

The aquaculture supply chain in the time of pandemic: vulnerability, resilience, solutions and priorities at global scale

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Abstract

A year after its appearing COVID-19 global pandemic has severely hit the perishable food supply chains (PFSC) by triggering large, unpredictable, synchronous impacts affecting all the chains' levels, across multiple sectors and spatial scales. Here we present a rapid assessment, performed on global scale to assess the effects of COVID-19 situation and related control measures specifically on the aquaculture supply chain sector. Aquaculture as one of the most vital sector in contributing to global food security directly by the production of high-quality animal proteins showing a steady stable increasing trend of production worldwide. COVID-19 effects on the socio-economic dimension have been analysed by surveying the perceptions of stakeholders to depict potential supply-side disruption, vulnerability and resilience patterns along the production pipeline (4 main SC components: hatchery, production/processing, distribution/logistic and market; 4 main farming strategies: land- and sea-based, both extensive and intensive, with and without IMTA). Apart from the evaluation of the economic distress, interviewed were asked to indicate the mitigation solutions adopted at local or internal (i.e., farm-site) scale, and to express their preference on national and external scale mitigation measures among a set of *a priori* selected option. Interesting patterns emerged across the PFSC, the farming strategies and countries. The surveyed perceptions generated a global snapshot, highlighting causes of disruption, ripple effects, sources of food insecurity and socio-economic conflicts. The collated evidence represents a first baseline study, useful to address future disaster-driven responses as well as to reinforce the resilience of the sector and to facilitate the design of tailored reconstruction plans and financial aid strategies.

Key words: COVID-19, Perishable Food Supply Chain, IMTA, disruption, economic distress, mitigation measures, stakeholders' perception, rapid-assessment

Introduction

A year ago, in March 2020, the World Health Organization (WHO, 2020f) declared the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) disease, officially known as COVID-19, as a global pandemic. Since its first recognition in China, in late December 2019, the virus spreading vastly, reaching all the countries in the world, causing more than 2,907,944 deaths and counting 140,322,903 confirmed cases (<https://www.who.int/emergencies/diseases/novel-coronavirus-2019> accessed at 18/04/2021), numbers second to the Spanish flu only in the contemporary age. In a fight against time to slow the spread and to contain the severe deadly outbreak across the Planet, the affected countries have made enormous efforts, by imposing containment and suppression measures with several degrees of rapidity and strictness (Guan et al., 2020). People experienced unprecedented measures in their lifestyle, full lockdown, closed borders, severely restricted – in some cases fully suspended – international travels, no public gatherings and with clear impacts on the worldwide productive sectors (FAO and CELAC 2020).

By now, a year after its appearing, COVID-19 global pandemic has severely hit the food supply chains (FSCs) – among which perishable food supply chains (PFSC) are the worst hit – by triggering large, unpredictable, synchronous impacts affecting all the chains' levels, across multiple sectors and spatial scales, showing all the features of a shock event which risks ranged from humanitarian and social issues to an uncertain business environment (Cottrell et al., 2019). By affecting four food security main pillar, availability, accessibility, utilization, and stability (Laborde et al., 2020), with a long-term duration and ripple effects propagation (i.e. both supply shortage and demand shrink leading to simultaneous or sequential forward and backward propagations of disruptions), the COVID-19 outbreaks represents a special case of FSC disruption (Ivanov, 2020; Li et al., 2021 and references therein), with impacts characterised by unpredictable local disruption, hence hard to prepare for and manage. Dozens of scientific studies, reports and policy briefs have been produced for several nations focusing on FSCs essential services in a pandemic (see Queiroz et al, 2020; Chowdhury et al., 2021 and references therein), in the attempt to: report the immediate short-term and preliminary consequences on the environment, societies and economies (GFCM 2020; ILO, 2020a, 2020b; UNCTAD, 2020); describe the larger, unpredictable, and synchronous impacts recorded; report a lack of resilience and flexibility (Chenarides et al. 2021); disentangle severe disruption phenomena on various parts of the FSC (e.g. GFCM, 2020; FAO 2020a-d; Love et al., 2020); focus on the effects on more vulnerable categories (e.g. small scale fisheries, Bennet et al., 2020; small and medium enterprises, Caballero-Morales 2021); looking at the synergistic impacts with anthropogenic stressors (Sarà et al., 2021). A lack of pre-pandemic data baselines has been

underlined (White et al., 2021), alternative seafood networks have been proposed (Stoll et al., 2020), surveys have been mostly used to - also virtually - reach stakeholders (van Senten et al., 2021; Smith et al., 2020), non-traditional indicators (White et al., 2021; Love et al., 2021), simulations and modelling (Guan et al. 2020; Ivanov, 2020; Ivanov & Dolgui, 2020; Stoll et al., 2020) and literature review (Queiroz et al., 2020; Chowdhury et al., 2021) have been applied. A huge effort of data collation and analyses always culminating with the promotion of novel frameworks and mitigation strategies, recommendations, best practices and tools (Li et al., 2021; Love et al. 2021; Marusak et al., 2021; Nandi et al., 2021; Kumar et al., 2021; Jamwal & Phulia, 2021), useful to help building system's resilience (see seafood system, Love et al. 2020; crop sector, Chenarides et al. 2021; PFSC, Kumar et al., 2021; regional food system, Marusak et al., 2021). A series of credible, salient and crucial evidence aimed at informing policy makers dealing with the emergency to protect economy locally, i.e. when designing emergency governmental legislations from the perspective of both developing or advanced economies (International Monetary Fund <https://blogs.imf.org>; The World Bank 2020).

Here, we present a rapid assessment, performed on global scale, to assess the effects of COVID-19 and related control measures specifically on the aquaculture supply chain sector, a PFSC, generally analysed as convergent to the seafood supply chain, or rather fisheries sectors, together with fishing (Love et al., 2021; White et al., 2021). Aquaculture has been selected for its importance in contributing to food security directly by the production of high-quality animal proteins showing a steady stable increasing trend of production worldwide (FAO, 2020e). We surveyed the perception of stakeholders – from owners to managers – operating on both sea- and land-based aquaculture systems, farming following both intensive and extensive strategies. The effects due to COVID-19 on the socio-economic dimension of this PFSC have been analysed by surveying the perceptions of stakeholders to depict potential supply-side disruption, vulnerability and resilience patterns along the production pipeline, by considering four main components: hatchery, production/processing, distribution/logistic and market. Apart from the evaluation of the economic distress, we asked the interviewed to indicate the mitigation solutions adopted at local / internal (i.e., farm-site) scale, and to express their preference on national / external scale mitigation measures. Interesting patterns emerged across the PFSC, the farm strategy and *per* country, common responses emerged intra- and inter-farming strategies. The perceptions collated by our rapid assessment generate a global snapshot, highlighting causes of disruption, sources of food insecurity and socio-economic conflicts that may exacerbate as the pandemic continues and considering the high likelihood of more pandemics into the future. The emerged pattern of vulnerability and resilience may represent a first baseline useful to

facilitate the design of tailored future reconstruction plans and financial aid strategies (i.e., countries recovery plans) and to address future adaptive and disaster-driven responses to reinforce the resilience of the sector.

By also surveying systems that adopted an Integrated Multi-Trophic Aquaculture (IMTA) we tested the hypothesis that this practice could add resilience to the aquaculture PFSC and production systems by increasing the diversity of fished species, local production (Troell et al., 2014) and allow farmers to circumvent deadlocks in some steps of the PFSC. Up to date we are unaware of studies that have tested this hypothesis for aquaculture PFSC neither that zoomed on aquaculture PFSC at this global scale.

Methods

A semi-structured questionnaire (study approved by the Ethical Committee at the University of Palermo, UNPA-183-Prot. 767-05/05/2020 n. 1/2020 29/04/2020; see supplementary material) was designed, translated into 12 languages (English, Italian, Spanish, Chinese, Croatian, Portuguese, Arabic, Turkish, Swedish, Greek, Divehi, Albanian) and transferred on Qualtrics (<https://www.qualtrics.com>) an online platform that allowed the creation of a web survey that was distributed to stakeholders by asking all the co-authors to promote the compilation of the survey among their communication and dissemination channels linked to the aquaculture sector. A brief presentation of the project and authors was added on the first page, mainly to explain the reason for collecting information and the potential final outcomes, as well as to obtain the informed consent of the respondents. The web survey distribution lasted three weeks (5 - 29th, May 2020). We decided to keep the survey active during a short temporal window - while the COVID-19 pandemic was fully active in most countries - to ensure a data collection representative of the reactive phase of the emerging crisis and to avoid including any later post-pandemic stages and to facilitate a rapid-assessment (Sarà et al., 2021) a temporal frame in line with severe disruption already clear of other FSCs (Chenarides et al., 2021).

Replies were coded as a function of geographic position of the farms and the typology of reported aquaculture system (four *a priori* selected categories: land based extensive aquaculture [fish, invertebrates, algae etc.; LBE], land based intensive aquaculture [tanks/ponds; LBI], sea based extensive aquaculture [mollusc-culture, algae, echinoderms etc.; SBE], sea based intensive aquaculture [cages; SBI]). We asked to report also if the system was based on Integrated Multi-Trophic Aquaculture system (IMTA). With the aim to collect information on the economic distress perceived by the interviewed, the survey started asking to report economic and job losses associated

to COVID-19 outbreaks (scaled from 1 = no economic loss at all, to 10 = very high economic loss and subsequently ranked into four categories: no effect 1, low 2 – 4; moderate 5 – 7 and high 8 – 10). Consecutive specific questions were asked to rapidly assess the effects on the four selected stages of the aquaculture PFSC. To investigate potential effects on the hatchery stage, we asked respondents to specify if they encountered difficulties (resulting in economic loss scaled from 1 = no economic loss at all, to 10 = very high economic loss) respectively with: lack of juvenile/fry supply, lack of raw materials provision (both in term of reduction of available raw materials - feeds, packaging material - and price increase), issues with insurance coverage (i.e. difficulty/insolvency or block/abandonment by insurance companies), block of auctions (i.e. licences). The production/transformation stage was surveyed by asking if issues were encountered with infrastructures (i.e. missing freezing container, smoking room, packaging, other), labours failure (i.e. seasonal recruitment of farmers) and difficulties of suppliers in collecting seafood. Effects on distribution / logistic stage were surveyed asking for increase in transportation prices and restriction / block on transportation (e.g., flight cancellation, closures of geographical borders between countries). Effects on market stage were explored as potentially resulting from: farmed products price decrease / loss (i.e. depreciation due to a load in production and a loss in request), impossibility/difficulty in selling to national buyers/consumers, to enter the international markets, absence of customers on the distribution channel (e.g., tourists, schools, restaurants, etc.) and of middlemen. Participants have also been asked to indicate any adopted mitigation solutions at local / internal scale (i.e., farm-based and related to the SC; expressing preference scaled from 1 = not adopted, to 10 = very high adopted) among the proposed: social distancing (e.g. working shift), increase work efficiency, hiring (e.g. new professional profiles), firing personnel, integrated-multi trophic solutions, change in farm techniques, reduction of farm dimension (e.g. cages number or used surface), stocking solutions (e.g. freezing and smoking). We additionally asked to express their preference on foreseen national / external scale mitigation measures: i.e., direct sales to final customers, foster supply chain, search new market (e.g. canning industry), demand economic support (e.g. economic subsidy from regional or national bodies), explore new market strategies (e.g. online retail system and brand), demand support to scientists (see supplementary materials).

Data on economic distress were represented *per* each farming strategy and with and without IMTA (Figure 1, 2). To summarise the results obtained respectively on: encountered difficulties and related economic loss across the PFSC stages, the adoption of internal mitigation measures and the preference of external mitigation measures, we calculated the mean response value to each specific

question given by stakeholders grouped by nation (Figures 3, 5) to produce heatmaps by using the ComplexHeatmap package for R (Gu, Z., 2016).

The effects of IMTA in buffering economic distress was tested by using a 2-way mixed ANOVA with Poisson family error distribution for discrete dependent variable (Score from 1 to 10) using the R package “*lme4*” (Bates et al., 2015). Predictive variables were “farming strategy” (fixed with four levels “LBE”, “LBI”, “SBE”, “SBI”) and “IMTA” (fixed, orthogonal to “farming strategy” with two levels “Yes” and “Not”). The “position of farm” (i.e. Country) was used as a random intercept to account for any source of variability linked with the various surveyed countries. Once the model was run, we checked the absence of any pattern dealing with the residuals and their normality distribution. Estimated marginal means (EMMs) for factor combinations was used as post-hoc test after mixed ANOVA (R package “*emmeans*”; Russell et al., 2021). Principal Components Analysis on a multivariate dataset of answers related to effects reported *per* every aquaculture PFSC stage (Hatchery, Production / transformation, Distribution / logistic, Market) and *per* adopted both internal farm-site mitigation measures and external potential mitigation measures were computed using the R packages “*vegan*” (Oksanen et al., 2020) and “*stats*”. The function “*envfit*”, which fits environmental vectors or factors onto an ordination, was used to graphically displayed correlation between multivariate dataset of answers and explanatory variables (“IMTA Yes vs IMTA Not”; “Land- vs Sea-based”, and “Intensive vs Extensive”). The p-values and correlation values between each explanatory variable and PCA axis have been also calculated. Linear mixed regression models using the “*glmer*” function (R package “*lme4*”; R Core Team, 2020) were used to test significant correlation between explained variables and PCA scores of axes 1 and 2. The “position of farm” (i.e. Country) was used as a random intercept to account for any source of variability linked with the various surveyed countries.

Results

Our rapid assessment web survey allowed to cover stakeholder’s perception from all around the globe encompassing the five continents and reaching 52 countries (Figure S1, supplementary materials). The survey was filled by 585 stakeholders (80% male, 14% female and 6% other), aged from 18 to more than 60 years old (4% of 18 - 29 y/o, 28% of 30 - 39 y/o, 32% of 40 - 49 y/o, 30% 50 - 59 of y/o, 6% of > 60 y/o) reporting a medium/high instruction level (4% primary school, 23% secondary school, 54% university [bachelor or master], 19% PhD). Respondents declared to operate on the four *a priori* selected farming strategies, respectively: 43% land based intensive aquaculture (LBI), 16% land based extensive aquaculture (LBE), 23% sea based intensive aquaculture (SBI) and

18% sea based extensive aquaculture (SBE). A 20% of total surveyed farming strategies have been structured into IMTA (22% LBI, 23% LBE, 23% SBI and 18% SBE).

Participants reported economic distress due to COVID-19 outbreaks in terms of both economic and job losses, responses clearly differ among farming strategies (see percentages *per* four categories: no effect 1, low 2 – 4; moderate 5 – 7 and high 8 – 10; Figures 1, 2). The highest levels of economic loss were reported at extensive systems both on land and at sea (i.e., LBE 45% and SBE 42%), the lowest economic loss was reported under IMTA at SBI (10%). The highest percentage of no-effect were reported at IMTA LBE (36%) and SBI (51%; Figure 1). Countries as India and South Africa reported higher economic loss associated to LBI and SBE; associated to LBE in Portugal, Ireland and Algeria; to SBI in Northern Europe. Therefore, the reported economic loss was not significant among the farming strategy neither if looking at the presence of IMTA (mixed ANOVA test, factor “farming strategy” $df = 3$, $p = 0.236$; factor “IMTA” $df = 1$, $p = 0.625$; “Interaction farming strategy / IMTA” $df = 3$, $p = 0.154$). Countries *per* farming strategy have experienced various pattern of job loss (Figure 2), the highest percentage interested the LBE (35%), while the lowest was recorded at LBI (59%). The job loss was significantly correlate with the farming strategy and depended on the combination of farming strategy and the presence of IMTA (mixed ANOVA test, factor “farming strategy” $df = 3$, $p < 0.001$; factor “IMTA” $df = 1$, $p = 0.96$; “Interaction farming strategy / IMTA” $df = 3$, $p < 0.05$). Specifically, without IMTA, LBE showed the highest rate of job loss compared to the other farming strategy (Estimated marginal means tests: LBE vs LBI $p < 0.0001$; LBE vs SBE $p = 0.0001$; LBE vs SBI $p < 0.004$). All the farming strategy with IMTA recorded lower values of job loss (Estimated marginal means tests: IMTA vs noIMTA $p = 0.013$).

Stakeholders working both at land- and sea-based systems reported major difficulties and associated economic loss associated with “distribution / logistic” and “market” stages of the aquaculture PFSC, specifically with “transportation restriction” and difficulties to enter products on “international markets” and to generally reach buyers (from “consumers” to “middlemen”, “customers” and “retailers”; Figure 3). Specifically, a PCA performed on a multivariate dataset of answers related to “hatchery” stage revealed that the examined variables significantly correlated with PCA ordination (PC1 explained the 56.28% and PC2 the 19.40% of total variance, respectively; Figure 4). “Intensive / extensive” (Chisq = 6.348, $df = 1$, $p = 0.011$) and “IMTA” (Chisq = 4.674, $df = 1$, $p = 0.03$) were significantly correlated with PCA scores of axes 1, and more specifically the presence of IMTA and extensive aquaculture were associated with major difficulties in the juvenile, fry and raw materials supply and insurance and auction licence respectively, as also confirmed by comments left by some of the interviewed farmers (Table 1; Figures 3, 4). When performing PCA ordination on multivariate

datasets of answers related to “Production/transformation” stage” (PC1 = 66.61%, PC2 = 22,05%), “Distribution / logistic” (“ PC1 = 78.48%, PC2 = 21.52%) and “Market” (PC1 = 63.28%, PC2 = 13.27%) stages of the PFSC none of the explained variables were significantly correlated with PCA ordination scores. Therefore, dealing with economic loss at the production / transformation stage interviewed farmers reported the unbalance by farms maintenance costs and revenues, operational constraints, labour’s higher costs (see more comments in Table 1; Figure 3). At the market stage interviewed farmers reported the higher economic loss associated to liquidity shortage and excessive fall in prices (Table 1; Figure 3).

Participant from all the surveyed farming strategies recognised social distancing and the related working shift as the most adopted internal mitigation measure, followed by the increase of work efficiency. At LBE and SBE stocking was expressed as the third most adopted mitigation solution, followed by hiring and firing while the adoption of integrated solutions and the changes in farm techniques and dimension were less successfully recognised. LBI and SBI recognised a higher importance to integrated solutions and changes in farm techniques and dimension compared to firing (Figure 5). A PCA performed on a multivariate dataset of answers related to “internal mitigation measures” revealed that the examined variable significantly correlated with PCA ordination (PC1 explained the 41.45% and PC2 the 13.35% of total variance, respectively; Figure 4). “IMTA” (Chisq = 20.51, df = 1, $p < 0.001$) was significantly correlated with PCA scores of axes 1, and more specifically the presence of IMTA was associated with high score answer of the following variables: hiring (PC1 0.998, $p = 0.001$), stocking (PC1 0.902, $p = 0.001$), integrated-multi trophic solutions (PC1 0.898, $p = 0.001$), change in farm techniques (PC1 0.798, $p = 0.001$), increase work efficiency (PC1 0.771, $p = 0.001$), reduction of farm dimension (PC1 0.716, $p = 0.001$), firing (PC1 0.627, $p = 0.001$). Specifically, several among stakeholders left specific comments to report their experience in adopting “changes in farm techniques”, “integrated-multi trophic solutions” and “reduction of farm dimension” (see Table 1, Figures 4, 5).

External mitigation measures to be explored showed very heterogeneous pattern of preference across the farming strategies (Figure 5). At LBE the higher importance has been recognised to direct sale, followed by the opportunity to foster the supply chain, the search for new market, the demand of economic support and the exploration of new market strategies. The request of economic support has been recognised of higher importance at LBI, SBI and SBE followed by direct sale, new markets and new market strategies, and the opportunity to foster the supply chain at sea-based systems. The request of support from scientists reached the lowest scores across all the investigated farming systems. A PCA performed on a multivariate dataset of answers related to “external mitigation

measures” revealed that the examined variable significantly correlated with PCA ordination (PC1 explained the 50.51% and PC2 the 15.19% of total variance, respectively; Figure 4). “IMTA” (Chisq = 8.50, df = 1, p = 0.003) was significantly correlated with PCA scores of axes 1, and more specifically the presence of IMTA was associated with high score answer of the following variables: new markets (PC1 - 0.949, p = 0.001), new market strategies (PC1 - 0.916, p = 0.001), economic support (PC1 - 0.984, p = 0.001), direct sales (PC1 - 0.611, p = 0.001), scientists support (PC1 - 0.586, p = 0.001), foster supply chain (PC1 - 0.484, p = 0.001). When asked to report their preference on external mitigation measures to be adopted into the future, specifically several among stakeholders expressed their preference on “new market strategies” and “foster the supply chain” by providing more articulated comment on the need for “economic support” (see Table 1, Figures 4, 5).

Discussion

Our rapid global assessment allowed to identify specific circumstances that inhibited or made more difficult the stakeholders efforts to adapt to the pandemic-induced challenges across the four surveyed farming strategies. Data collated allowed to depict the ripple effects propagation of the COVID-19 outbreaks along the four analysed stages of aquaculture PFSC, identifying the main reasons of supply shortage (e.g. shortage and higher price of raw material at the hatchery stage; absence of stocking infrastructure at the production stage; transports interruption at the distribution stage) and demand shrink (e.g. food industry and markets closure at the market stage) causing the lack of resilience threatening the aquaculture sector, the most efficient, productive and promising food industry in the world (FAO, 2020e). The limited options to transport products represented the weakest link of the aquaculture pipeline across the four surveyed farming strategies, with farmers paying more for the transport being underpaid for their products. Both transport restrictions and transport prices rise have been recognised as a common cause of disruption propagation both forward - up to the market where the accumulation of perishable biomass with market value lost caused a shrink in demand - and backward - back to the production and hatchery stage with reduction of raw materials supply and price increase. The market stage has been recognised as the second vulnerable link encountering severe disruption due to the closure of local, national and international markets as well as the stopping of the HoReCA channel (i.e. hotels, restaurants and catering industry) resulting from sudden and prolonged lockdowns, being also source of relevant forward disruption propagation and the main cause of demand shrink.

The widely reported economic distress propagated both ways along the aquaculture PFSC and across the four analysed stages. Economic loss associate to insurance coverage (i.e. difficulty/insolvency or

block/abandonment by insurance companies) on the initial hatchery stage, generated a key source of financial instability, as farmers can only produce if having access to finance. As a main consequence, not surprisingly, the request of economic support was the more acclaimed external mitigation measures by our stakeholders. Financial sustainability is in fact essential for stakeholder of the FSC and has been reported among the top risk mitigating strategies for PFSC (Cullen, 2020; Kumar et al., 2021).

Following Christopher & Peck (2004) definitions of the fundamental trade-off between FSCs efficiency and resilience, evidence from our global assessment, confirmed that aquaculture PFSC - at the surveyed shock stage of the COVID-19 pandemic - failed in maintaining the three elements to achieve resilience, or rather, agility (i.e. ability to respond rapidly), visibility (i.e. ability to see “end to end” in the pipeline), and increasing velocity (i.e. time/distance reduction). To promote agility and visibility stakeholders should work to foster a more horizontal collaboration, one of the resilience components reported for the land based FSCs (Marusak et al. 2021), by building contingency plans for their operations that include different stakeholders, to facilitate cooperation among the FSC stages and among different SCs more in general. Contingencies, as well as new opportunities in the market and business environments, should be catalogued, communicated and exchanged among stakeholders to allow clustering their logistics activities and assets, promoting shared transportation, stocking and processing facilities to reach a greater velocity and efficiency while reducing logistics costs (Pomponi et al., 2015).

Practicing social distancing and the reduction of physical interactions were essential mitigation measures to contain COVID-19 diffusion, not surprisingly here reported as the most adopted internal mitigation measures by the participants to the survey, across all the farming strategies, therefore being aquaculture a PFSC characterised by operations that require a lot of physical contact and human interaction for various activities, this might have been also one of the reasons fostering job loss.

The buffering power of Integrated Multi-Trophic Aquaculture vision

By surveying systems that adopted an Integrated Multi-Trophic Aquaculture (IMTA), we were able to report a buffering power of IMTA on one of the components of economic distress that we surveyed and specifically on job loss. Indeed, when IMTA was used the respondents reported less loss of jobs. Interestingly IMTA which was revealed as a promising system in buffering anthropogenic driven shocks (Sarà et al., 2021) and showing ecological resilience by increasing the diversity of farmed species (i.e. farmed species having various trophic level and functional diversity;

Troell et al., 2014), seems to confer larger resilience also to the productive system efficiency at local scale. IMTA appears to allow farmers to circumvent deadlocks in some steps of the PFSC as showed by the selected internal and external mitigation measures respectively adopted and preferred. While interviewed stakeholders from all the farming strategies expressed less interest on hiring option as internal mitigation measure on farm-site, farmers using IMTA expressed more interest in adopting hiring as internal measure, an important response under a social resilience perspective among the COVID-19 shock responses of the aquaculture PFSC. IMTA farmers adopted stocking strategies, key response to disruption risk, preferred more flexible business model as integrated solutions and increase work efficiency, without scarifying to much the farm asset (i.e. changes in farm techniques) and preserving the human dimension (i.e. firing was the less adopted mitigation measure). Among external mitigation strategies, farmer applying IMTA expressed their interest on the exploration of new market strategies, new markets and direct sales, scientists support and foster supply chain contrary to farmers not applying IMTA that expressed higher preference for economic support requests. Farmers working with IMTA showed a higher level of proactiveness preferring tools typical of “Flexible business models” referred as among the best mitigation strategies to cope with disruption risk mitigation in PFSC (Kumar et al., 2021). Therefore, aquaculture PFSC based on IMTA suffered more on the first stage; hatchery was the more vulnerable link of the SC, reporting higher economic loss associate with key sources of financial instability as the lack of insurance coverage, the higher price of raw materials and the provision of juvenile / fry supply.

Future of the aquaculture PFSC after the shock: the long path toward resilience

The observed patterns through this rapid assessment approach based on the experience of stakeholders - a snapshot of the various impacts of COVID-19 pandemic on the aquaculture PFSC at the shock phase - should be monitored more extensively and comprehensively in time and space into the future, in order to create an inventory of actions acting on the “food system resilience action cycle” (*sensu* Tendall et al., 2015). This will be crucial to allow resilience building in SCs, to capture the full social and economic effects of shocks and handle external situations (e.g. lockdowns) and policy measures (e.g. rapid support of support decision-making in a crisis). The lack of information baselines, information flow, transparency, accuracy, management and speed of information have been recognised as maximising FSCs vulnerabilities to risk and shock by several authors (Vlajic et al., 2012; White et al., 2021). The knowledge baseline should be built to the higher spatial, geographical, resolution level possible, considering both more resilient and organised responses from the developed countries and the labour intensive and unorganised responses from the developing countries (Kumar et al., 2021; Onuma et al., 2020; Love et al., 2021) and considering all the potential

farming strategies something that in our assessment allowed to see geographic clusters of responses (with southern countries of the planet as South Africa and India suffering more of economic distress). As recently suggested by Jamwal & Phulial (2021) – more widely referring to seafood FSC – we agree that also the future of aquaculture should reflect the “collaborative, multisectoral, and transdisciplinary” One Health approach (OHC, 2020). By looking at four stages of the aquaculture PFSC and four farming strategies plus IMTA, we collated a pattern of preference regarding internal and external mitigation measures that clearly open a reflection on the need for more system- and SC stage-based tailored measures. The “one-size-fit-all” may be an unsuccessful approach for planning recovery plan of the aquaculture PFSC, with the risk to keep ineffective the future recovery funds strategies and the reactive actions (i.e. absorb, react, restore) and preventive actions (i.e. learn, build robustness *sensu* Tendal., 2015) that will take place in the next months (Love et al., 2021). In fact, in these months and more into the future, various nature of financial aids will be assigned to foster and support the public health sector, the private business, the social insurance funds, the medium business and enterprises, working people and vulnerable groups in the community (International Monetary Fund <https://blogs.imf.org>; The World Bank 2020).

We support the need to transform the COVID-19 pandemic shock in a “window of opportunity” (Folke et al., 2010) as recently proposed by Love et al., (2021), in this direction we believe that our rapid assessment may support the engagement in transformations over which the resilience thinking built (Folke et al., 2010) avoiding wasting the opportunity to change future direction in aquaculture.

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Competing interests

The authors declare no competing interests.

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Figure captions

Figure 1. Economic distress due to COVID-19 in term of economic loss, responses are showed per farming strategy (LBE = Land-based extensive, LBI = Land-based intensive, SBE = Sea-based intensive, SBI = Sea-based extensive) with and without Integrated Multi-Trophic Aquaculture (IMTA). Economic loss scaled from 1 = no economic loss at all, to 10 = very high economic loss and here reported as percentages grouped into four categories: no effect 1, low 2–4; moderate 5–7 and high 8–10. Maps report mean of answers *per* every country.

Figure 2. Economic distress due to COVID-19 in term of job loss, responses are showed per farming strategy (LBE = Land-based extensive, LBI = Land-based intensive, SBE = Sea-based intensive, SBI = Sea-based extensive) with and without Integrated Multi-Trophic Aquaculture (IMTA). Economic loss scaled from 1 = no economic loss at all, to 10 = very high economic loss and here reported as percentages grouped into four categories: no effect 1, low 2–4; moderate 5–7 and high 8–10. Maps report mean of answers *per* every country.

Figure 3. Heatmaps representing data on the encountered difficulties and related economic loss (scaled from 1 = no economic loss at all, to 10 = very high economic loss) on the four selected stages of the aquaculture perishable food supply chain and related affected aspect. Hatchery: juvenile/fry supply, raw materials, insurance, auctions. Production / transformation: infrastructures, labours failure, suppliers. Distribution / logistic: increase in transportation prices, restriction/block on transportation. Market: price decrease, impossibility/difficulty in selling to national buyers/consumers, international markets, customers and of middlemen. Responses are showed per farming strategy (LBE = Land-based extensive, LBI = Land-based intensive, SBE = Sea-based intensive, SBI = Sea-based extensive) with and without Integrated Multi-Trophic Aquaculture (IMTA).

Figure 4. Principal component analysis (PCA) on stakeholder responses on disruption effects (resulting in economic loss, scaled from 1 = no economic loss at all, to 10 = very high economic loss) associated with hatchery stage of the aquaculture PFSC, respectively: lack of juvenile/fry supply; lack of raw materials provision (both in terms of reduction of available raw materials - feeds, packaging material - and price increases); issues with insurance coverage (i.e., difficulty / insolvency or block / cancellation by insurance companies); and / or difficulties in obtaining licences – light blue) depending on the four explored aquaculture systems (land- and sea-based intensive and extensive) with and without IMTA [upper panel]. PCAs stakeholder responses on adopted internal mitigation measures [lower panel left side] and preferred external mitigation measures [lower panel right side].

Figure 5. Heatmaps representing data on the adoption of internal and external mitigation measures (scaled from 1 = no adopted loss at all, to 10 = very high adopted). Internal mitigation measures social distancing, increase work efficiency, hiring, firing, integrated-multi trophic solutions, change in farm techniques, reduction of farm dimension, stocking solutions. External mitigation measures: direct sales, foster supply chain, search new market, demand economic support, explore new market strategies, demand support to scientists. Responses are showed per farming strategy (LBE = Land-based extensive, LBI = Land-based intensive, SBE = Sea-based intensive, SBI = Sea-based extensive) with and without Integrated Multi-Trophic Aquaculture (IMTA).

Table 1 Comments reported by interviewed stakeholders, quotation have been reported by interviewed by also reporting the associated country, the farming strategy, the presence or absence of Integrated Multi Trophic Aquaculture – IMTA.

Country	Farming strategy	IMTA/noIMTA	Comment
Hatchery level of the aquaculture PSFC			
Tunisia	SBE	IMTA	<i>“We are encountering difficulty of quality control of fingerlings before shipping, and more in general difficulty in getting fingerlings for fattening”.</i>
Philippine	LBI	noIMTA	<i>“The restrictions brought about by the COVID-19 lockdown resulted on materials and other pond inputs being not readily available or could not be transported to the pond areas. Regular inspections and consultant for breeding/spawning induction could not also be conducted due to quarantine measures imposed by the government thus delaying necessary measures on concerns to be addressed on operational processes. Schedule of fry transfers, grow out preparations, etc. are all delayed because of the COVID-19 situation. Maintenance and development schedules had also been affected further delaying crop schedules. Only maintenance of natural food organisms and breeding stocks is being done”.</i>
Nigeria	LBI	noIMTA	<i>“I had to afford more high production costs due to more feeding needed to maintain fishes”.</i>
Ecuador	SBE	noIMTA	<i>“I had to afford robberies for non-official surveillance”.</i>
Production / transformation level of the aquaculture PSFC			
Sweden	LBI	IMTA	<i>“No market but continue costing for electricity, water, heat, feed so fish can survive”</i>
Portugal	SBE	noIMTA	<i>“Seasonal personnel could not be contracted, leading to significant operational constraints, higher costs and extreme workload for existing personnel”.</i>
Italy	LBI	noIMTA	<i>“Overload in biomass of the structures for non-sales due to a lack of coordination of placing on the market, lack of coordination of access to credit and management of the 'unsold”.</i>

Market level of the aquaculture PSFC			
Portugal	LBE	IMTA	<i>“Liquidity shortage due to the loss of money on credit of the restoration channel because many went into insolvency and I will not receive their money. Others cannot fulfil their obligations and will not pay for now”.</i>
Croatia	SBE	noIMTA	<i>“70% of the sales depends on the touristic season (we supply the high-end markets (hotels/restaurants etc), 30% and less is for domestic market the closure of HoReCA channels and local markets is the main reason of economic loss”.</i>
Turkey	LBI	noIMTA	<i>“Imbalance in supply-demand and excessive fall in prices”.</i>
Internal (farm scale) adopted mitigation measures to cope with COVID-19 disruption			
China	SBE	IMTA	<i>“I’m increasing the level of mechanization of offshore production, increasing the use of advanced equipment to reduce dependence on people”.</i>
India	LBI	IMTA	<i>“I’m planning for low density to avoid risk”.</i>
Turkey	SBI	noIMTA	<i>“I’m trying new aquaculture species, producing low-cost products”.</i>
Egypt	LBE	noIMTA	<i>“I’m dividing the harvest into different periods”.</i>
China	LBI	noIMTA	<i>“I’ll increase varieties with high added value, and improved survival rate”.</i>
Italy	SBI	noIMTA	<i>“I will test the introduction of new species such as sea urchins, sea cucumbers, oysters, etc.”.</i>
External preferred mitigation measures to cope with COVID-19 disruption			
China	SBE	IMTA	<i>“We are working to expand sales channels, such as e-commerce and live broadcast; change communication methods with customers and internal staff: such as online communication”.</i>
Italy	SBI	IMTA	<i>“I suggest a remodelling of the EMFF management system, the provision of measures to support companies, an updating of the National Aquaculture Plan, definition of the role of Producers Organisations at the level of representation in a homogeneous way to other countries, a National Communication Plan on the</i>

			<i>benefits of farmed fish such as safety, traceability, freshness, inclusion of companies in accelerators, improved access to credit”.</i>
Italy	LBI	noIMTA	<i>“We are destinating our products to pet food”.</i>
China	LBI	noIMTA	<i>“I suggest strengthening industry emergency system”.</i>
India	LBE	noIMTA	<i>“I suggest creating awareness the health benefit of shrimp consumption through celebrities. Maintain BMC (Broodstock Maturation Center) cannot depend upon brooder supply chain from other countries to import”.</i>
India	LBI	noIMTA	<i>“Increase the use of Artificial Intelligence will be highly helpful during lockdown to monitor the farms during pandemic times”.</i>
Italy	SBI	noIMTA	<i>“Incentivize the purchase of farmed fish, finance the activities they produce in a sustainable way and IMTA”.</i>
Croatia	SBE	noIMTA	<i>“I suggest that the Government pays us an incentive per kilogram of products produced. And for the bank to write off interest for 9 months this year”.</i>
Greece	SBI	noIMTA	<i>“I suggest financial contribution for the maintenance of unsold biomass and for extra airfreight costs”.</i>
Brazil	LBI	noIMTA	<i>“I suggest a reduction of government fees so that we can reduce the price and gain market again, with the international crisis scenario the population's purchasing power decreases, so we need to reduce the price to sell again”.</i>
Brazil	SBE	noIMTA	<i>“I propose a relief from tax obligations and contribution to Social Security, until the restoration of commercial normality, especially in the operation of restaurants”.</i>

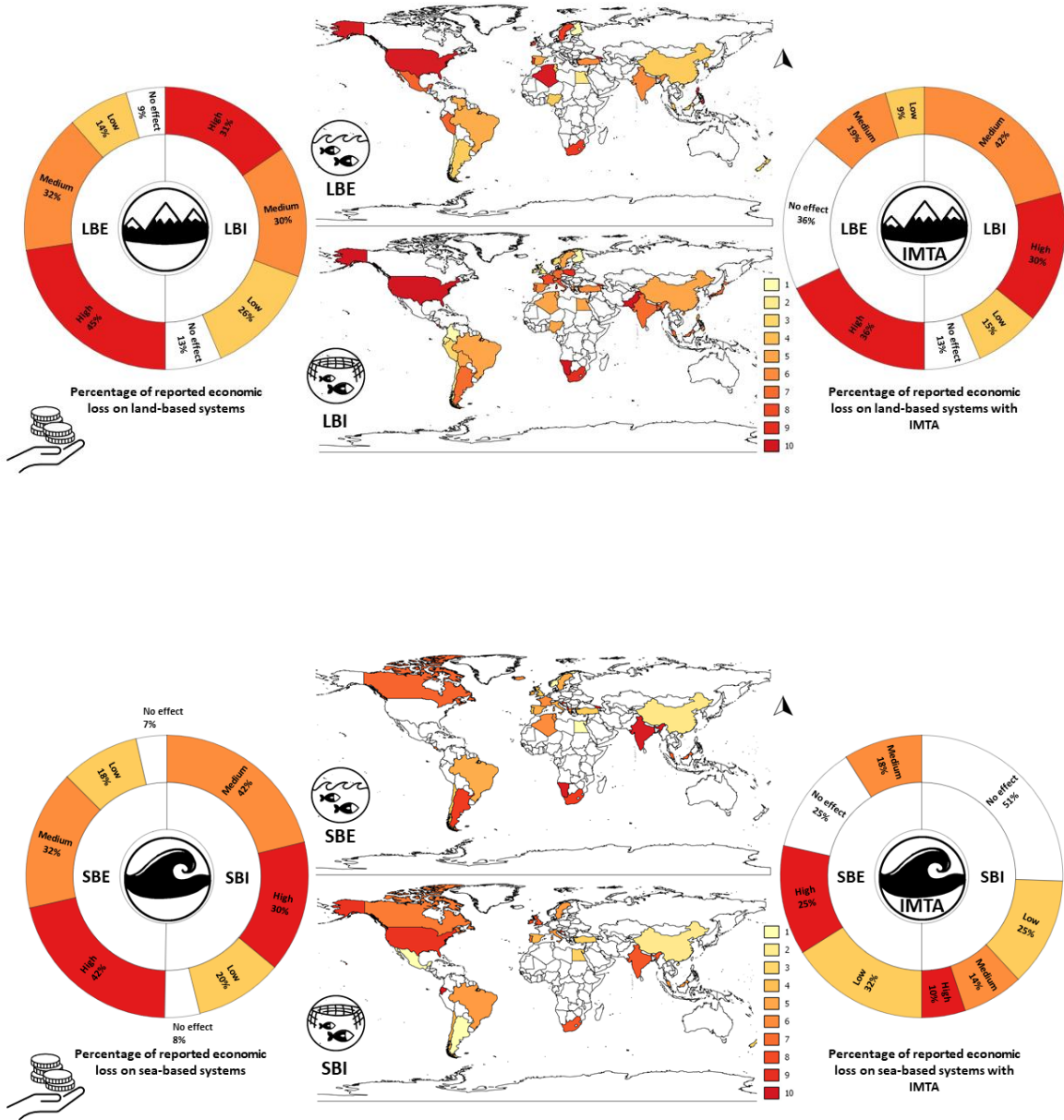


Figure 1.

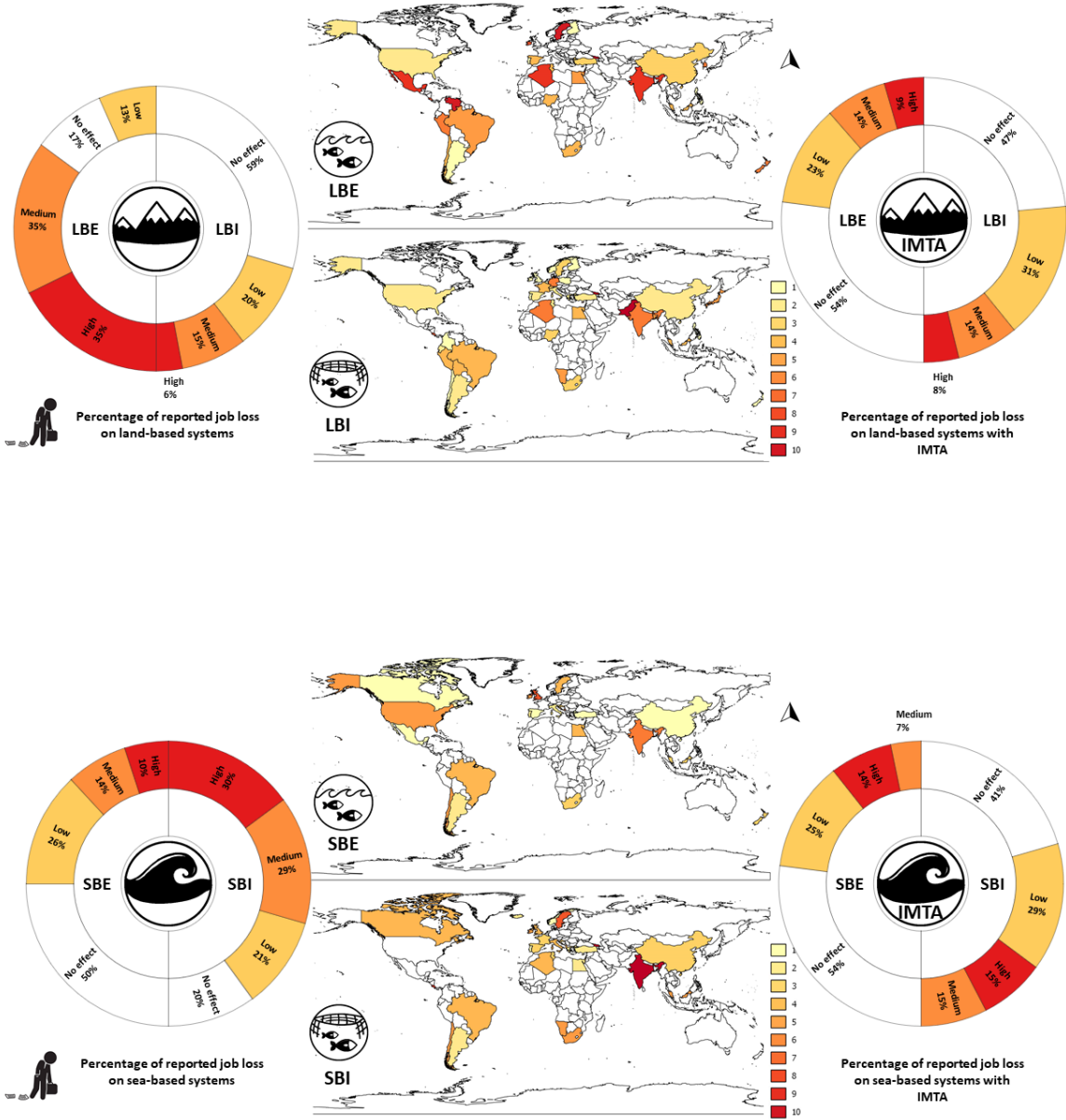


Figure 2.

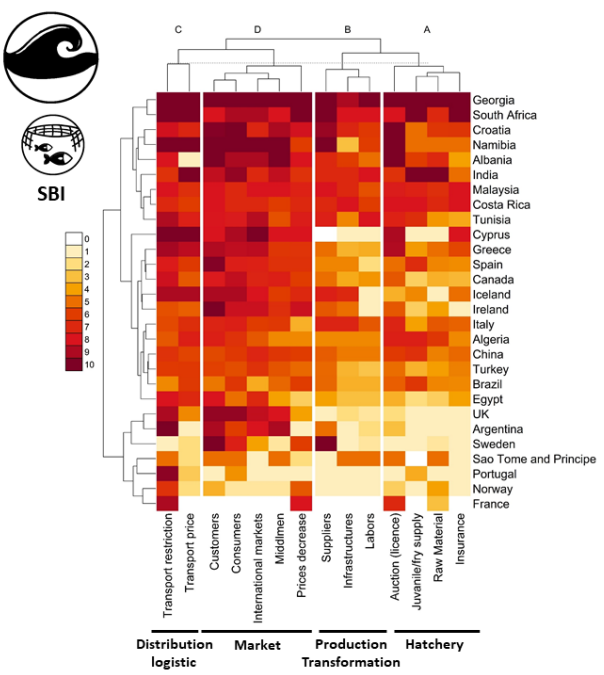
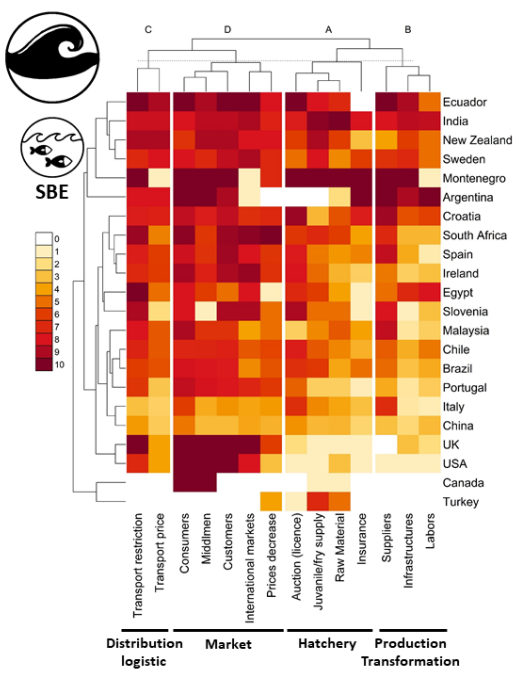
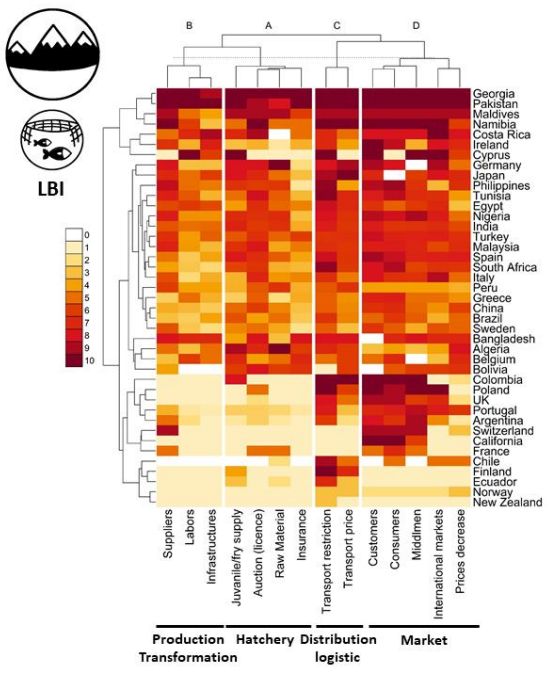
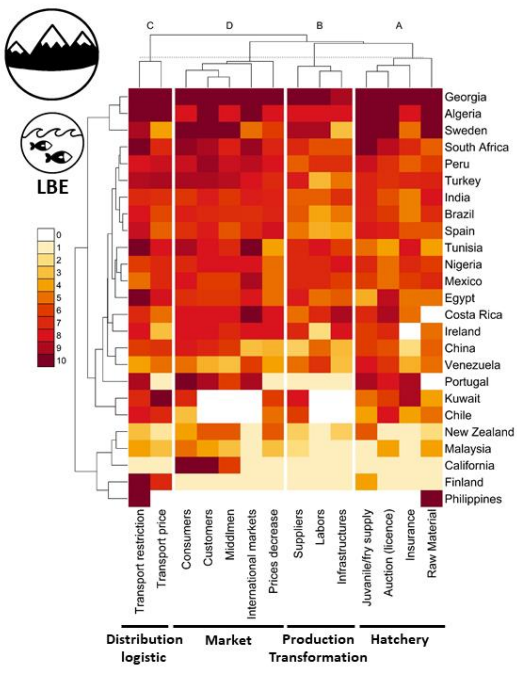


Figure 3.

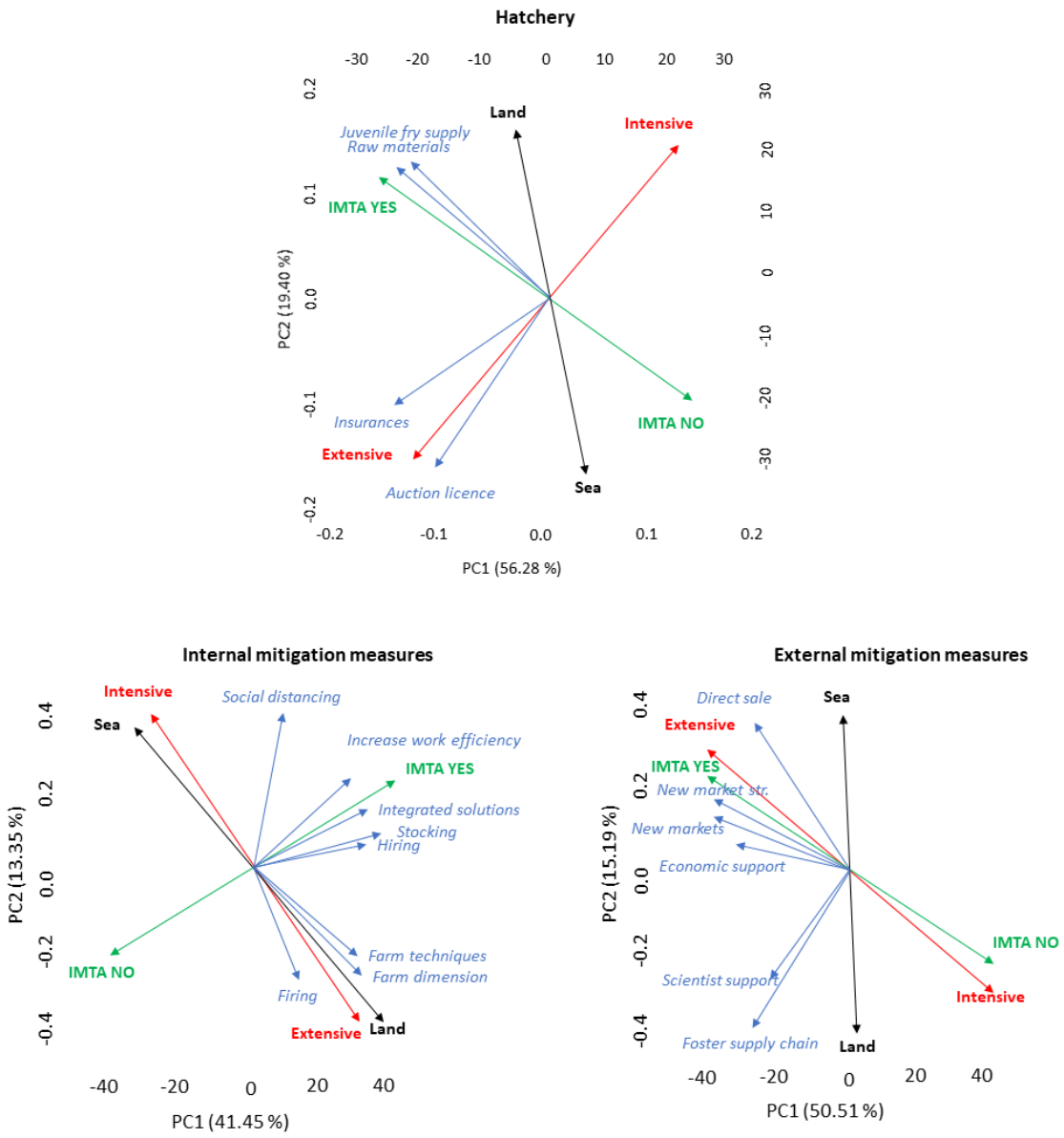
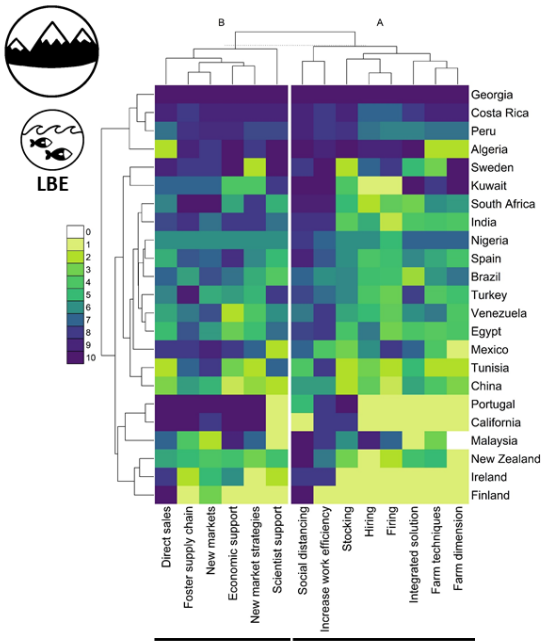
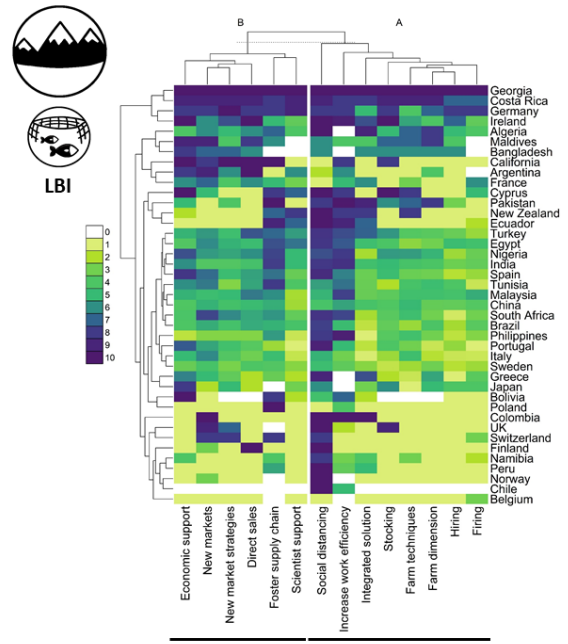


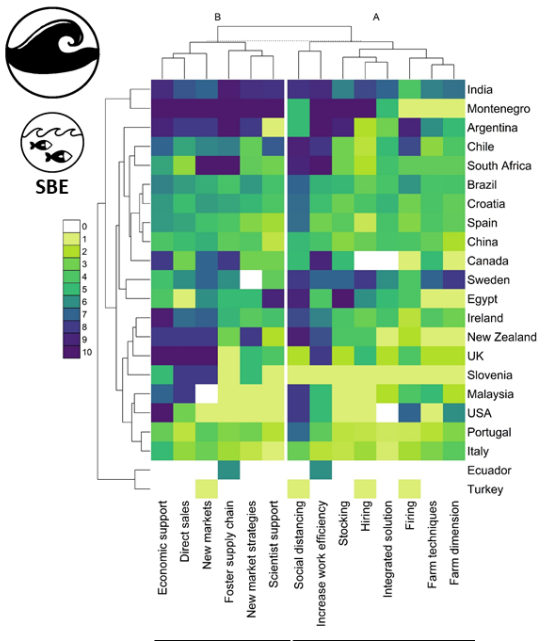
Figure 4.



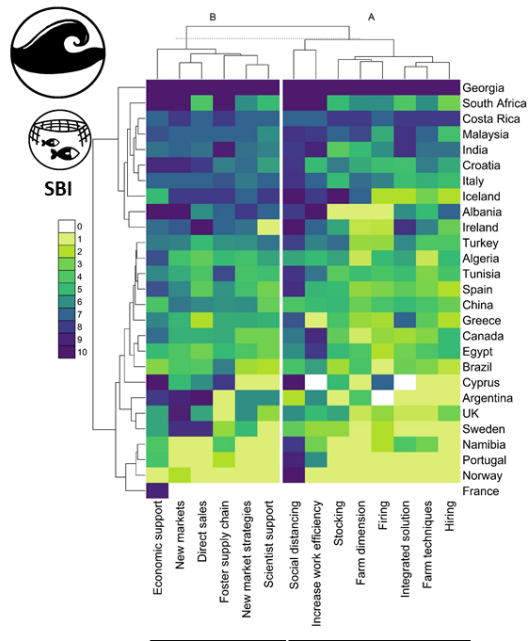
External mitigation measures Internal mitigation measures



External mitigation measures Internal mitigation measures



External mitigation measures Internal mitigation measures



External mitigation measures Internal mitigation measures

Figure 5.

Supplementary Materials for

THE AQUACULTURE SUPPLY CHAIN IN THE TIME OF PANDEMIC:

VULNERABILITY, RESILIENCE, SOLUTIONS AND PRIORITIES AT GLOBAL SCALE

Mangano^{1,*}, M.C. et al.

The semi-structured questionnaire designed with main aim to collect stakeholders' perception

Figure S1

Questionnaire English version

The global impact of COVID-19 on aquaculture

Welcome! The coronavirus (COVID-19) outbreak is increasingly impacting on the global economy with unpredictable consequences, and the aquaculture sector is no exception. As such, we invite you to complete this survey. But before we need to focus on the following few lines below are mandatory as formalities under the privacy laws. We ask for your consent to participate in a research project conducted by the University of Palermo, Department of Earth and Sea Science (DISTEM), Laboratory of Ecology, on the effects of the coronavirus COVID-19 on aquaculture. Your participation is essential, and we invite you to complete the questionnaire below by answering some questions designed to evaluate the socio-economic effects of the pandemic on the sector and its operators. Evaluate ALL claims. There are no right or wrong answers, in some it will be possible to opt for more than one answer (this possibility will always be indicated). Your participation is **ABSOLUTELY VOLUNTARY**, you are free not to fill in the questionnaire or not to complete it, without any penalty or repercussion. However, we would be very grateful if you would like to collaborate by completing the whole questionnaire, in all its parts and questions. We guarantee the protection of anonymity and confidentiality. **DO NOT** write your name or any form of identification on the questionnaire. The data will be recorded, processed, managed and archived, automated and computerized for the exclusive purposes connected with the research, in an **absolutely anonymous form**. The data, collectively collected, will be subject to statistical processing and in this form, always absolutely anonymous, inserted in publications and / or congresses, conferences and scientific seminars. This information may be useful in developing future programs to support the sector in times of emergency. No direct benefit is expected from this study, the results will be made public and disseminated, any product will not have a commercial purpose. The compilation of the questionnaire will take approximately 10 minutes of your time.

Study approved by the Ethical Committee at the University of Palermo, UNPA-183-Prot. 767-05/05/2020 n. 1/2020 29/04/2020.

All information from this study will be destroyed 3 years after the end of the study.

In case of questions or comments on this study, you may contact Prof. Gianluca Sarà (gianluca.sara@unipa.it / gsara.unipa@gmail.com)

I agree to participate.

- Yes
- Not

Q1 Which is the typology of your farming activity?

- Sea based intensive aquaculture (cages)
- Land based intensive aquaculture (tanks/ponds)
- Sea based extensive aquaculture (mollusc-culture, algae, echinoderms etc.)
- Land based extensive aquaculture (fish, invertebrates, algae etc.)

Q1.2 Do you use Integrated multi-trophic aquaculture (IMTA)?

- Yes

No

Q2 Which are the main farmed species (please indicate the 5 most cultivated species in you farm)

Species 1 _____

Species 2 _____

Species 3 _____

Species 4 _____

Species 5 _____

Q3 Could you please indicate if there was an economic loss (direct or indirect economic loss) in your farm due to COVID-19? From 1 = no loss at all, to 10 = very high economic loss.

1 2 3 4 5 6 7 8 9 10

Q4 Can you indicate if there was any any loss of jobs? (Failure of seasonal recruitment) From 1 = no loss at all, to 10 = very high loss.

1 2 3 4 5 6 7 8 9 10

Q5 Please indicate how important each of the following reasons have been regarding the socio-economic impact suffered by your aquaculture activity due to the crisis caused by COVID-19 on the 4 main stages of the supply chain (hatchery, production/transformation, distribution / logistic, market). From 1 = no importance at all, to 10 = very high importance.

Hatchery

Lack of juvenile/fry supply 1 2 3 4 5 6 7 8 9 10

Lack of raw materials provision (both in term of reduction of available raw materials - feeds, packaging material - and price increase) 1 2 3 4 5 6 7 8 9 10

Issues with insurance coverage (i.e. difficulty/insolvency or block/abandonment by insurance companies) 1 2 3 4 5 6 7 8 9 10

Block of auctions (i.e. licences) 1 2 3 4 5 6 7 8 9 10

Production/transformation

Lack of infrastructures (i.e. missing freezing container, smoking room, packaging, other)

1 2 3 4 5 6 7 8 9 10

Labour's failure (i.e. seasonal recruitment) 1 2 3 4 5 6 7 8 9 10

Difficulties of suppliers in collecting seafood 1 2 3 4 5 6 7 8 9 10

Distribution / logistic

Increase in transportation prices 1 2 3 4 5 6 7 8 9 10

Restriction / block on transportation (e.g., flight cancellation, closures of geographical borders between countries) 1 2 3 4 5 6 7 8 9 10

Market

Farmed products price decrease / loss (i.e. depreciation due to a load in production and a loss in request) 1 2 3 4 5 6 7 8 9 10

Impossibility/difficulty in selling to national buyers/consumers

1 2 3 4 5 6 7 8 9 10

Impossibility/difficulty in selling to enter the international markets

1 2 3 4 5 6 7 8 9 10

Absence of customers on the distribution channel (e.g., tourists, schools, restaurants, etc.)

1 2 3 4 5 6 7 8 9 10

Absence of middlemen 1 2 3 4 5 6 7 8 9 10

Q6 Do you have comments on the above reasons of socio- economic impact suffered by your aquaculture activity due to the crisis caused by COVID-19 on the 4 main stages of the supply chain (hatchery, production/transformation, distribution / logistic, market)?

Q7 What mitigation measures at local / internal scale (i.e., farm-based and related to your supply chain) has you/your organization implemented/is in the process of implementing to face the crisis caused by COVID-19? Please, express preference scaled from 1 = not adopted, to 10 = very high adopted.

Social distancing (e.g. working shift) 1 2 3 4 5 6 7 8 9 10

Increase work efficiency 1 2 3 4 5 6 7 8 9 10

Hiring (e.g. new professional profiles) 1 2 3 4 5 6 7 8 9 10

Firing personnel 1 2 3 4 5 6 7 8 9 10

Integrated-multi trophic solutions 1 2 3 4 5 6 7 8 9 10

Change in farm techniques 1 2 3 4 5 6 7 8 9 10

Reduction of farm dimension (e.g. cages number or used surface)

1 2 3 4 5 6 7 8 9 10

Stocking solutions (e.g. freezing and smoking) 1 2 3 4 5 6 7 8 9 10

Q8 Do you have comments on the applied mitigation measures at local / internal scale adopted to cope with COVID-19 disruption?

Q9 What mitigation measures at national / external scale would you/your organization prefer / recommend implementing to face the crisis caused by COVID-19? Please, express preference scaled from 1 = not adopted, to 10 = very high adopted.

Direct sales to final customers 1 2 3 4 5 6 7 8 9 10

Foster supply chain 1 2 3 4 5 6 7 8 9 10

Search new market (e.g. canning industry) 1 2 3 4 5 6 7 8 9 10

Demand economic support (e.g. economic subsidy from regional or national bodies)

1 2 3 4 5 6 7 8 9 10

Explore new market strategies (e.g. online retail system and brand)

1 2 3 4 5 6 7 8 9 10

Demand support to scientists 1 2 3 4 5 6 7 8 9 10

Q10 Do you have suggestions on possible coping mitigation measures / solutions to adopt to cope with COVID-19 disruption?

Q11 Organization/farm name (not obligatory) _____

Q12 Town/City/Village/ Country (where the farm is located; not obligatory)

Q13 Occupation in the organization _____

Q14 Your gender (not obligatory) Female Male Other

Q15 How old are you? 18-29 30-39 40-49 50-59 60 or more

Q16 Which is your education level?

Primary school Secondary school University bachelor or master Phd

Contact e-mail/mobile phone (not obligatory) _____

Comments – notes – suggestions _____

- Global survey**
- Albania
 - Algeria
 - Argentina
 - Bangladesh
 - Belgium
 - Bolivia
 - Brazil
 - Canada
 - Chile
 - China
 - Colombia
 - Costa Rica
 - Croatia
 - Cyprus
 - Egypt
 - Finland
 - France
 - Georgia
 - Germany
 - Greece
 - Iceland
 - India
 - Ireland
 - Italy
 - Japan
 - Kuwait
 - Malaysia
 - Maldives
 - Mexico
 - Montenegro
 - Namibia
 - New Zealand
 - Nigeria
 - Norway
 - Pakistan
 - Peru
 - Philippines
 - Poland
 - Portugal
 - Sao Tome and Principe
 - Slovenia
 - South Africa
 - South Korea
 - Spain
 - Sweden
 - Switzerland
 - Tunisia
 - Turkey
 - UK
 - USA
 - Venezuela

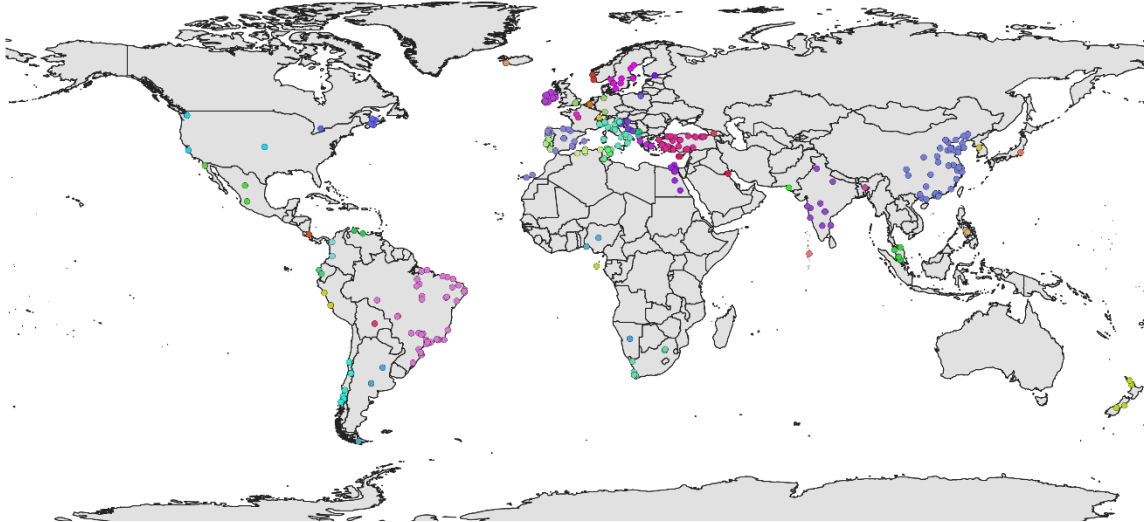


Figure S1. Countries covered by the global web survey (launched on 5th and closed on 29th May 2020), coloured dots have been grouped per each of the 52 countries reached across the five continents (see legend).