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Anticipating trade-offs and promoting synergies between small-scale fisheries and aquaculture to improve social, economic, and ecological outcomes

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Blue food systems are crucial for meeting global social and environmental goals. Both small-scale marine fisheries (SSFs) and aquaculture contribute to these goals, with SSFs supporting hundreds of millions of people and aquaculture currently expanding in the marine environment. Here we examine the interactions between SSFs and aquaculture, and the possible combined benefits and trade-offs of these interactions, along three pathways: (1) resource access and rights allocation; (2) markets and supply chains; and (3) exposure to and management of risks. Analysis of 46 diverse case studies showcase positive and negative interaction outcomes, often through competition for space or in the marketplace, which are context-dependent and determined by multiple factors, as further corroborated by qualitative modeling. Results of our mixed methods approach underscore the need to anticipate and manage interactions between SSFs and aquaculture deliberately to avoid negative socio-economic and environmental outcomes, promote synergies to enhance food production and other benefits, and ensure equitable benefit distribution.

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INTRODUCTION

Aquatic, or 'blue', foods captured or cultured in marine and freshwater ecosystems are important sources of food and nutrition globally[1–3]. Over 3 billion people receive at least 20% of their animal protein from aquatic foods[4], and micronutrients found in aquatic foods are crucial for addressing nutrient deficiencies worldwide[5–7]. Aquatic food also supports livelihoods for an estimated 800 million people globally[2].

Demand for aquatic foods has increased despite the leveling-off of fisheries production since the 1990s[4,8] and is projected to nearly double by 2050[9,10]. While SSF catch is not well-documented, it is estimated to be at least 40% of global catch and two thirds of catch for human consumption[4,11]. SSFs exhibit extremely high diversity in their characteristics and circumstances, and vary greatly in their assets, diversification of products and activities, governance, and relation to markets[12]. While many SSFs face growing threats and are declining, there is great potential, and urgency, to support SSFs for social and environmental benefit[12,13].

Aquaculture has grown rapidly in the past two decades, primarily driven by growth in freshwater aquaculture in China and other Asian countries[14]. The aquaculture industry is pushing for even faster growth, including in marine and brackish aquaculture, to fill the gap between fishery production and seafood demand and achieve food security and livelihood goals (e.g., the UN Sustainable Development Goals). As a result, many governments are promoting and subsidizing the development of aquaculture, both in fresh and marine waters[15]. Marine aquaculture expansion is expected to help meet the needs of a growing global population[16], but see[17] and offset many losses from SSFs due to climate change[18]. However, the development of the aquaculture sector has not occurred in a void. The current expansion of aquaculture in marine environments occurs mostly in nearshore waters, which are often already being used by many other sectors, including SSFs. In this paper, we focus on the interactions between marine aquaculture and SSFs.

Both capture fisheries and aquaculture will be necessary to help achieve ambitious global goals to end hunger and malnutrition, and to generate more livelihoods without adverse environmental or social impacts. Hence, there is an urgent need for guidance and best practices for how to promote benefits and reduce the likelihood of negative interactions between SSFs and aquaculture to optimize social, economic, and ecological performance of blue food systems that include both sectors. Here, we identify benefits and trade-offs between SSFs and aquaculture through a review and analysis of 46 case studies, across diverse systems,

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geographies, and conditions. We further explore these interactions through qualitative modeling. Results highlight high heterogeneity of interactions and outcomes, and the need for intentional coordination and management to maximize benefits and reduce negative interactions.

Hypothesized synergism and trade-offs between SSFs and aquaculture

While SSFs and aquaculture are often characterized as distinct elements of blue food systems, in reality, they exist along a spectrum[19]. Historically, and recently, small-scale fishing communities have developed aquaculture operations as an alternative or complement to wild capture fisheries[20–22]. For example, Hawaiian fishers prior to European colonization created and maintained fishponds to support local food security. More recently, the Tongan government began creating protected clam circles for broodstock in the late 1980s after several species were listed as endangered and one species went extinct within Tongan waters[21].

By contrast, other aquaculture endeavors are developed by entities external to SSF communities, without directly accounting for impacts on fishing communities[23,24]. Moreover, aquaculture development can occur through a suite of regulations and processes that involve national or international companies, often without coordination between groups working in fishing and aquaculture research and innovation. For example, high start-up costs of Filipino milkfish aquaculture limit ownership of the installations, often to foreign owners, who are also the sole decision-makers in the operations. This lack of distributed decision-making power, along with a lack of regulation on overstocking and feeding practices, and the privatization of previously public fishing waters, have resulted in the marginalization of many fishers as these types of farms expand[25]. Moreover, while in some cases producing the same products, fishing and farming may require fundamentally different investments, technology, and knowledge. Finally, aquaculture expansion is expected to contribute to food security and nutrition by enhancing and stabilizing the supply of aquatic foods, but unintended consequences have been documented. In Bangladesh, because of aquaculture expansion, fish consumption increased by 30% between 1991 and 2010, but iron and calcium intake from fish decreased over this period, reflecting the lower nutritional quality of the farmed species[26]. The implementation of aquaculture under different regulatory or immanent scenarios can result in varying success, in terms of achieving implementation goals[27]. This highlights the need for understanding the drivers of success within aquaculture, and its interactions with small-scale fisheries.

While aquaculture and fishing can both contribute to the goals of achieving food security, nutrition, employment, and livelihood opportunities, they can also compete in several ways[28]. They both make use of natural ecosystem processes and productivity, largely in nearshore waters. Aquatic foods from both sectors can enter the same markets. Moreover, fisheries and aquaculture may confer food security and livelihood benefits to different groups of people, due to differences in access and rights, distribution, pricing, consumer preference, or other factors. Therefore, aquaculture expansion in waters being used by SSFs could result in the production of less nutritious food, reduced livelihood support, and negative social, cultural, and ecological impacts[16,25,29].

Based on a literature review and the authors' experience in diverse blue food system contexts, we hypothesize that three main factors influence whether interactions between aquaculture and SSFs in coastal and marine settings are synergistic (i.e., taken together, the two sectors generate overall positive environmental, social or economic outcomes) or antagonistic (i.e., result in trade-offs and negative impacts of aquaculture on SSFs) (Fig. 1): 1) access to resources and allocation of rights; 2) the nature of interactions in markets and through supply chains; and 3) exposure to and management of risks from exogenous factors, e.g., disease, habitat degradation and climate change, including extreme events. We recognize that varying definitions exist for the terms we use throughout this article. As such, the definitions used here are included in the Supplementary Materials (Suppl. Table 1).

Access to resources and allocation of rights

The clear delineation of rights and allocation of resources within social-ecological systems (SES) is associated with positive collective action outcomes, such as equitable access and sustainable use of ecosystem goods and services[30] (Fig. 1a). In contrast, poorly defined rights or access to resources may result in inequitable opportunities to benefit from employment, food security, or otherwise, as power dynamics often play a larger role (Fig. 1b). Consideration of the rights of SSFs, including human rights in addition to tenure rights, and vulnerabilities of fishers to the implementation of aquaculture installations are expected to be key factors driving positive or negative social, economic, and public health outcomes[31].

Whereas user rights determine who has the "*right* to benefit", access determines who has the "*ability* to derive benefits". Thus, access extends beyond what is sanctioned by law, custom, or convention, to include structural and relational factors determining who benefits and how[32]. Access to both resources and information within adaptive ocean governance systems is a key factor for the continued development of these governance systems[33]. Where aquaculture and SSFs are co-located, without integrated spatial planning that accounts for Indigenous rights and pre-existing uses, negative impacts on local livelihoods or cultural activities are likely to increase (Fig. 1b).

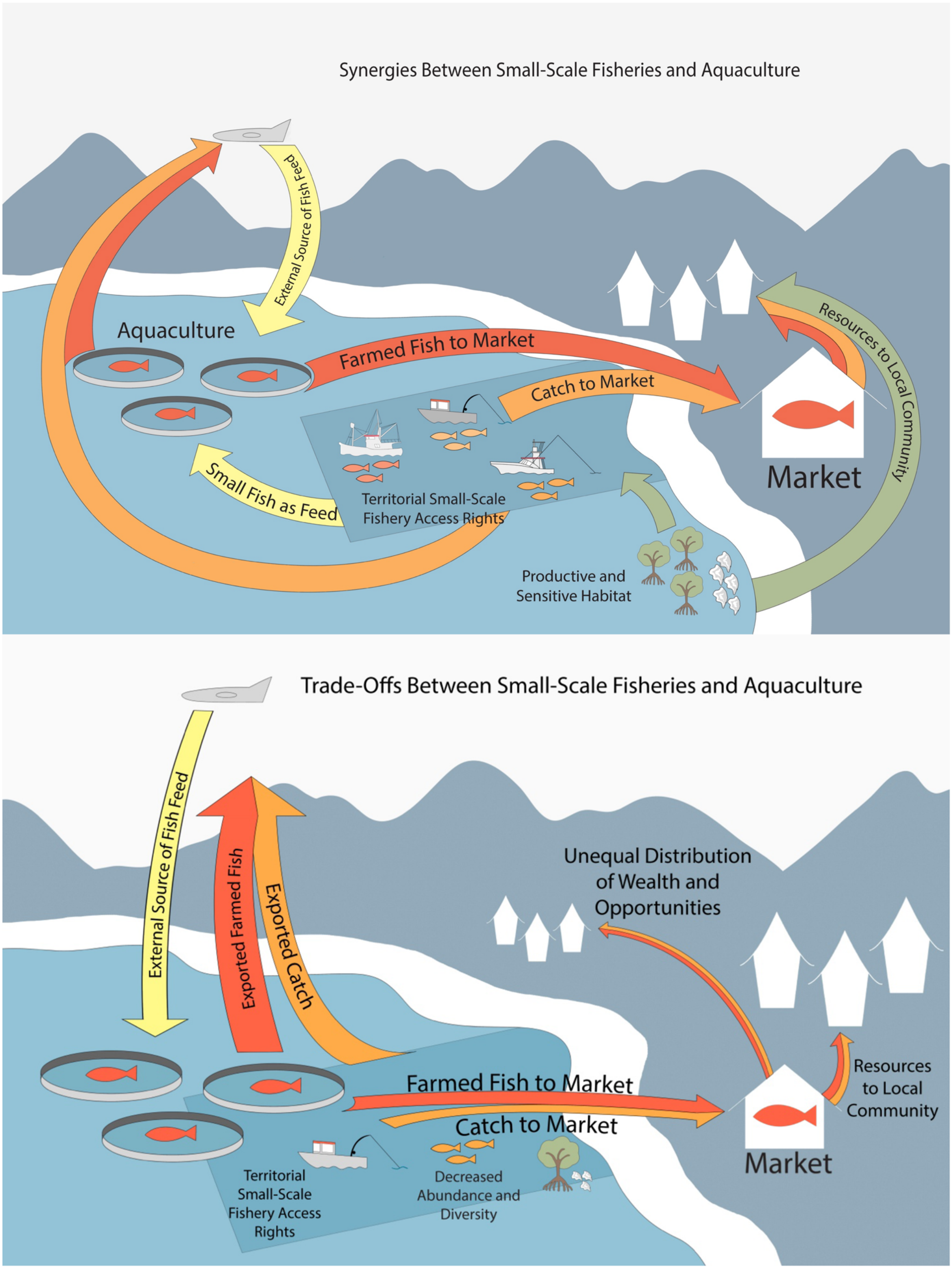
Interactions in markets and through supply chains

The distribution of products to both local and foreign markets allows for the diversification of seafood markets, thereby buffering fisheries against local or global fluctuations in demand and transport cost, and managing risks from an unpredictable market. Additionally, the existence of a community-owned, or managed, market which receives products from both local aquaculture and wild-caught fisheries could provide the community with nutritional support, and cultural and livelihood security (Fig. 1a). However, the implementation of aquaculture alongside a SSF may result in competition within the same markets, particularly when the species grown in aquaculture facilities are the same ones caught in the fishery or can be substituted for them[34–38]. Additionally, reliance on external feed for aquaculture (from both ocean and land-based sources), and foreign markets for sales from both industries, makes some types of aquaculture susceptible to exogenous fluctuations in supply, demand, and transport costs[39]. The replacement of demand for locally wild-caught seafood with less expensive farmed seafood imported from distant sources can negatively impact or exclude SSFs and can preclude potential for upgrading the production and marketing of wild-caught seafood in local and national markets.

Inclusion of local stakeholder links within the aquaculture supply chain – e.g., by providing aquafeed ingredients derived from locally-generated wild-caught products, or locally-grown plant-based feed, and inclusion of products in local markets – could prompt strong local investment in both sectors (Fig. 1a). In contrast, without a connection between the two sectors, there may be little incentive for the aquaculture industry to invest in sustainable fisheries and conservation of local fish stocks (Fig. 1b).

Unequal access to resources, direct competition within markets, reliance on singular foreign markets in the supply chain, and lack of community engagement in governance and risk mitigation, create the potential for the success of corporate aquaculture at the expense of wild-caught fisheries and/or the local community[40,41] (Fig.1b). For example, a privately-owned or controlled

(a)



(b)

aquaculture installation where most of the product is sold internationally, could result in the products that do remain local going to a select set of actors (e.g., those who maintain majority control over the management and processing of the product), limiting access to these benefits to a subset of the community. As a consequence of these conditions there would be limited, or unequal, access to resources, such as food and employment, for local communities, particularly the poorest members. This lack of access could lead to food, nutrition and livelihood insecurity and inequities[42].

Fig. 1 Hypothesized conditions leading to synergies or trade-offs between small-scale fisheries and aquaculture. a Hypothesized general conditions leading to synergies between small-scale fisheries and aquaculture. Yellow arrows represent aquaculture inputs of external and locally caught fish feed. Red arrows represent aquaculture outputs and orange arrows represent fisheries outputs, where farmed or wild-caught fish, respectively, are sold to local and foreign markets. Green arrows represent ecosystem outputs, those that provide stock to the fisheries and subsistence and protection to the community in the existence of a productive coastal habitat. Well defined rights of and access for SSFs and aquaculture operations help counterbalance power dynamics and create conditions for collective actions that promote synergy, such as the protection of water quality and coastal ecosystems being important to both sectors. Fish from SSFs and aquaculture are sold into both export and local markets. Threats to conditions that enable fisheries and aquaculture production such as pollution are perceived as risks by both sectors, promoting collective actions to reduce such risks. **b** Hypothesized conditions leading to trade-offs between small-scale fisheries and aquaculture. Yellow arrows represent aquaculture inputs of externally sourced fish feed. Red arrows represent aquaculture outputs and orange arrows represent fisheries outputs, where farmed or wild-caught fish, respectively, are sold in majority to foreign markets. Those outputs that are sold locally may be in very small quantities and only to a select population of the local community creating an unequal distribution of resources and wealth within the community. Unclear rights, competitive markets, diverse regulations and license costs, and failure to manage risks could result in negative interactions or tradeoffs. Impacts from fishing, along with potential pollution or non-native organism escapes from aquaculture, may lead to decreased biodiversity and abundance of wild populations.

Exposure to and management of risks

Management of risks from climate change, harmful algal blooms, threats to water quality, disease, and other factors are key for the success of both fisheries and aquaculture. Assessments, monitoring, spatial planning, and other risk mitigation and adaptation efforts can help manage those risks within both sectors, with the potential for the generation of benefits to both sectors. Well-funded corporate, or locally-led, aquaculture installations could support climate change mitigation strategies, water quality monitoring, and investment in sustainability protections that benefit both the aquaculture operation and surrounding fisheries. The provisioning of aquaculture with locally caught or grown, and thus low-cost, feed or seed (Fig. 1a) could drive support from the industry, through increased interdependence, for sustainability measures within the SSF to help manage risks[43]. Moreover, if fishers become owners and operators of aquaculture facilities, this may also enhance opportunities to recognize and implement measures that enhance synergy, such as buffer zones around farms to protect fish that aggregate near the farms and increase fisheries yield. In contrast, the negative ecological impacts of aquaculture operations on coastal habitats and water quality would further exacerbate risks and erode the resilience of SSFs in the face of climate change and extreme events[44] (Fig. 1b).

RESULTS

Case studies

The 46 case studies we used to characterize interactions between SSFs and aquaculture had a global distribution across thirty different countries and varied in interaction scale from local to international (Fig. 2). In addition, the cases studies are varied in terms of spatial, management, and market scales. Species caught or grown in aquaculture and fisheries were diverse, with some species overlap between the two sectors. The identified literature which informed the analysis of these case studies tended to be relatively recent, with the oldest article from 1998.

The greatest number of studies originated in Asian (13) and European (12) countries, jointly accounting for over half of all studies. In contrast, there were limited numbers of studies from Africa (5), North America (7), Latin America and the Caribbean (5), and Oceania (4). It is worth noting that this distribution of studies is not reflective of the distribution of global aquaculture production as Asian countries produce about 92% of all aquaculture production across the globe (including both marine and freshwater production), but European countries are reported to produce only 2.7%[4]. The case study distribution may be reflective of the limitations of only including English language publications, and additional insights are likely gained from the inclusion of literature published in additional languages.

Nearly half of the case studies (20 of 46) comprised local interactions. These were cases that examined direct interaction between SSFs, and aquaculture installations located within the waters of the study sites. For example, one such case in Turkey considered the competition for space between fishers and the increasing number of seabream fish farms in the area, highlighting the decreasing access to fishing grounds and ensuing conflicts[45]. Regional case studies focused on impacts of aquaculture and interactions with fishing for a region rather than local communities, such as the shrimp aquaculture-fishing conflicts around the Chilika Lagoon in India. This case did not focus on specific sites, but instead on a broader region, highlighting the reduction in fishers' rights to marine space that has resulted from aquaculture development and the lack of economic benefits for communities within the region with the onset of aquaculture installations owned by groups from outside the region[46,47]. National studies were those that examined interactions between fisheries and aquaculture across an entire country's aquaculture and SSF system. For example, in China, aquaculture drives forage fish demand at the national scale due to the need for fishmeal as a key ingredient in aquafeeds[48,49]. Finally, the single international case identified focused on how the salmon fishery of Bristol Bay, Alaska, interacts with salmon aquaculture from Chile and Norway in international markets[50]. Here, interactions between the two geographically separated salmon sources are in markets and pricing.

Typologies and drivers of interactions between SSFs and aquaculture

Twenty-seven case studies contained enough information on rights, markets, and risk management for statistical analysis. Notably, few cases where there were weak SSF property rights remained after this filtering step. Factor Analysis of Mixed Data (FAMD) identified seven main clusters of systems characteristics from the 27 case studies (Fig. 3; Suppl. Fig. 1). *Cluster 1* includes two case studies from developed nations, both with extensive industrial aquaculture intended for export and supplied by imported seed and manufactured feed. These case studies are regional in scale, aquaculture is stable, and both fisheries and aquaculture are economically important. *Cluster 2* is comprised of two case studies focused on industrial shrimp farming in developing nations, which are dependent on imported feed and where the shrimp are produced for export. The local small-scale fisheries are considered overfished and aquaculture has negative impacts on the ecosystem. *Cluster 3* is comprised of large finfish aquaculture systems from developing nations which use hatcheries and imported feed, ranging from local to national scales, generally characterized by a strong influence and role of fisheries on income and livelihood and competition between the two sectors. *Cluster 4* includes local systems from developing nations, mainly characterized by strong local rights for SSFs, and high importance of fishing to local income and livelihood. This cluster includes both operations that use wild seed and/or feed in

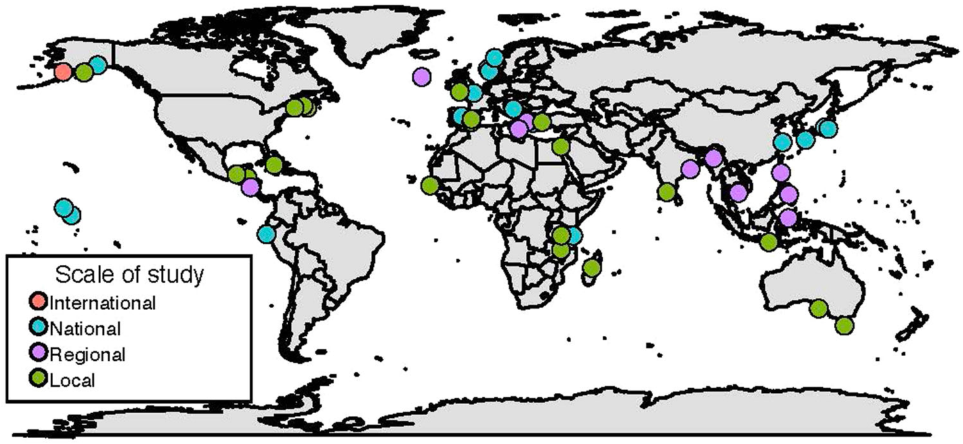


Fig. 2 Case study locations. Map of the illustrative case studies of co-occurrence and interaction of small-scale fisheries and aquaculture in coastal and marine settings. Colors represent the scale of each study, local to international, for 46 cases across 30 different countries.

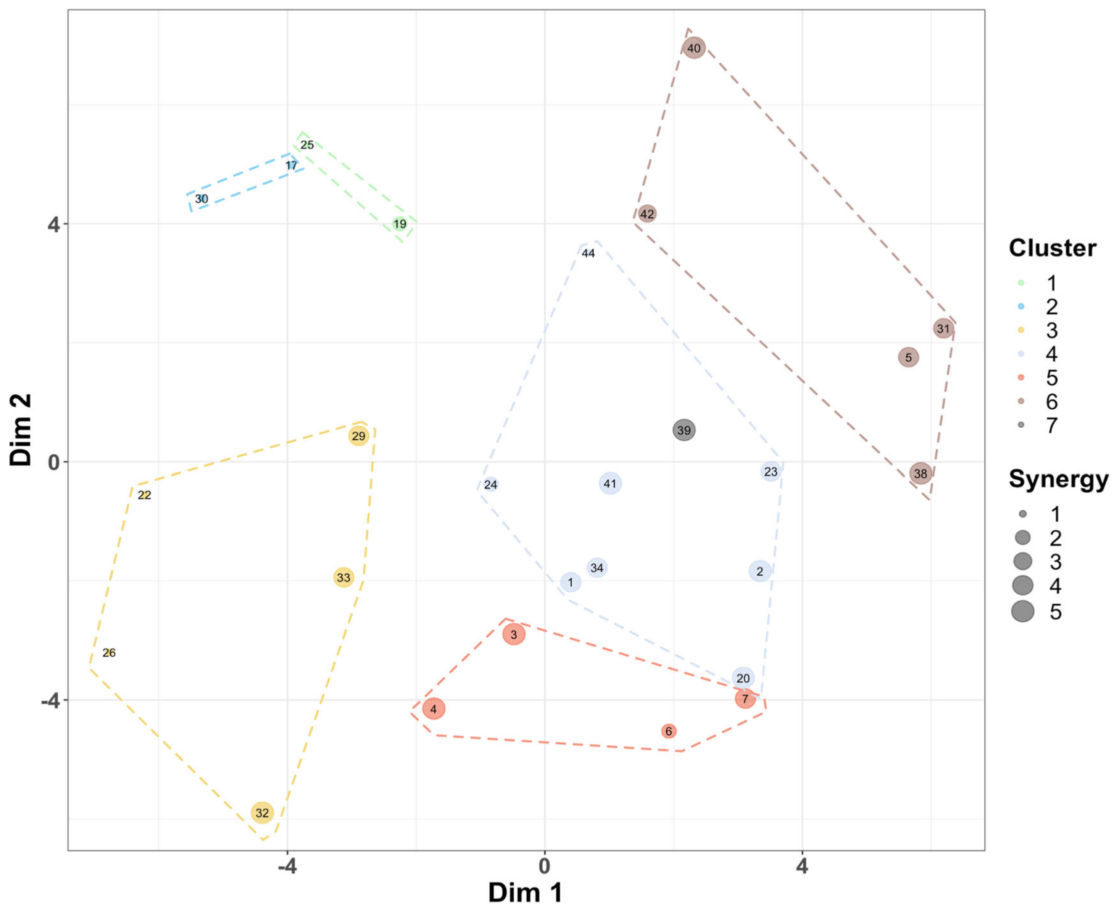


Fig. 3 Clustering of the Factor Analysis of Mixed Data. Results of FAMD on scores for the 27 case studies for which there was sufficient information across all categories (less than 5 cells containing no information). FAMD identified seven distinct clusters (labeled with different colors). The size of circles represents the level of synergy between small-scale fisheries and aquaculture for each case study, scores 1-2 correspond to negative impact of aquaculture on SSFs or competition between the two sectors, 3 - no effect or independence, and 4-5 a positive outcome or synergy (e.g., benefits from aquaculture for SSFs). While cluster 7 sits within cluster 4 in this plot it is separate in higher dimensions and comes out as a clear cluster if a dendrogram is performed on FAMD scores (see Suppl. Figure 1).

aquaculture, which have limited direct interaction with SSFs, and semi-intensive pen-based aquaculture developments, which have strong competition and conflict between the two sectors, e.g., through encroachment on fishing grounds or competition in markets. *Cluster 5* is made up of national, large-scale industrial and extensive operations that are mainly pond and pellet-based, where aquaculture is conducted by local farmers and has very little market or physical interaction with the fisheries, though some of the catch is used as feed in the farms. While blue food production of both kinds is important to communities, neither

Box 1. Examples of contrasting outcomes of interactions between SSFs and aquaculture. Details of two case studies which share several characteristics and are within the same cluster in the FAMD (Fig. 3, Suppl. Figure 1). Cases result in different synergy outcomes, highlighting the context-dependent outcomes of SSF-Aquaculture interactions.

Case Number & Location	Aquaculture details	Fishing details	Case Similarities	Synergy Outcome
24. China multi-species aquaculture	- National level, farming over 200 species - Aquaculture comprises 60% of global production[14,48] - Rely on imported fishmeal - Increasing demand for Chinese supplied 'trash fish' for feed[48] - Strong property rights - Concern about over-stocking, over-feeding, and antibiotic use in coastal installations[72,73]	- Wild capture is one-fifth of the global catch - 80% low-value small pelagic species, many over-exploited[49,74] - 'Trash fish' catches often not documented, assessed, or monitored - Strong property rights - Concern about increasing demand for unassessed 'trash fish' fisheries	Developed nation status Extensive farming Strong rights for farmers Fishery important to community	2 – Negative impact
41. Alaska seaweed farming	- Collaboration between researchers, government agencies & production companies - Rapid expansion without negative impacts on fisheries or community[75,76] - Regulatory barriers for entry, but government support for mariculture	- Aquaculture provides supplemental income for salmon fishers - Fishers included in aquaculture development - Fishers able to engage in aquaculture in the off season of salmon fishing - Co-design allowed for positive outcomes in both sectors[77]		5 - Synergistic

farmers nor fishers have strong rights, and regulations and management are established by central governments. *Cluster 6* is comprised of small-scale farms in developing nations that rely on wild seed and non-fed stocks (e.g. mussel farming) and their product supplies domestic markets. Some, but not all of these operations have strong *de* jure rights. The local SSF are overfished but there is no conflict or competition with the farms. The final cluster, *Cluster 7*, includes a single case of a foreign-owned aquaculture operation from a developed nation (Australia) where product is exported. While this case study is marked by initial strong conflict when aquaculture first began, subsequently no competition occurred, and the two producers make use of some of the other's product.

Clusters were broadly grouped by different levels of synergy between SSFs and aquaculture, based on the synergy score assigned to each case study (Fig. 3). Clusters 1 and 2, both comprised of cases of large-scale aquaculture, imported feed and export of aquaculture product, generally coincide with cases coded for antagonistic (negative) interactions between SSFs and aquaculture, with negative impacts and poor environmental, social and/or economic outcomes. Clusters 3 and 4 show both positive and negative outcomes. The strongest synergy is seen in clusters 5, 6 and 7. Shared characteristics of these synergistic cases include local ownership of large-scale aquaculture operations or small-scale farms, and/or a lack of competition or conflict between the two sectors.

It is important to note that, of the 27 focal cases that had sufficient information to be included in statistical analyses, 18 (66.7%) had relatively high synergy scores (4, 5), suggesting that, based on this sample, many cases of SSF-aquaculture interactions result in some social, economic, or environmental benefit. Conversely, however, one third of cases had negative outcomes. This large fraction of negative outcomes highlights a need for investigation of its potential drivers, and policy development to minimize these common negative outcomes of aquaculture development on SSFs.

The FAMD groupings point to system characteristics that may support synergies, or, conversely, negative impacts of aquaculture development on SSFs. In particular, among the hypothesized factors promoting synergies or trade-offs between SSFs and aquaculture, competition for resources (e.g., space) or in markets most commonly coincide with poor outcomes. The lack of case studies in the statistical analyses where SSFs had weak rights precludes inferences about the role of rights in shaping interactions with aquaculture in as rigorous a manner. Looking over the entire unfiltered list of 46 case studies does not help, as most studies with weak SSF rights did not provide sufficient information to judge whether there was synergy or not even at a discursive level. Of the 7 case studies where there were weak SSF rights and information on synergy, there did appear to be some form of synergy in 4 cases and independence in the other 3 – suggesting there is no simple answer in terms of the role of rights. Results also highlight that no single factor leads to positive or negative outcomes. Instead, combinations of characteristics and circumstances are associated with synergies, or conversely, trade-offs, even within the same cluster of case studies. This result is exemplified by Cluster 4, where some cases (e.g. cases 41 and 24) shared several characteristics such as strong aquaculture rights and importance of fishing to the community, but had opposite interaction outcomes (i.e., low or high synergy) (Box 1).

Qualitative modeling analysis of policy options

Because the outcomes of interactions between aquaculture and SSFs clearly depend on many factors, we used qualitative models to examine the potential social, economic, and environmental outcomes of interactions between SSFs and aquaculture under a range of possible arrangements of system elements (i.e., system structures) (Suppl. Note 1). Model analyses indicated a broad range of possible outcomes that were strongly dependent on the specific structure of the systems and assumptions about the types and effects of interactions, consistent with the high variability of outcomes from the review and analysis of empirical studies (Fig. 3).

Qualitative modeling highlighted the following main results for each policy category examined: 1) Policies that incentivize the development of small-scale aquaculture, with no other structural change, might result in an increase of this sector and external markets, but may negatively impact SSF, as well as equity, local markets, and secondary industries. 2) Policies that incentivize large-scale aquaculture are expected to result in an increase of this sector and external markets, as well as secondary industries, but could lead to negative impacts on SSF, equity and local markets. 3) Policies that incentivize integration of SSFs and aquaculture could lead to a mix of positive and negative outcomes, including expansion of both sectors, local and external markets and secondary industries, but possible negative outcomes for environmental status and equity.

A key insight of this analysis is that, while benefits or impacts on the different dimensions of the systems, such as SSF, aquaculture, markets, or the environment, were variable, many model structures and perturbations resulted in negative outcomes in terms of equity. This result suggests a high likelihood of policies having unintended differential benefits and impacts on different actors unless equity is intentionally considered and addressed in policy design and implementation. Moreover, none of the realistic structures implemented in the models resulted in stable systems, suggesting that aquaculture development that is not actively managed to promote synergy may result in unanticipated negative impacts. Thus, modeling corroborated the general insight from our case study analysis that promoting synergy between SSFs and aquaculture requires active, system-wide management and policies, informed by local contexts, needs and constraints.

DISCUSSION

Our analysis of marine aquaculture-SSF interactions shows that these interactions can result in a broad range of outcomes, from synergies to negative impacts, even within systems that share similar characteristics. Negative impacts on SSFs and different dimensions of blue food systems were common (~ 1/3 of empirical case studies, and a majority of model outcomes) and policies aimed at promoting aquaculture that do not explicitly consider SSFs and the multiple environmental, social and economic dimensions of coastal SES are likely to result in trade-offs, or unstable outcomes (e.g., initial benefits that are not maintained). To avoid negative outcomes, and to achieve synergy and equity in blue food systems that include SSFs and aquaculture, it will be important to intentionally design and actively manage these systems. Within the assessed cases, there are examples of multi-dimensional benefits across social, economic, and ecological outcomes; others have positive outcomes in only one or two of these dimensions, which are influenced by varying system characteristics and sector-specific goals. The strong context dependency of these results further highlights the need for careful design of policies supporting the development of aquaculture alongside SSFs so as not to compromise overall food production, food security, and the equitable distribution of benefits from both sectors.

SSFs often contribute non-monetary benefits to communities through nutrition, inclusion of women in the sector, and cultural value and livelihood, many of which are lost when SSFs disappear[11]. There can be unintended, yet severe consequences and disproportionate impacts on certain social groups, e.g., women and Indigenous communities, when SSFs are squeezed out by other sectors' growth[12]. This finding highlights a need for governments to establish safety nets for SSFs to provide social, economic, and public health protection from unplanned expansion of aquaculture into fishing areas.

FAMD analysis further highlighted context dependency of interaction outcomes by the seven clusters of systems with similar characteristics identified in the 27 case analysis. Four of these clusters were associated with either positive or negative outcomes in the interactions. In contrast, clusters 3, 4 and 5 were more heterogeneous, and included a mix of both. Overall, there was no single defining characteristic that led to a synergistic relationship between the two sectors, which appeared to be associated with different combinations of characteristics (Suppl. Table 5). Qualitative modeling further suggests that outcomes of interactions depend upon specific system structures and interaction assumptions, and that synergy is unlikely to occur without intentional implementation and active management. Conversely, some of these cases suggested that intentional design of an aquaculture operation with an explicit goal of enhancing fishery production resulted in a positive impact on the fishery, as would be expected. Such is the case of sea cucumber mariculture in Madagascar (case 2), which was developed collaboratively and intentionally between local communities and non-governmental organizations in partnership with private stakeholders[51].

Qualitative modeling also emphasized the potential for unintended impacts and unstable outcomes on different dimensions of SESs when SSFs were not considered and engaged during aquaculture development. Policies should prioritize economic and human development, and community health and well-being collectively, and consider contextual circumstances, feedbacks, and interactions within dynamic SESs[12]. Policies supporting the development of each sector in isolation carry high risks of negative impacts on SSFs or on some dimensions of social-ecological systems, including unstable provision and/or inequitable distribution of benefits.

Three broad factors can influence the interactions between aquaculture and SSFs: rights and access, markets and supply chains, and risks. Indeed, competition for space and in markets often underlie negative outcomes for SSFs in the case studies[52,53]. Policies and governance systems that provide clear and equitable rights and access, reduce competition in markets, and reduce exogenous risks to both aquaculture and SSFs are likely to increase synergies and reduce conflict between these sectors. Continual monitoring of indicators of these goals, and commitment to synergy between SSFs and aquaculture operations in the long term could help further the longstanding success and sustainability of both sectors. Further research assessing SSF-aquaculture interactions with the continued expansion of marine aquaculture may shed light onto the relative importance of these factors and help drive the improvement of blue food system design over time.

Because aquaculture and fisheries are often managed under different laws, policies, and management entities, planning and active management aimed at achieving positive outcomes for both aquaculture and fisheries is rare. However, coupled SES research suggests that promoting synergies between aquaculture and fisheries is possible through iteratively co-developing an integrated vision, and solutions, with diverse stakeholder interests[54,55]. Understanding the importance of fishing within the community can ensure maintenance or improvement of ecological, social, economic, and cultural factors within communities[56]. Furthermore, elevating SSF actors' voices and rights within the larger Blue Economy dialogues could help drive the development of policies that do not prioritize rights of the, often more powerful, aquaculture industry at the expense of local coastal communities[57]. Based on these results, we recommend that parties interested in promoting aquaculture in coastal regions should be intentional in their design and goals for application, carefully consider interactions with existing fisheries in targeted. Because the outcomes of interactions between aquaculture and SSFs are highly context-dependent, it will be important to employ participatory processes to elicit context-specific information on rights, markets, risks, and other factors, allowing for the implementation of blue food systems that are likely to result in synergies.

The delineation of space for fishing and aquaculture, and inclusion of diverse stakeholder input prior to aquaculture implementation, can allow each sector to maintain access to ecosystem goods and services and reduce competition for space and resources[58]. Additionally, the delineation of secure space-use privileges is expected to enhance clarity about regulations, rights, and responsibilities, potentially reducing conflict between the sectors[30].

SSFs provide crucial nutrition, livelihoods, poverty alleviation, and inclusion of women in the workforce[11,12]. However, the development of aquaculture and other blue economy sectors that limits or erodes the rights and access of existing SSFs can reduce these benefits and/or create inequitable distributions of benefits[59]. This analysis highlights that adopting human rights and equity as key goals in aquaculture development is critical for ensuring more sustainable and equitable paths for blue food systems[31]. The potential for adverse impacts on SSFs when aquaculture and SSFs interact also suggests a need for more balanced investment in both sectors, including continued investment in SSFs[12]. This, combined with participatory planning and implementation, can help promote the success of both sectors, and help promote synergistic outcomes.

Rights-based governance allows for consideration of actors who are deriving benefits from the marine environment and continued protection of this access, resulting in social and economic benefits[60]. The intersectionality of these aquaculture actors, the centering of human rights and equity in aquaculture, and the implementation of inclusive solution models have been suggested as a way to move forward in aquaculture development[61]. Continual investment in addressing system-wide coastal community needs, through engagement with coastal stake- and rightsholders, can help balance development outcomes, and ensure equitable distribution of benefits[62]. Additionally, engagement with SSF actors can allow for a balance of investment between the two sectors, particularly when the needs of SSFs are often less clear than those of the aquaculture sector, a result of differences in power and political influence, along with the diffuse and diverse nature of SSFs. As such, a clear delineation of rights and understanding of how communities can derive benefits from access in both sectors is recommended for promoting synergy and reducing conflict between aquaculture and SSFs.

In this work, we showcase how context and objectives matter in the implementation of aquaculture alongside SSFs, and reveal how intentional, proactive management is key to the mitigation of negative social, economic, or ecological outcomes. In the absence of planning, design, and active management, the strong interest and investment aimed at increasing aquaculture production worldwide could result in increasingly negative consequences for local food production, livelihoods, and environmental quality in SSFs, at a time when the world needs to increase food production while simultaneously improving the social and ecological performance of all food systems[63,64]. Results of this review and analysis highlight that managers and decision-makers should consider approaching aquaculture implementation in a collaborative and adaptive manner, with clearly defined goals, understanding of local SSF importance and contexts, and attention to the ways in which access, rights, markets, and risk management can affect food production, livelihoods, equity, ecological outcomes, and the distribution of benefits across blue food sectors and actors.

METHODS

To examine the interactions between SSFs and marine aquaculture and evaluate whether the hypothesized drivers, rights, markets, and risks, result in synergisms or trade-offs across diverse contexts, we identified 46 case studies of SSF-aquaculture interactions reported within literature published in English. Literature written in other languages was not included due to language limitations.

Case study selection

Identification of case studies for analysis involved the following steps. First, co-authors provided and vetted possible case studies from their knowledge of diverse systems, during two workshops. Case study identification utilized the expertise of fisheries and aquaculture experts from a diversity of geographies and contexts. These potential case studies were further evaluated through an initial literature search to select cases in which interactions between small-scale wild capture fisheries and aquaculture or mariculture were explicitly investigated. Information on these suggested case studies was then tracked and identified through web-based searches (e.g., press releases, project reports, Google scholar) to identify all published and grey literature on the cases. Additional examples were also included from the searches and identified resources. This iterative process resulted in the selection of 46 focal case studies (Suppl. Table 2). These case studies should not be viewed as a comprehensive database of all systems, but rather as illustrative examples of SSF-aquaculture interactions. The aim was not to comprehensively review all available information, but instead to span a range of contexts, geographies, and modes of marine aquaculture development alongside SSFs, with the goal of increasing understanding of how different types of aquaculture operations affect fisheries through interactions in ecological, economic, or social realms within the communities.

For each case study, relevant documents were reviewed, and the following information was extracted for each of these five categories of information on both sectors, their interactions, and the impact of aquaculture implementation (Suppl. Table 3):

(i) Social-ecological characteristics of the aquaculture operation. This includes information such as location, market orientation, scale, species cultivated.

(ii) Fisheries characteristics before the aquaculture operation began. The characteristics of the fishery prior to aquaculture installation in the region were extracted from each case study. This includes information such as how the fishery was managed, the strength of property rights associated with the fishery, and the presence of physical infrastructure supporting the fishery, such as processing plants.

(iii) Interactions during the initial implementation. The interactions between the fishery and aquaculture while the aquaculture operation was first being installed are described. This includes information such as the proportion of fishers who became aquaculturists, the initial presence and strength of conflict between the two industries, and any initial concerns of the fishers.

(iv) Interactions once the installation was fully operational. Changes in the interactions between aquaculture and fisheries are described as aquaculture developed over time. Examples include changes in economic revenue and strength of property rights for each industry.

(v) Outcomes of the SSF-aquaculture interaction. The nature of the interaction is described. This includes information on the importance of the aquaculture operation to the local community, the nature of risk involved, and the reliance of each industry on the other, such as reliance of aquaculture on wildfeed. It also includes information on who bears the greatest risk, the stability of the aquaculture operation, synergies between the sectors, and market interactions.

Information extracted in these five categories was coded for presence/absence or along a gradient scale (weak to strong, 1-5) from available information, using the rubric included in Supplementary Materials (Supplementary Table 4). Any missing information was left blank. Each case study was assigned a score from 1-5 ranking the degree of synergy between the fishing and aquaculture sectors. An overall score of 1-2 indicated strong to mild negative, or antagonistic, impact of the interaction on the environmental and/or human dimension of the SSF; a score of 3 no evident impact, either negative or positive; and a score of 4-5 mild or strongly positive impact, meaning case studies reported benefits, from aquaculture, for the environmental, socioeconomic, and human health dimensions of SSFs (Supp Table 4).

Case studies analysis and initial scoring was conducted by research interns as part of the Yale Environmental Protection Clinic program in 2018 and subsequently completed by research interns in the Environmental Defense Fund's Oceans Program in 2019, under the guidance and supervision of co-authors RF and KR. After the completion of this first analysis, co-authors EJM, RF and FM conducted a second review of the case studies and scores to ensure consistency before statistical analysis. Thus, coding and scores were independently assigned and verified by multiple co-authors.

Statistical analyses

Factor Analysis of Mixed Data (FAMD), one of the recommended multivariate clustering methods when using a mix of quantitative, categorical and ordinal data[65], and Ward-D2 hierarchical clustering of the scores was used to identify clusters of cases with similar characteristics and examine whether clusters corresponded to different levels of synergy between SSFs and aquaculture. This was undertaken via the *stats* package of R version 4.0.2[66] and the *FactoMineR*[67] and *factoextra* packages[68]. Because each of the attributes listed above were included in the analysis, cases with substantial missing data (i.e., assessed characteristics could not be rated given available information) could impact the outcome. Consequently, we excluded case studies with more than 5 blank cells from the FAMD due to lack of data availability. This resulted in 27 case studies that had sufficient information to be included in this statistical analysis. We used these 27 cases to identify clusters of case studies that share similar characteristics, while we reviewed the remaining cases to draw general, qualitative insights and examples of interactions and outcomes. Additional analyses were run with more/less missing data to verify stability of the results with 5 or less missing scores. Most of the omitted case studies were at a national scale from Europe.

Qualitative model analysis of policy options

Analysis of case studies and review of the literature highlighted a suite of policies and investments that have been implemented to support aquaculture development, representing different goals and contexts. In addition to examining the resulting interactions and outcomes through case studies, we explored them more generally through qualitative models (in the form of signed digraphs and loop analysis, following the methods outlined in[69]). Different approaches have been proposed to explore the possible outcomes of interactions within complex social-ecological systems[70]. We applied qualitative modeling because this approach has been used widely across many contexts to understand the internal structure and dynamics of complex systems and is useful in both eliciting understanding but also ensuring consistency in conceptual models (Suppl. Note 1).

Qualitative models were drawn up based on the expertise represented by the author group and from information available in the publications reviewed. The key components of each system and the nature of their connections – i.e. whether the increase in activity in one component is expected to cause an increase, decrease or no change in connected components, as shown in Suppl. Note 1- were identified and vetted in a series of workshops. These models considered three categories of policies that are expected to influence the interactions between aquaculture and SSFs and the outcomes (e.g. synergistic or antagonistic) of these interactions: 1) policies that incentivize the development of small-scale aquaculture (e.g. low-level investment in infrastructure, space allocations, or incentives for conversion of small scale fishers to farmers); 2) policies that incentivize large-scale aquaculture (high investment in infrastructure, markets for high trophic level species, e.g. salmon); and 3) policies that incentivize integration of SSFs and aquaculture (e.g. development of aquaculture within Territorial Use Rights for Fishing - TURFS; SSFs for parts of the supply chain; aquaculture for ecological restoration). Simple stability metrics and press perturbation analyses were then applied to these models to explore potential responses to the development of different seafood sectors or changes in the market or environment[71].

DATA AVAILABILITY

Data that support these findings are available from the corresponding authors upon reasonable request.

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AUTHOR CONTRIBUTIONS

E.J.M. and F.M. are co-first authors and led the design of the study, writing, editing, and finalization of the manuscript. E.J.M. provided data analysis and manuscript formulation. F.M. developed the study concept and hypotheses, manuscript formulation, and data analysis. RF was a part of the concept development, advised the data collection and scoring, provided second-wave data analysis, and made significant contributions to writing and editing the manuscript. E.A.F. performed all

quantitative modeling and PCA analysis of the data and contributed to concept development and finalization of the manuscript. R.B., L.C., E.F., S.G., S.G., H.P., M.R., A.S., R.S., C.W. and M.J.W. were all a part of the concept and hypotheses development and contributed to finalizing the manuscript drafts. BD contributed to data collecting and case study scoring, and K.R. advised data collection and scoring along with initial concept and hypothesis development. R.N. contributed to the concept and hypotheses development and manuscript formulation and writing. All authors read, edited, and approved the final manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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