increasingly on palm oil to meet domestic energy demand) [38, 39]. Within each segment of the marine aquaculture value chain, we outline and discuss the interconnectedness and ramifications of regionalization, focusing on what we consider to be the most prominent implications.

This methodological framework enables us to capture the multi-dimensional nature of sustainability outcomes caused by regionalization, highlighting both benefits and challenges while recognizing that different trade-offs between the various dimensions of sustainability exist. Our analysis is exploratory in nature, thus aiming to encourage forward-thinking deliberations about the regionalization of aquaculture. However, a more in-depth understanding and analysis of the value chain at the regional level is necessary to draw robust conclusions regarding its sustainability. The insights presented here stem from expert knowledge discussions within the ICES Working Group on the Social and Economic Dimensions of Aquaculture (WGSEDA), validated through consultations with other marine aquaculture experts and stakeholders—including industry representatives and policy-makers—and further supported by literature review.

## 3 | Implications of Regionalization in Marine Aquaculture Supply-Chains

We explored, for each segment of the marine aquaculture value chain, the interplay between the five dimensions of sustainability (ecological, social, economic, cultural, and governance). To ensure applicability of the analysis, we focused on four critical segments of the value chain (Figure 1), each illustrated by specific showcase examples: (1) the upstream segment, where we evaluated the sustainability implications of regionalizing feed production, (2) the production stage, where we assessed the implications of regionalizing broodstock and seed production, (3) the downstream added-value segment, where we examined the consequences of regionalizing secondary processing, and (4) the distribution segment, where we considered the broader implications of regionalized market access. In each instance, we focused on the central question of whether regionalization does or does not contribute to sustainability outcomes and how risks and barriers influence production and market dynamics.

### 3.1 | Upstream Implications

In marine finfish aquaculture, feed is the key input [40–42] and thus the most critical component of the upstream segment of the value chain in the context of regionalization. The regionalization of feed production holds significant potential for economic and ecological benefits. However, it also presents various

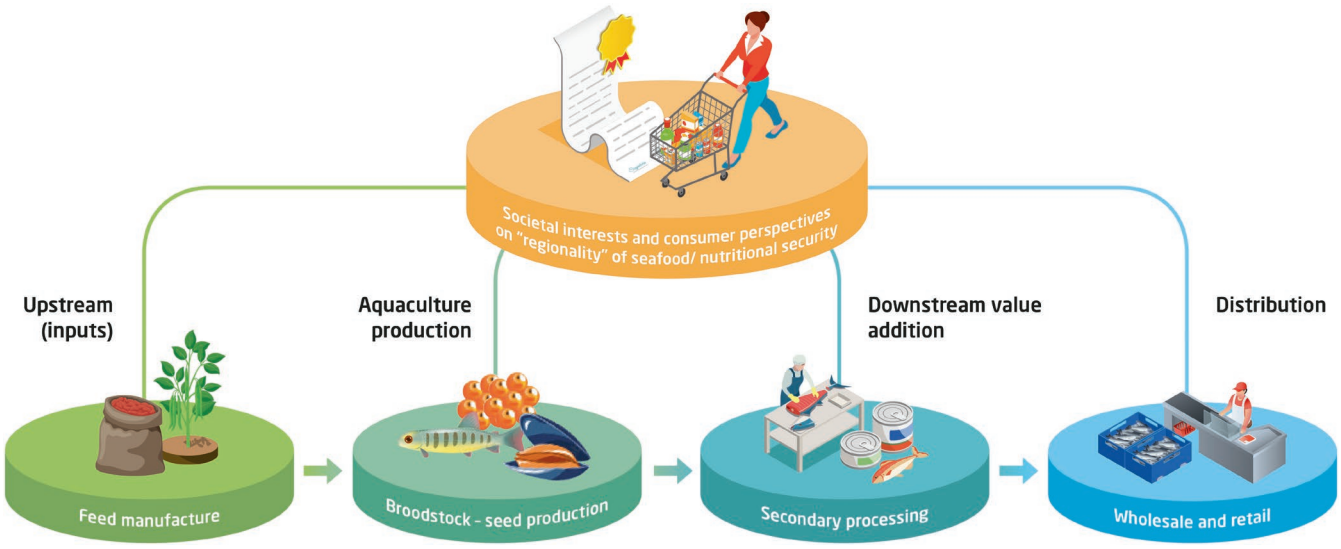


**FIGURE 1** | Segments of the value chain to evaluate the implications of regionalization for marine aquaculture. At each step, societal interests and priorities, economic aspects, regulations, and consumer perspectives influence the set-up of the elements therein (Graphic: stock.adobE.com/Inge Glinsmann/AWI).

ramifications across all sustainability dimensions that must be carefully considered (Figure 2).

In globalized economies, input materials for finfish feed are often sourced from distant areas, such as soy from Brazil for Norwegian aquaculture. Thus, one of the primary advantages of regional production of feed is the potential reduction in transportation costs and $CO_2$ emissions [43, 44]. By replacing globally sourced ingredients, such as soy or fishmeal and oil, with regionally produced alternatives such as lupine seeds [45–47], microalgae feed ingredients [48], or insects [49], a further contribution to lower environmental impacts can be expected. Under the concept of a circular economy, ingredients such as fish meal and oil from bycatch or discarded fish as well as animal proteins from livestock processing side-streams are promising feed ingredients among other regionally sourced materials [50–54]. These ingredients enhance overall sustainability by reducing waste and promoting a more efficient and circular use of animal resources [55].

In addition to these ecological benefits, regionalization could contribute to social sustainability [35]. By fostering the use of local resources, it has the potential to generate increased local employment opportunities and align aquaculture practices more closely with community needs and values, thereby enhancing social acceptance of the industry [56, 57]. Moreover, a regionalized model of feed production could strengthen local governance frameworks, encouraging greater participation in decision-making processes, for example, by encouraging tailored cooperation between governments, aquaculture producers, feed manufacturers, and research institutions. This would allow for the incorporation of local knowledge and concerns into supply chain management, resulting in more transparent, responsive, and sustainable governance structures that endorse equity and value pluralism [13].

Despite these benefits, several challenges must be addressed for regionalization to be truly effective. One major issue is the likelihood of increased production costs and logistical limitations. In regions with limited agricultural capacity—such as high-latitude areas where salmon farming is prevalent—the local availability of essential feed ingredients like soy or canola may be insufficient, which could increase input costs and undermine the economic viability of regionalized feed production [42]. Similarly, fishmeal and fish oil or substitutes may not be sufficiently available at the regional level. In the case of fishmeal and oil, for example, limited availability is due to a lack of fisheries commonly used to produce these commodities, for example, anchovies or herring. Moreover, the loss of access to global markets may result in supply shortages or higher prices, further complicating the regionalization of feed production and reducing its cost-effectiveness.

The social and cultural sustainability implications of regionalization also warrant careful consideration. While regional input production could help generate local employment by new production lines [57], the quality of these jobs is a critical concern. There is a risk that employment opportunities may be low-wage or precarious, which could limit the social benefits of regionalization [56]. However, potentially there could be a rising demand for animal nutritionists, research and development specialists, and production supervisors that foster the utilization of regionalized feed, which would result in an increase in high skilled and high paid jobs. Additionally, industrial expansion in response to regionalized feed production could lead to land-use conflicts (due to the need for e.g., raw material storage, extrusion equipment, and storage/distribution facilities) which might disrupt local cultural practices and values and alter landscape identities, particularly in regions where such developments were previously inconceivable [58, 59]. Furthermore, regions

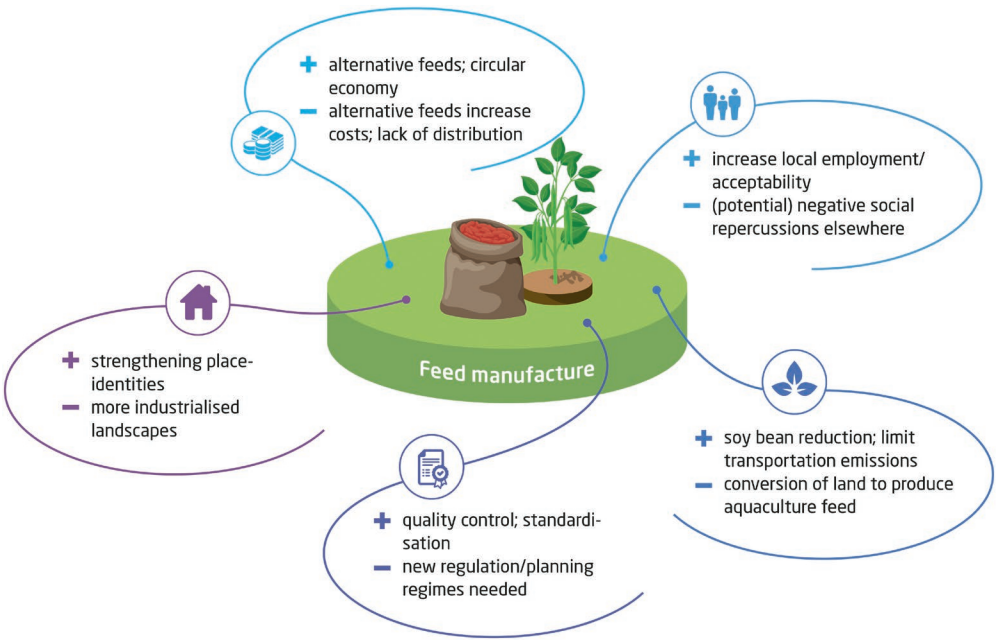


**FIGURE 2** | Potential positive and negative effects of regionalization on the different sustainability dimensions (clockwise: Economic, social, ecological, governance and cultural) of feed manufacture as an example for the upstream segment of the value chain (Graphic: stock.adobE.com/Inge Glinsmann/AWI).

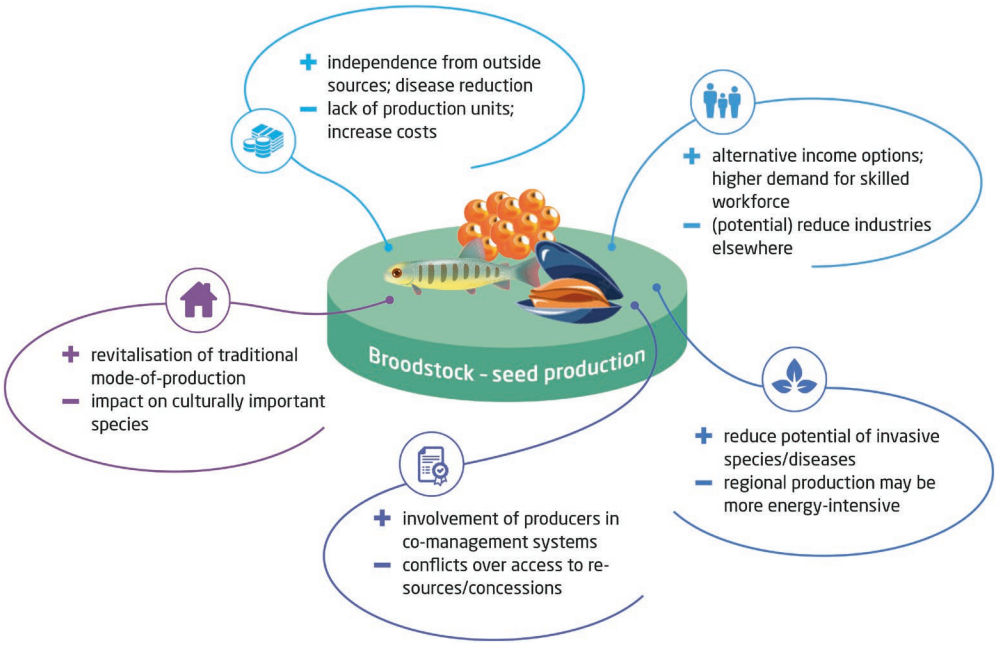


**FIGURE 3** | Potential positive and negative effects of regionalization on the different sustainability dimensions (clockwise: Economic, social, ecological, governance and cultural) of broodstock/seed production as an example for production implications (Graphic: stock.adobE.com/Inge Glinsmann/AWI).

that were previously integrated into global supply chains may face economic displacement as their role in the value chain is reduced.

From a governance perspective, the transition to regionalized feed production may pose significant challenges, especially to implement good governance, that is: legitimacy, accountability, participation, fairness, equity, transparency, and value pluralism [13, 60]. A focus on regionalization would thus potentially strengthen participation with this bottom-up profile, achieving greater robustness while being closer to the direct needs and challenges of local actors and regions. It would also contribute to fostering a better inclusion of regional knowledge and local concerns, which in turn may benefit shorter supply chains and increase sustainability as new "rules-of-the-game" are imposed. While countries with strong governance structures could effectively adapt to this shift, those with weaker governance, such as those grappling with corruption or insufficient regulatory frameworks, may struggle to ensure the transparency and accountability needed for such a transition [60]. In these contexts, the potential benefits of regionalization could be undermined by the lack of robust institutional frameworks to support it.

In conclusion, while regionalizing feed production in marine finfish aquaculture offers the promise of enhanced economic, ecological, and social sustainability, it also entails considerable trade-offs. These include the risk of higher production costs, potential social displacement, and the limited capacity of effective governance in less stable regions. A nuanced, context-specific approach is required to navigate these challenges and ensure that regionalization contributes positively to the long-term sustainability and equity of aquaculture systems and its potential for circular production.

### 3.2 | Production Implications

Below, we focus on the implications of regionalization of seed and broodstock production in marine aquaculture to showcase possible production implications of regionalization. Seed and broodstock regionalization presents a complex set of opportunities and sustainability challenges that are intricately tied to both economic and social dynamics. This process is influenced by the interplay between local, national, and international scales, and the dominance of private sector interests, which often prioritize profitability and efficiency over broader sustainability goals [61]. The implications of regionalization are multifaceted, with potential benefits and drawbacks that may affect not only the aquaculture sector itself but also wider society (Figure 3).

Many countries face significant bottlenecks in fry or seed production, which can be a limiting factor in the sustainable growth of species such as spotted wolffish (*Anarhichas minor*) [62]. Overcoming this bottleneck through regional production would not only ensure a more reliable supply but also reduce vulnerability to fluctuations in global markets. Hence, the regionalization of seed production would not only address the lack of availability of broodstock some farmers are facing (e.g., [4]) but also pave the way to independence from outside sources. Although the initial investment in infrastructure and energy required for such a transition may lead to higher prices in the short term, the long-term economic returns could be substantial, with new income opportunities created within the local economy. To date, the required initial investments, for example, to establish hatcheries and infrastructure, are the main bottleneck that prevents regionalization from occurring.

Regionalization could also enhance the cultural component of marine aquaculture and thus yield significant social benefits.

By fostering local species production, it has the potential to revitalize coastal communities, strengthen local knowledge, and reinforce regional identity [63–65]. Furthermore, the increased demand for a skilled workforce could lead to enhanced educational and training opportunities, potentially benefiting the broader local economy. Inclusive capacity building approaches that involve low-skilled workers could also provide additional positive social impacts, as underscored particularly in the wake of the workforce disruptions caused by the COVID-19 pandemic.

Additionally, the regionalization of aquaculture production has the scope to improve governance structures by promoting better direct control and coordination of production activities. As such, the proximity to production sites allows for more effective planning and a reduction in supply chain disruptions [66]. Furthermore, regionalization can facilitate co-management systems, where stakeholders are more actively involved in decision-making processes. Such systems may foster trust and collaboration, improving social relationships among producers, regulators, and other stakeholders, and the stronger involvement of producers and their specific needs [67, 68]. The integration of local knowledge into governance frameworks can further enhance communication and reduce transaction costs, ultimately contributing to more sustainable practices in aquaculture [66]. Although initially, regionalized governance may lead to higher transaction costs due to the need for additional facilitation, these costs could decrease over time as relationships stabilize [69, 70].

From an environmental standpoint, regionalizing seed production could help mitigate some of the ecological risks associated with global aquaculture practices. For example, sourcing broodstock locally can reduce the risk of introduction of invasive species and diseases, which are often linked to the importation of foreign seed [71]. Additionally, local seed production could reduce transportation-related emissions, contributing to a reduction in the overall carbon footprint of the sector. However, the environmental benefits of regionalization in terms of greenhouse gas emissions are likely to be modest, particularly when compared to emissions from other aspects of the aquaculture supply chain, such as feed and harvested products. Furthermore, small-scale regional production could be less efficient in terms of $CO_2$ emissions than centralized operations, potentially offsetting some of the environmental benefits from reduced transport.

A key challenge in the regionalization of aquaculture production is the need to obtain and maintain a Social License to Operate (SLO), which is increasingly important for companies in the context of political and social polarization and divides [72]. Gaining SLO involves navigating complex socio-political dynamics and aligning business practices with local values, environmental concerns, and community needs (Eriksen and Mikkelsen 2024; [73, 74]). While regionalization may help companies improve their corporate social responsibility (CSR) and SLO, all of which link to maintaining their reputation [75–77], this requires careful management of relationships with stakeholders, as production sites can become contested areas, particularly when opposition arises from local communities or other industries [78]. The process of obtaining SLO is often multi-faceted and complicated, as it depends on context-specific settings such as place identity, sense of place, human rights, state of the environment, and respective institutional settings [79, 80].

Despite all above-listed potential benefits, the regionalization of broodstock and seed production in the production stage of aquaculture comes with several challenges that must be carefully managed. The initial costs associated with the establishment of regional production infrastructure and skilled personnel are significant [81]. These investments may lead to higher prices for aquaculture products, which could hinder market competitiveness. Important investments in research and development often take place to improve the productivity and resilience of the broodstock and seed produced, so new establishments may produce lower-quality inputs. Moreover, the shift toward regional production could disrupt existing aquaculture operations, potentially leading to job losses in areas where production is reduced or relocated. The increased demand for skilled labor in regional production sites may also place additional pressure on local educational systems, requiring adjustments to training structures to address workforce gaps [4].

### 3.3 | Downstream Added Value Implications

The downstream industries following aquaculture production include value-added ventures, with the processing industry being upfront. Primary processing (e.g., gutting) already tends to be a regionalized business taking place at or near the site of aquaculture production, whereas secondary processing (e.g., filleting) is more often left to external companies, frequently sent to other countries with cheaper labor and/or better infrastructure or historical position in fish value chains. Accordingly, the regionalization of secondary processing in aquaculture products presents the most susceptible part of the downstream step of the value chain hosting both opportunities and challenges in terms of economic, social, and cultural sustainability, as well as environmental impacts (Figure 4) [82].

One of the key advantages of regionalization of this segment is that shorter transportation routes between producers, processors, and consumers can reduce logistics costs and lower the carbon footprint of the supply chain [83]. This reduction in transport distances could also potentially extend product shelf life, which not only alleviates environmental pressure but also reduces packaging requirements [84]. Furthermore, regionalization can stimulate local economies by creating jobs and promoting skill diversification, particularly in rural areas, thereby supporting regional economic development [85]. Fostering cooperative management, regional revenue sharing, fair trade, certification, and corporate social responsibility (CSR) can also contribute to more equitable revenue distribution, potentially addressing economic inequalities and promoting a more sustainable economic model [86].

In terms of social and cultural sustainability, regionalization offers significant potential. Inclusive business models that prioritize the integration of migrant workers can improve working conditions and reduce cultural tensions, fostering a more culturally sustainable workforce [87]. Creating local processing jobs can also help alleviate poverty in rural areas and provide greater social mobility [85]. Additionally, positive spillover effects can be expected by the promotion of skill diversification through regional processing facilities that may bring long-term socio-economic benefits to rural (socially marginalized) areas

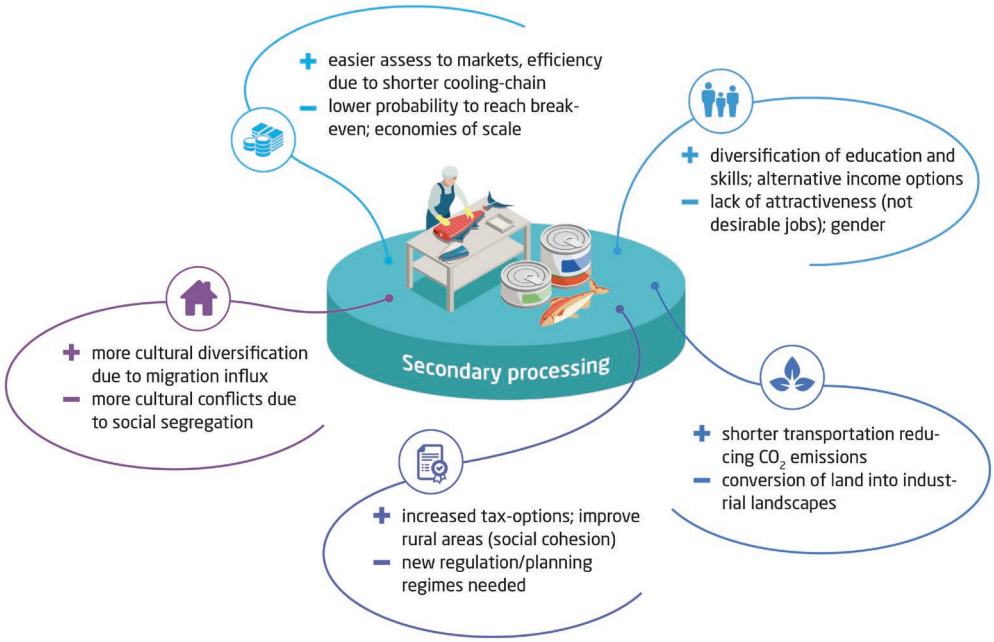


**FIGURE 4** | Potential positive and negative effects of regionalization on the different sustainability dimensions (clockwise: Economic, social, ecological, governance and cultural) of secondary processing as an example for downstream added value implications (Graphic: stock.adobE.com/Inge Glinsmann/AWI).

[85]. While these interventions can be more or less suited to regionalized aquaculture and the management of the resources it relies upon, they are themselves prone to power asymmetries and governance obstinacies.

There are also notable challenges, particularly from an economic perspective. Similar to input industries, there is a limit to what can be processed locally. Potentially restricting factors include the regional availability of employees and prevailing salaries, rents, and taxes, which may hinder the economic feasibility of local processing plants [88]. Furthermore, the established economies of scale in centralized processing systems pose a challenge, as regional processing infrastructures could lead to higher costs and inefficiencies [88], despite addressing a key vulnerability of production systems dependent on international transport chains [4]. In addition, given the seasonal fluctuations in aquaculture production, it may not be economically viable to operate regional processing plants year-round if production volumes are insufficient [88, 89]. However, one possible option to address this challenge is by processing a variety of species in the same location, as different species would be harvested at different times. Thus, processing plants might not just be for one species and may host different types of processing, for example, smokehouses and filleting.

Another social issue may arise from the increased reliance on migrant workers, as the less attractive working conditions in processing often lead to the employment of seasonal labor from abroad. As demonstrated in the meat processing industry during the COVID-19 crisis, this can lead to social tensions and cultural conflicts if migrant workers face travel restrictions or work under poor conditions [87]. At the same time, the loss of jobs in regions where secondary processing is currently centralized could result in negative social and economic impacts, potentially exacerbating existing inequalities [85].

From an environmental perspective, regionalization of production and processing can also yield positive effects. Shorter transportation routes can reduce $CO_2$ emissions, especially by minimizing air transport [83]. However, the need for additional space for processing facilities near coastal areas could lead to industrialized land use, potentially affecting sensitive ecosystems. Moreover, the benefits of specialization and optimal environmental conditions in global supply chains may outweigh the potential ecological advantages of regionalized processing in some cases, as specialized production might offer greater efficiency and lower $CO_2$ emissions [83]. Another environmental concern could be the difficulty in implementing circular economy principles, such as the reuse of fish trimmings in regional processing settings, which may limit the sustainability potential of such practices [90].

In sum, while regionalization of secondary processing in aquaculture products offers significant benefits in terms of economic, social, and environmental sustainability, it also presents numerous challenges that must be carefully addressed. Successful implementation will require innovative governance structures that counteract the risk of being prone to power asymmetries emerging from the interplay of powerful international actors versus regional management systems, for example, by the establishment of multi-layered governance structures involving national, regional, and local stakeholders to mitigate conflicts and ensure sustainable development of aquaculture in Northern Norway [91] and inclusive business models to mitigate the potential downsides related to inefficiencies, social tensions, and environmental impacts.

### 3.4 | Distribution Implications

As noted in the introduction, at all stages of the value chain, aquaculture production is usually subject to economies of scale,

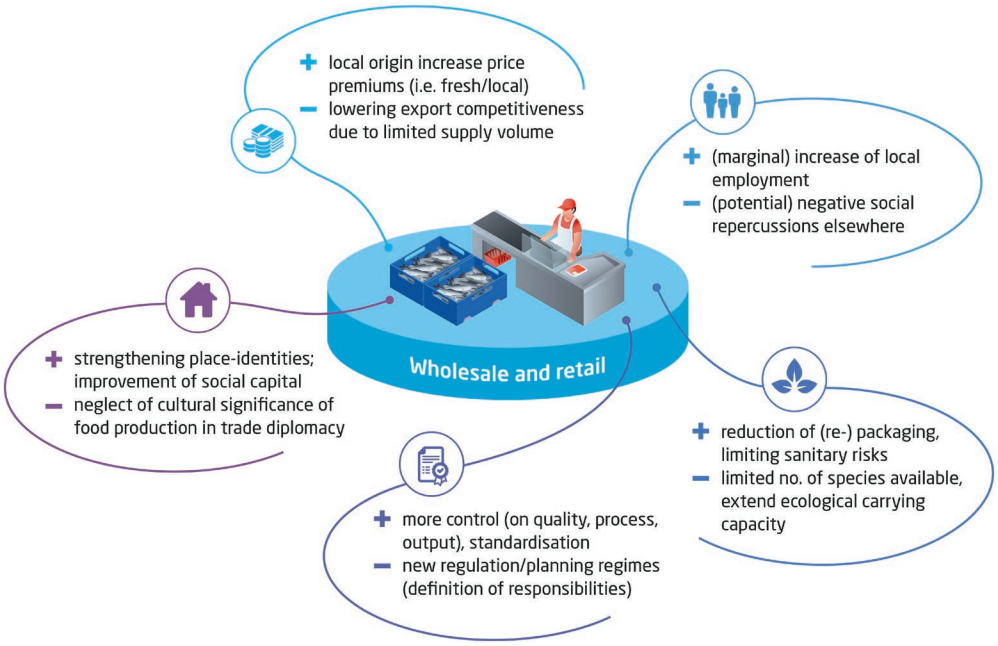


**FIGURE 5** | Potential positive and negative effects of regionalization on the different sustainability dimensions (clockwise: Economic, social, ecological, governance and cultural) of wholesale and retail as an example for Distribution-Marketing Implications (Graphic: stock.adobe.com/Inge Glinsmann/AWI).

resulting in large production volumes. Therefore, companies usually seek market expansion to reach economies of scale as the outputs are often difficult to absorb by consumption at the regional scale [92]. The potential shift to regional production and distribution could lead to trade-offs at the wholesale and retail stages (Figure 5).

For example, regionalization of aquaculture distribution could align with currently shifting consumer preferences in Western societies as "locally produced" is increasingly gaining importance as a criterion for purchase decisions [51, 52, 93–96], which might promote sales [97]. This trend could bolster sales by offering fresher products, potentially reducing $CO_2$ emissions, enhancing production transparency, and supporting local businesses. Consumers' willingness to pay a premium for regional products could offset higher production costs, further supported by "political consumerism" [98] and "ethical consumerism" [99] trends; the Canadian consciously boycotting US products and services in reaction to US imposition of tariffs is a case in point. Indeed, distribution and marketing are closely linked to end-consumers' perspectives and preferences that potentially have the power to encourage stronger regionalization of marine food production systems while supporting the circular economy dimensions.

Environmental sustainability could benefit from shorter supply chains, reduced transportation routes, and lower packaging demands, minimizing risks associated with sanitation and long-distance distribution [84]. Similar to other steps of the value chain, regionalization fosters opportunities for the potential creation of regional jobs, building place-identity by "branding" regionality, and strengthening ownership, which could enhance the social and cultural dimensions of sustainability [100].

A more localized distribution model could improve governance by enabling regionally specific standardization, facilitating better evaluation and monitoring, and promoting co-management or new forms of cooperative frameworks. These localized regimes could facilitate stakeholder collaboration and create synergies with other industries, which typically result in increased trust and collaboration among stakeholders, potentially enhancing interactions with other sectors.

Conversely, regionalization may undermine export revenues and international competitiveness by constraining access to larger markets, making it challenging to achieve economies of scale. For instance, major producers like Norwegian salmon industries may find it impractical to fully integrate into regional markets, while regions currently reliant on imports (e.g., the USA and the EU) might face rising prices and limited product availability, with some of the currently most consumed species disappearing from the counters. For the latter, the USA is a case in point where two atlases to guide aquaculture expansion in the Gulf of Mexico and California have been released [101].

Environmental benefits are not guaranteed, as smaller-scale operations may lack efficiency, potentially offsetting $CO_2$ reductions from shorter transportation routes. Additionally, restructuring distribution could negatively affect international trade networks, potentially leading to job losses in export-dependent regions. Social conflicts may arise due to divergent stakeholder values and interests, as seen in the State of Maine's current aquaculture lease process [102]. Balancing new regulatory regimes with existing interests might provoke tensions, complicating governance reforms.

In summary, while regionalizing aquaculture distribution offers some opportunities for sustainability, such as local empowerment and alignment with emerging (Western countries') consumer preferences, it also presents significant economic and

operational challenges that may vary by region. Next, regionalism may potentially lead to a lower variety of supply for some (foreign) species and oversupply for local species, contrasting current globalized supply regimes, in which certain species, such as salmon, are sent to where consumers demand them.

## 4 | Discussion: Positive and Negative Sustainability Effects of Marine Aquaculture Regionalization

This study critically evaluates the implications of regionalizing marine aquaculture production, focusing largely on finfish. Global crises, including the COVID-19 pandemic, the Russian invasion of Ukraine, the Israel-Hamas conflict, as well as the looming US tariffs and counter-tariffs, all of which threaten to significantly disrupt global trade, present an opportunity to reconsider existing frameworks and priorities within global, national, and regional food systems. That said, it is important to recognize that regionalization need not be an all-or-nothing proposition. In practice, the development of regional capacity alongside existing global supply chains creates diversification that can enhance overall system resilience. The partial regionalization of certain value chain components creates redundancy and alternatives that can buffer against disruptions in either regional or global systems.

To address this, an integrative approach is necessary—one that considers all dimensions of sustainability across the value chain to assess the full range of consequences associated with the regionalization versus globalization debate. Such an approach must extend beyond aquaculture to encompass broader systems, such as the food-water-energy-soil nexus, which exemplifies the interconnections between critical resources [103, 104]. Failing to adopt this holistic perspective risks underestimating potential benefits, but importantly also overlooking unintended negative outcomes. For instance, developing regional feed production capacity while maintaining access to global feed markets provides producers with options that can mitigate price volatility and supply risks. This diversification aspect of regionalization can create greater competition in the provision of products and services throughout the value chain, potentially leading to innovation and lower costs for consumers in the long term. For this competitive dynamic to function effectively, however, regional capacity must achieve sufficient scale and efficiency to be substantially cost-competitive with global options, particularly in segments like feed production where economies of scale are significant.

To tackle these complexities, this study uses a sustainability framework that integrates four interconnected dimensions: environmental, economic, social, and governance [105–107]. Additionally, it includes a cultural pillar, thus emphasizing the importance of cultural sustainability, which highlights the deep connections between food systems and cultural identity, traditional values, ethical considerations, and consumer perceptions [53, 54, 63, 108–110]. This cultural dimension also addresses ethical issues frequently associated with modern aquaculture practices [108, 111, 112]. To this end, this analysis serves as a visualization tool for academia, governments, international agencies, and industry to evaluate the trade-offs inherent to regionalization. Our findings emphasize the importance of addressing region-specific nuances, such as biophysical factors and societal influences, which ultimately shape the relative importance of the different sustainability dimensions in decision-making in spatial planning, providing funds and business development. Only by acknowledging these nuances can regionalization strategies yield meaningful and context-specific outcomes.

While the primary focus of this study is on marine aquaculture, the general framework linking value chain stages with sustainability dimensions is adaptable to other sectors. Applying this framework to alternative food production systems could uncover parallels and shared dynamics, enhancing our understanding of regionalization's broader implications across four segments of the value chain (upstream, production, downstream added-value, and distribution). By this, the potential short- and long-term effects of increased regionalization in response to social-ecological crises can be identified, while recognizing that societal interests and consumer preferences are critical drivers shaping the value chain [51, 52, 113]. This interdisciplinary approach underscores the complexity of sustainability transitions and highlights the need for adaptive policies and practices that address these multifaceted challenges effectively.

The regionalization of marine aquaculture presents complex and context-dependent sustainability outcomes. While it holds promise for addressing challenges such as supply chain disruptions and $CO_2$ emissions, regionalization does not inherently guarantee sustainability. Economic and equity impacts vary significantly across regions and production contexts, emphasizing the need for localized strategies tailored to specific socioeconomic and ecological conditions [43]. The two examples below showcase in a nutshell bivalve how regional aquaculture production and their interconnections can be assessed with this framework. Some potential steps toward more sustainable regionalization of production are outlined.

### 4.1 | The Netherlands

In the Netherlands, mussel cultivation is commonly seen as environmentally beneficial, providing low carbon footprint food products. In light of national climate objectives, there is shared interest in regional strategies that support the development of local markets and production systems that enable local producers to compete with imported cheaper mussels from, for example, New Zealand. The latter negatively affects accounting sustainability outcomes by increased CO2 emissions. In the upstream value chain, efforts are currently targeted at adapting cultivation systems and fostering innovations that enable regional offshore cultivation to increase the resilience of the sector as a whole.

### 4.2 | Spain–Galicia

Galicia has a high import of clam and oyster seed from France for the upstream input to initiate mussel aquaculture production. These, however, inherit potential risks of transmission of

cross-border diseases and invasive species. Supporting strategic actions for increased seed production regionally (e.g., hatchery seed production) would ensure an efficient and environmentally friendly production, guaranteeing the availability of mussel seed without relying on natural collection and/or imports. This ultimately would improve sustainability dimensions of mussel aquaculture through, that is, providing more alternative income options for the region and growing seed better adapted to local environmental conditions.

A critical dimension of this discourse is the role of cultural and social values. Cultural sustainability, encompassing ethical considerations, societal identity, and values linked to food systems, emerges as vital. Regionalization strategies must incorporate and respect these values to ensure inclusive and equitable food security [63, 109]. By acknowledging the cultural significance of food systems, regionalization transcends economic and environmental considerations, addressing broader human values and community well-being. The integration of systems thinking provides a promising pathway for aligning economic, social, cultural, and ecological objectives to inform broader discussions on global food security, climate change mitigation, and resource equity, highlighting synergies and trade-offs across interconnected systems [114, 115].

In the context of global crises—such as geopolitical tensions and economic instability—the urgency of fostering resilient food systems has intensified. Nations are increasingly prioritizing regionalization and circularity to address vulnerabilities like supply chain disruptions, social inequalities, and food insecurity. However, these efforts are complicated by a broader geopolitical landscape characterized by rising protectionism, declining multilateralism and global trade, and growing state and business debts. For instance, state and business debts are expected to surpass 100% of Gross Domestic Product in many nations [116], while protectionism, shorter supply chains, and reduced global trade persist. Such dynamics underscore the need for adaptive governance to navigate the complexities of modern food systems. Transformative changes require aligning sustainability objectives with governance structures and normative policies, reconciling regionalization efforts with international frameworks such as the United Nations Sustainable Development Goals (SDGs). Addressing equity, resilience, and environmental justice in a balanced manner allows regionalization to contribute to sustainable and inclusive food systems [117, 118].

These trends threaten globalization and free trade (Kaiser et al. 2021) [13]. Geopolitical shifts—including the USA's wavering global leadership, the EU's internal realignments, China's expanding influence, and Russia's efforts to reclaim historical power—exacerbate global uncertainties. Meanwhile, the Global South faces humanitarian crises compounded by economic instability, inequality, and political unrest, with food insecurity looming large [119]. The ongoing repercussions of the Russian invasion of Ukraine further highlight the intertwined nature of food systems within broader socio-political dynamics [120]. Hence, the transformation toward healthy, just, and environmentally-friendly food systems needs to be reevaluated—and not abandoned—in the face of the suite of these multiple crises and cascading risks [117].

On a positive note, despite these challenges, crises have catalyzed discussions on healthy food security and systems thinking, emphasizing the importance of integrated approaches to stable, sustainable marine food production. Seafood from fisheries and aquaculture has been recognized as one of the top nutrient-rich animal-source foods, including pelagic fish, bivalves, and salmonids [121]. Additionally, it is considered a food source with a relatively lower ecological footprint compared to other types of food, such as meat production [122]. It is crucial to explore how aquaculture can contribute to key policy frameworks such as the United Nations SDGs [118]. Advancing transformative capacities for more inclusive and pluralistic forms of sustainability requires translating academic concepts into normative policies, social practices, and values, and understanding how this process has the potential to shape social, political, and environmental change [114, 115]. Discussions on regionalization versus deglobalization also inform broader climate change initiatives, including efforts to reduce greenhouse gas emissions [123, 124], enhance social equity [125], and address concerns for local place identity Kaiser et al. 2020; [5] by creating more positive trade balances from, for example, fish products.

This analysis points to the need to critically reflect on the narrative that regionalizing marine finfish aquaculture can enhance sustainability. While regionalization offers opportunities for improving local food security and reducing carbon footprints, it also poses risks, including unintended social and ecological consequences. A comprehensive, multi-dimensional approach is crucial to mitigate these risks and maximize benefits. Sustainability and equity outcomes, such as access to farmed aquatic food, remain highly variable across countries. Consequently, we do not provide universal conclusions about the feasibility or sustainability of regionalization in aquaculture, since the implications will differ according to the respective production context (e.g., intensive/extensive, industrial/subsistence/small scale aquaculture, state/corporate driven). Similarly, while some of the insights likely are applicable to food production systems more generally or other sectors, this study is not meant to provide conclusive arguments for or against regionalization in general. Instead, it emphasizes the importance of co-developing strategies that integrate environmental, economic, social, cultural, and governance dimensions. Such an approach can foster resilient, equitable food systems capable of addressing current and future challenges.

Recent shifts in economic priorities reveal a transition from overly utilitarian approaches to resource management—aimed at maximizing the overall value for human well-being—to a more nuanced understanding of natural resource use and its interconnections. Human values, seen as guiding principles or objectives, underpin attitudes and norms that serve as a basis for general principles of action [126–129]. In that sense, value-driven narratives may be deeply rooted in motivations or orientations of how things should be, ultimately guiding or explaining certain attitudes, (social) norms, and opinions. As such, regionalization per se may not always be the best pathway to sustainability and should not automatically be assumed to be "better"; however, understanding the advantages and disadvantages can aid the co-development of effective regional aquaculture strategies. Thus, consideration of the social, cultural, ecological, economic,

and political context holds the potential to achieve resilient food security in a balanced and equitable way.

## 5 | Conclusions

Our study is founded on several key assumptions: (i) regionalization is an emerging strategy pursued by some stakeholders in the marine aquaculture sector to enhance sustainability and build resilience to help mitigate economic risks; (ii) regionalization is already implemented to a varying extent across different segments of the value chain; (iii) regionalization has diverse positive and negative implications for sustainability dimensions, which vary across value chain segments; and (iv) risks and barriers associated with the regionalization of marine aquaculture span multiple sustainability dimensions.

Under these assumptions, regionalization holds the potential to provide healthier, more resilient, and stable food security compared to globalized strategies in many countries. However, the associated challenges and drawbacks must not be overlooked. Central observations from this analysis have identified (i) the likely common effects of regionalization across the major components of the aquaculture value chain (carbon intensity, employment, etc.); (ii) the components of the value chain that are likely to be the best candidates for regionalization, on balance; and (iii) which nations/regions regionalization is likely to be most successful or beneficial.

That said, a key point is that regionalization is not an "all or nothing" approach. In practice, it often involves selectively developing regional capacities in areas such as feed production, processing, and distribution. This creates competition, which can lower costs for consumers while boosting local economies. Thus, the central strength of regionalization is the push toward diversification that has the potential to counterbate the recent global shocks.

To understand the sustainability implications of regionalization, a systemic approach is essential. This implies the consideration of the interconnectedness of supply and value chains within a multi-level governance context. Failing to account for these linkages may lead to unintended consequences or an underestimation of potential benefits and challenges. Given the complexity of these interactions, trade-offs are inevitable, thus underscoring the need for a holistic perspective. Sustainability outcomes will vary depending on institutional and cultural contexts and path dependencies over time. Recognizing these interactions can inform priority-setting, identify bottlenecks in regionalizing marine food production, and promote collaborative efforts across sectors and stakeholders.

Regionalization also provides an opportunity to encourage dialogue and knowledge exchange across disciplines and institutions that can inspire creativity and innovative solutions. Such collaborative approaches can help design distributive aquaculture systems that align with sustainability and equity principles. Our multidimensional framework helps conceptualize these interactions and synergies. However, its true value to sustainability-focused decision-making will be realized through application in specific regional contexts.

In conclusion, it is crucial to critically assess the assumption that regionalization inherently leads to positive sustainability outcomes. Proactive reflection on this premise is essential to avoid oversimplification and to maximize the potential benefits of regionalization while addressing its challenges.

### Author Contributions

Due to the nature of this work, all authors contributed to its conceptualization. G.K. and R.F. took the lead in writing the original draft, and all authors contributed to the review and editing of the final document.


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### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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