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The aquaculture supply chain in the time of covid-19 pandemic: Vulnerability, resilience, solutions and priorities at the global scale

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ABSTRACT

The COVID-19 global pandemic has had severe, unpredictable and synchronous impacts on all levels of perishable food supply chains (PFSC), across multiple sectors and spatial scales. Aquaculture plays a vital and rapidly expanding role in food security, in some cases overtaking wild caught fisheries in the production of high-quality animal protein in this PFSC. We performed a rapid global assessment to evaluate the effects of the COVID-19 pandemic and related emerging control measures on the aquaculture supply chain. Socio-economic effects of the pandemic were analysed by surveying the perceptions of stakeholders, who were asked to describe potential supply-side disruption, vulnerabilities and resilience patterns along the production pipeline with four main supply chain components: a) hatchery, b) production/processing, c) distribution/logistics and d) market. We also assessed different farming strategies, comparing land- *vs.* sea-based systems; extensive *vs.* intensive methods; and with and without integrated multi-trophic aquaculture, IMTA. In addition to evaluating levels and sources of economic distress, interviewees were asked to identify mitigation solutions adopted at local / internal (*i.e.,* farm-site) scales, and to express their preference on national / external scale mitigation measures among a set of *a priori* options. Survey responses identified the potential causes of disruption, ripple effects, sources of food insecurity, and socio-economic conflicts. They also pointed to various levels of mitigation strategies. The collated evidence represents a first baseline useful to address future disaster-driven responses, to reinforce the resilience of the sector and to facilitate the design reconstruction plans and mitigation measures, such as financial aid strategies.

1. Introduction

In March 2020, the World Health Organization (WHO) declared the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), COVID-19, as a pandemic. Since it was first recognized the virus spread rapidly and globally, causing millions of deaths. In a fight against time to slow the spread and to contain the severe deadly outbreak across the planet, national governments have made enormous efforts, by imposing containment and suppression measures with varying degrees of rapidity and strictness (Guan et al., 2020) with people experiencing unprecedented disruptions to their daily lives. Cumulatively, these responses, aimed at preventing the spread COVID-19, had clear direct and indirect effects on global economic productivity (FAO and CELAC, 2020).

The COVID-19 global pandemic has had especially severe impacts on food supply chains (FSCs), among which perishable food supply chains (PFSCs) were the worst hit. Specifically, the pandemic and efforts designed to prevent its spread triggered large, unpredictable, synchronous impacts affecting all levels of the PFSC, acting across multiple sectors and spatial scales. These events thus show all the features of a shock event as risks ranged from humanitarian/social issues to creation of an uncertain business and investment environment (Cottrell et al., 2019). The COVID-19 pandemic affected all four main pillars of food security: availability, accessibility, utilization, and stability (Laborde et al., 2020) with a long-term duration and ripple propagation effects (*i.e.,* both supply shortage and demand shrinkage, leading to simultaneous or sequential forward and backward propagations of disruptions). The COVID-19 outbreak thus represents a special case of FSC disruption (Ivanov, 2020; Li et al., 2021 and references therein), with impacts characterised by unpredictable local disruptions, which make preparation and management exceedingly difficult. Dozens of scientific studies, reports and policy briefs have been produced for several nations focusing on disruption of essential services provided by FSCs in the pandemic (see Queiroz et al., 2020; Chowdhury et al., 2021 and references therein). Approaches have largely relied on online surveys (van Senten et al., 2021; Smith et al., 2020), but development of non-traditional indicators (White et al., 2021; Love et al., 2021), simulations and modelling (Guan et al., 2020; Ivanov, 2020; Ivanov and Dolgui, 2020; Stoll et al., 2020), and literature reviews (Queiroz et al., 2020; Chowdhury et al., 2021) have also been carried out. The goals of these reports were to: outline 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 that were recorded; quantify levels of resilience and flexibility (Chenarides et al., 2021); disentangle severity of disruptions on various parts of the FSC (*e.g.,* GFCM, 2020; FAO, 2020a, 2020b, 2020c, 2020d; Love et al., 2021); focus on the effects on more vulnerable sectors (*e.g.,* small-scale fisheries, Bennett et al., 2020; small and medium-sized enterprises, Caballero-Morales, 2021); and examine the synergistic impacts with anthropogenic stressors such as climate change (Sarà et al., 2021). These reports have advocated for 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 and Phulia, 2021) that can help build food system resilience (Love et al., 2021; Chenarides et al., 2021; Kumar et al., 2021; Marusak et al., 2021). These efforts have resulted in a number of credible, salient and crucial conclusions aimed at informing policy makers dealing with emergency packages and relief programs to protect domestic economies. Recommendations have been made on how to design emergency government legislation from the perspective of both developing and developed economies (International Monetary Fund https://blogs.imf.org; The World Bank, 2020).

However, considerably less is known about challenges of COVID-19 to PFSCs based on seafood aquaculture, which has features which can diverge from those of wild-caught fisheries (Love et at, 2021; White et al., 2021). Here, we present a rapid assessment, performed on a global scale, designed to assess the effects of the COVID-19 pandemic and related control measures on the aquaculture supply chain sector. Aquaculture contributes to food security directly by the production of high-quality animal protein, demand for which has been growing worldwide (FAO, 2020e; Naylor et al., 2021). We surveyed the perceptions of stakeholders, including farm owners and managers operating on both sea- and land-based aquaculture systems, and following both intensive (food provided from external sources) and extensive (food produced from within the system with no additional nutritional inputs) strategies. The socio-economic dimensions of PFSC disruptions were analysed based on the reported perceptions of stakeholders of supply-side disruption, vulnerability and resilience patterns along the production pipeline. Four components were included: a) hatchery, b) production / processing, c) distribution / logistics and d) market. In addition to evaluating sources and levels of economic distress, we asked the respondents to indicate the mitigation solutions adopted at local / internal (*i.e.,* farm-site) scale, and to express their preferences on a set of national / external scale mitigation measures. The intent of this rapid assessment was to generate a global snapshot, and to highlight causes of disruption, sources of food insecurity, resilience of food sector, livelihoods, emerging food sectors and socio-economic conflicts that may exacerbate as the pandemic continues. The ultimate goal of the study is to facilitate the design and tailoring of future reconstruction plans and financial aid strategies (*i.e.,* national and international recovery plans) and to address future adaptive and disaster-driven responses to reinforce the resilience of the sector.

Moreover, by surveying systems that did or did not adopt an Integrated Multi-Trophic Aquaculture (IMTA approach), we had the chance to underline the potential power of this practice in enhancing resilience to the aquaculture PFSC and production systems by increasing diversity of species produced, fostering local production (Troell et al., 2014) and allowing farmers to circumvent roadblocks in some steps of the aquaculture PFSC. We are unaware of any studies that have tested this hypothesis for aquaculture PFSC, or that have focused on aquaculture PFSC at the global scale.

2. Methods

A semi-structured questionnaire (study approved by the Ethical Committee at the University of Palermo, UNPA-183-Prot. 767-05/05/2020n. 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 to the online platform Qualtrics (https://www.qualtrics.com). This online survey was distributed to stakeholders through several communication and dissemination channels linked to the aquaculture sector. A brief presentation of the project and authors was added on the first page, to explain the reason for collecting information and the potential 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) on a time frame in line with severe disruption already evident in other FSCs (Chenarides et al., 2021).

Responses were coded as a function of the geographic position of the farms and the typology of the reported aquaculture system. Four categories were selected *a priori*: land based extensive aquaculture (fish, invertebrates, algae *etc.*; LBE), land-based intensive aquaculture (tanks/ponds; LBI), sea-based extensive aquaculture (mollusc farming, algae, echinoderms *etc.*; SBE) and sea based intensive aquaculture (cages; SBI). We also asked participants to report whether the system was based on Integrated Multi-Trophic Aquaculture (IMTA), *i.e.*, culture of multiple species belonging to different trophic levels within an intact food web.

With the goal of collecting information on respondents' perceived economic distress, the survey started by asking respondents to report economic and job losses associated with COVID-19 outbreaks (scaled from 1 = no economic loss at all, to 10 = very high economic loss and subsequently ranked into four categories: 1 no effect, 2–4 low, 5–7 moderate and 8–10 high). Consecutive questions were asked to rapidly assess the effects on the four selected stages of the aquaculture PFSC (*i.e.,* hatchery; production / transformation; distribution / logistics; market). To explore potential effects on the four stages, we asked respondents to indicate whether they experienced difficulties (resulting in economic loss, scaled from 1 = no economic loss at all, to 10 = very high economic loss) associated with several stage's specific aspects (Table 1). Participants were also asked to indicate any adopted mitigation responses at a local / internal scale (*i.e.,* farm-based and related to the SC; expressing preference scaled from 1 = not adopted to 10 = very highly adopted; Table 2) and their preferences on potential national / external scale mitigation measures (expressing preference scaled from 1 = not preferred to 10 = very highly preferred; Table 2). Data on economic distress were represented *per* each farming strategy with and without IMTA (Figs. 1, 2). We calculated the mean response value to each specific question given by stakeholders grouped by nation (Figs. 3, 5) to create heatmaps by using the *"ComplexHeatmap"* package for R (Gu, 2016).

The effect of IMTA in buffering economic distress associated with the four aquaculture PFSC stages (hatchery, production / transformation, distribution / logistic, market) was tested using a 2-way mixed ANOVA with Poisson family error distribution for the discrete dependent variable (economic loss scaled from 1 to 10), considering two predictive variables: "farming strategy" (fixed with four levels LBE, LBI, SBE, SBI) and "IMTA" (fixed, orthogonal to "farming strategy" with two levels, "Yes" and "Not") (R package "*lme4*"; Bates et al., 2015). Once the model was run, we checked for the absence of any pattern dealing with the residuals and their normality distribution. Estimated marginal means (EMMs) for factor combinations were used as a post-hoc test after the

Table 1
Four selected stages of the aquaculture PFSC and the surveyed associated specific aspects; respondents were asked to report the associated economic loss (scaled from 1 = no economic loss at all, to 10 = very high economic loss).

Hatchery	Production / transformation	Distribution / logistics	Market
Lack of juvenile/ fry supply	Lack of infrastructure (*e.g.,* freezers, smoking rooms, packaging, other)	Increases in transportation prices	Farmed products price decrease / loss (*i.e.*, depreciation due to surplus production or a loss in orders)
Lack of raw materials provision (both in terms of reduction of available raw materials - feeds, packaging material - and price increases)	Labour failures (*i.e.*, seasonal hiring of farmers)	Restrictions on transportation availability (*e.g.,* flight cancellation, closure of geographical borders between countries)	Impossibility / difficulty of selling to national buyers / consumers
Issues with insurance coverage (*i.e.*, difficulty / insolvency or blockage / cancellation by insurance companies)	Difficulties of suppliers in collecting seafood products		Entry into international markets
Difficulties in obtaining licences			Absence of customers in distribution channels (*e.g.,* tourists, schools, restaurants, *etc.*)
			Difficulty engaging intermediaries

Table 2
List of surveyed mitigation responses at a local / internal scale (*i.e.,* farm-based and related to the supply chain; respondents were asked to report their preference, scaled from 1 = not adopted to 10 = very highly adopted) and list of surveyed preferences on national / external scale mitigation measures (scaled from 1 = not preferred to 10 = very highly preferred).

Mitigation responses at a local / internal scale	Social distancing (*e.g.*, work shifts)	Increase work efficiency	Additional hiring (*e.g.*, new professional profiles)	Firing personnel	Adoption of Integrated Multi-Trophic Aquaculture solutions	Changes in farm techniques	Reduction of farm size (*e.g.*, number of cages or used surface)	Stocking solutions (*e.g.*, freezing and smoking)
Preferences on potential national / external scale mitigation measures	Direct sales to customers	Fostering supply chains	Seeking new markets (*e.g.*, canning industry)	Direct economic support (*e.g.*, economic subsidy from regional or national bodies)	Exploration of new market strategies (*e.g.*, online retail system and brand)	Direct support to scientists		

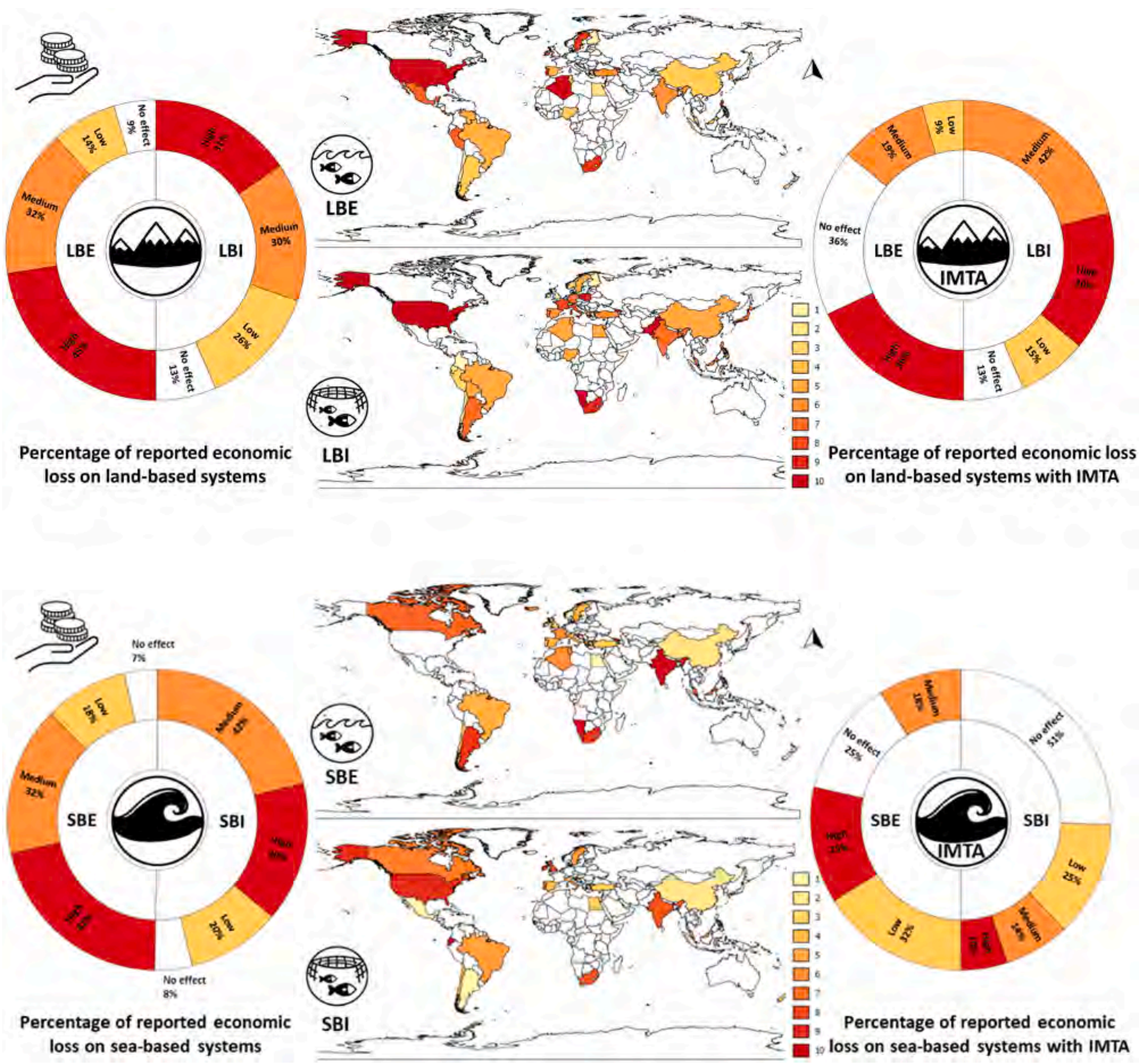

Fig. 1. Economic distress due to COVID-19 in term of economic loss, responses are showed per farming strategy (LBE = Land-based extensive, LBI = Land-based intensive, SBE = Sea-based extensive, SBI = Sea-based intensive) with and without Integrated Multi-Trophic Aquaculture (IMTA). Economic loss scaled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

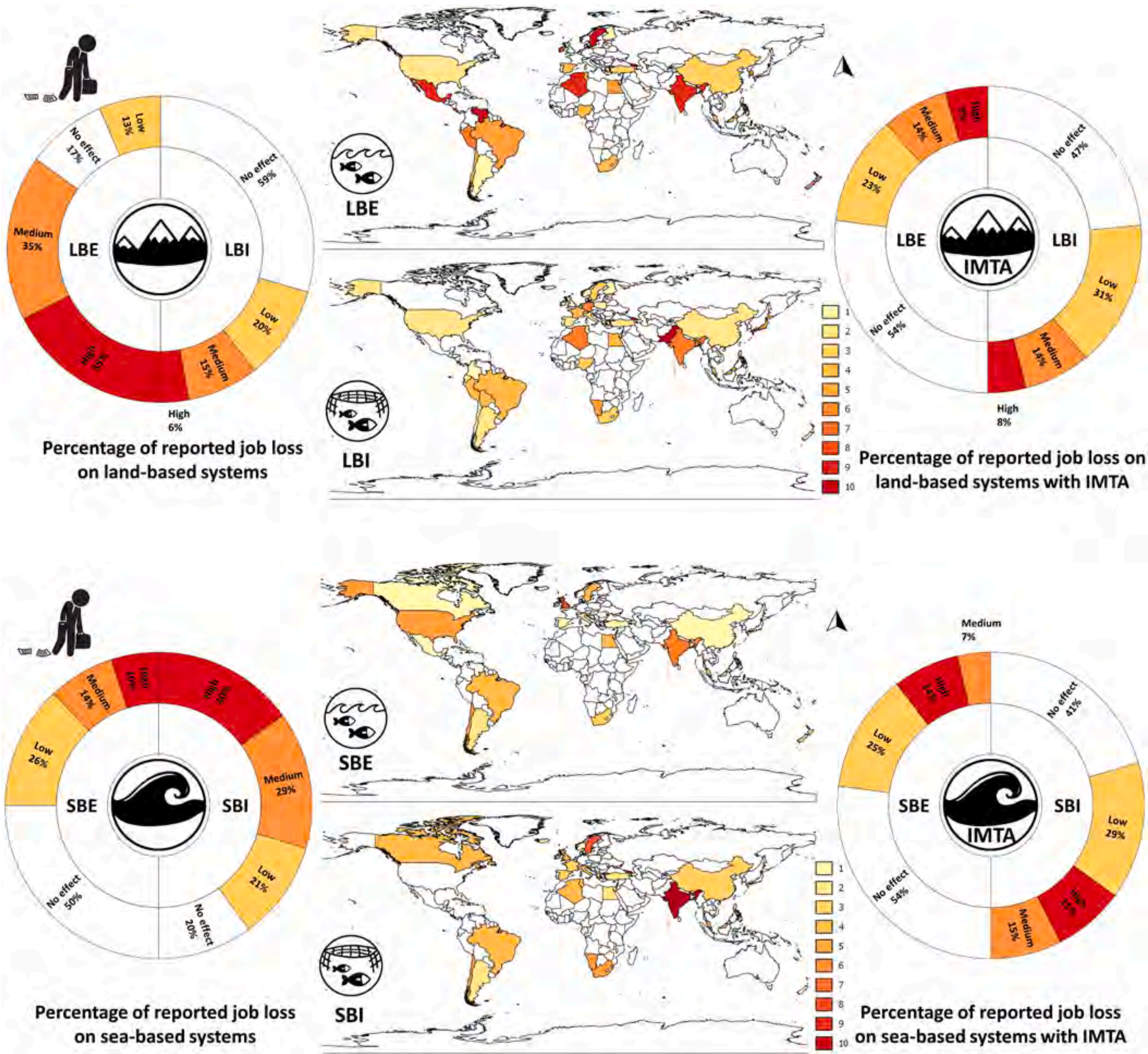

Fig. 2. Economic distress due to COVID-19 in term of job loss, responses are showed per farming strategy (LBE = Land-based extensive, LBI = Land-based intensive, SBE = Sea-based extensive, SBI = Sea-based intensive) with and without Integrated Multi-Trophic Aquaculture (IMTA). Economic loss scaled from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

mixed ANOVA (R package "*emmeans*"; Russell et al., 2021). Principal component analysis (PCA) on a multivariate dataset of answers related to the effects reported *per* aquaculture PFSC stage (hatchery, production / transformation, distribution / logistic, market) and *per* adopted 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 to an ordination, was used to graphically display correlations between multivariate data sets 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 the PCA axis were also calculated. Linear mixed regression models (LMRM) using the "*glmer*" function (R package "*lme4*"; R Core Team, 2020) were used to test for significant correlations between explanatory 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 in ANOVA and LMRM.

3. Results

The rapid assessment web survey allowed us to cover stakeholder's perceptions worldwide, reaching 52 countries (Fig. S1, Supplementary Materials). Complete survey responses were obtained from 585 stakeholders (80% male, 14% female and 6% other) aged from 18 to over 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) most reporting a medium / high instruction level (4% primary school, 23% secondary school, 54% university [bachelor or master], 19% PhD). Respondents represented each of the four *a priori* selected farming strategies: 43% land based intensive

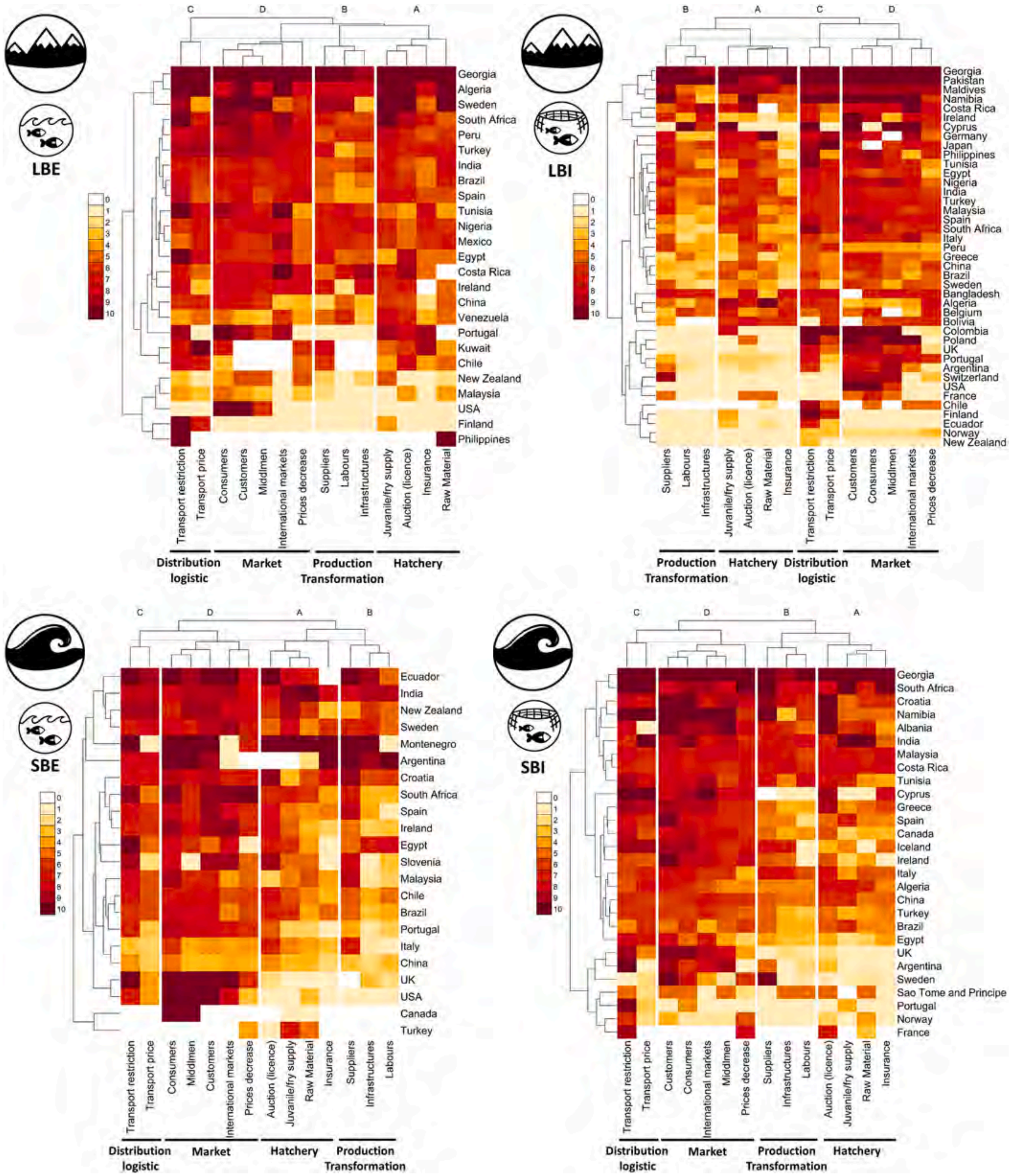

Fig. 3. Heatmaps representing data on the encountered difficulties and related economic loss (scaled from 1 = no economic loss at all, to 10 = very high economic loss) on the four selected stages of the aquaculture perishable food supply chain and related affected aspects. Hatchery: juvenile/fry supply, raw materials, insurance, auctions (licences). 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 shown *per* farming strategy (LBE = Land-based extensive, LBI = Land-based intensive, SBE = Sea-based extensive, SBI = Sea-based intensive) with and without Integrated Multi-Trophic Aquaculture (IMTA).

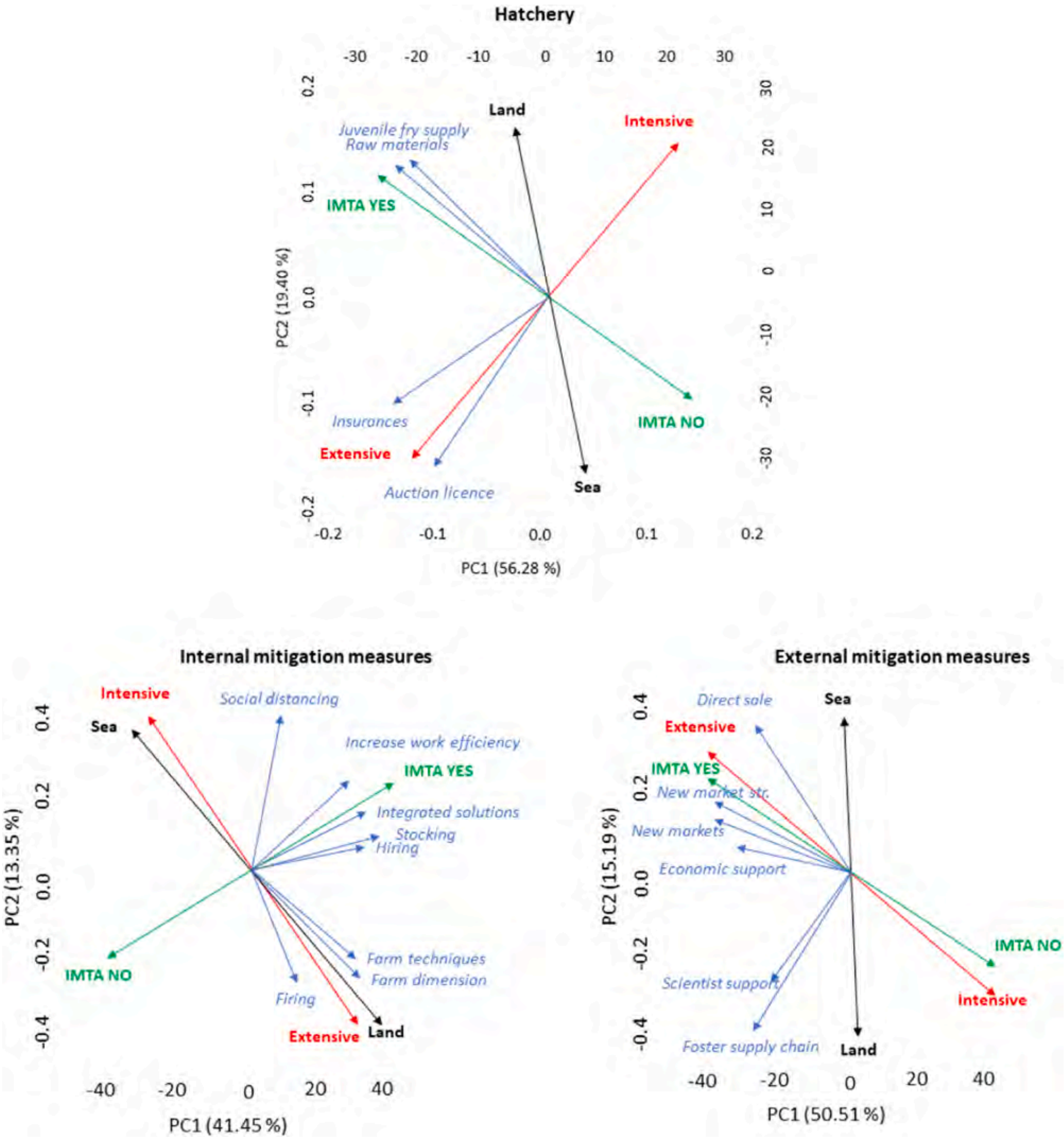

Fig. 4. Principal component analysis (PCA) on stakeholder responses on disruption effects (resulting in economic loss, scaled from 1 = no economic loss at all, to 10 = very high economic loss) associated with hatchery stage of the aquaculture PFSC, respectively: lack of juvenile/fry supply; lack of raw 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].

aquaculture (LBI), 16% land based extensive aquaculture (LBE), 23% sea based intensive aquaculture (SBI) and 18% sea based extensive aquaculture (SBE). One fifth (20%) of the respondents reported using IMTA approaches (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, with responses differing significantly between farming strategies (see percentages *per* four categories: 1 no effect, 2–4 low, 5–7 moderate and 8–10 high; Figs. 1, 2). The highest levels of economic losses were reported by those who used extensive systems both on land and at sea (*i.e.,* LBE 45% and SBE 42%), and the lowest economic loss was reported under IMTA at SBI (10%). The highest percentage of respondents who reported no effects of the pandemic were from IMTA LBE (36%) and SBI (51%; Fig. 1) categories. High economic losses in aquaculture systems differed by countries, which varied in which form of aquaculture was most susceptible. Those most vulnerable included LBI and SBE in India and South Africa; LBE in Portugal, Ireland, and Algeria; and SBI in Northern European countries. Therefore, the reported economic loss among the farming strategies was

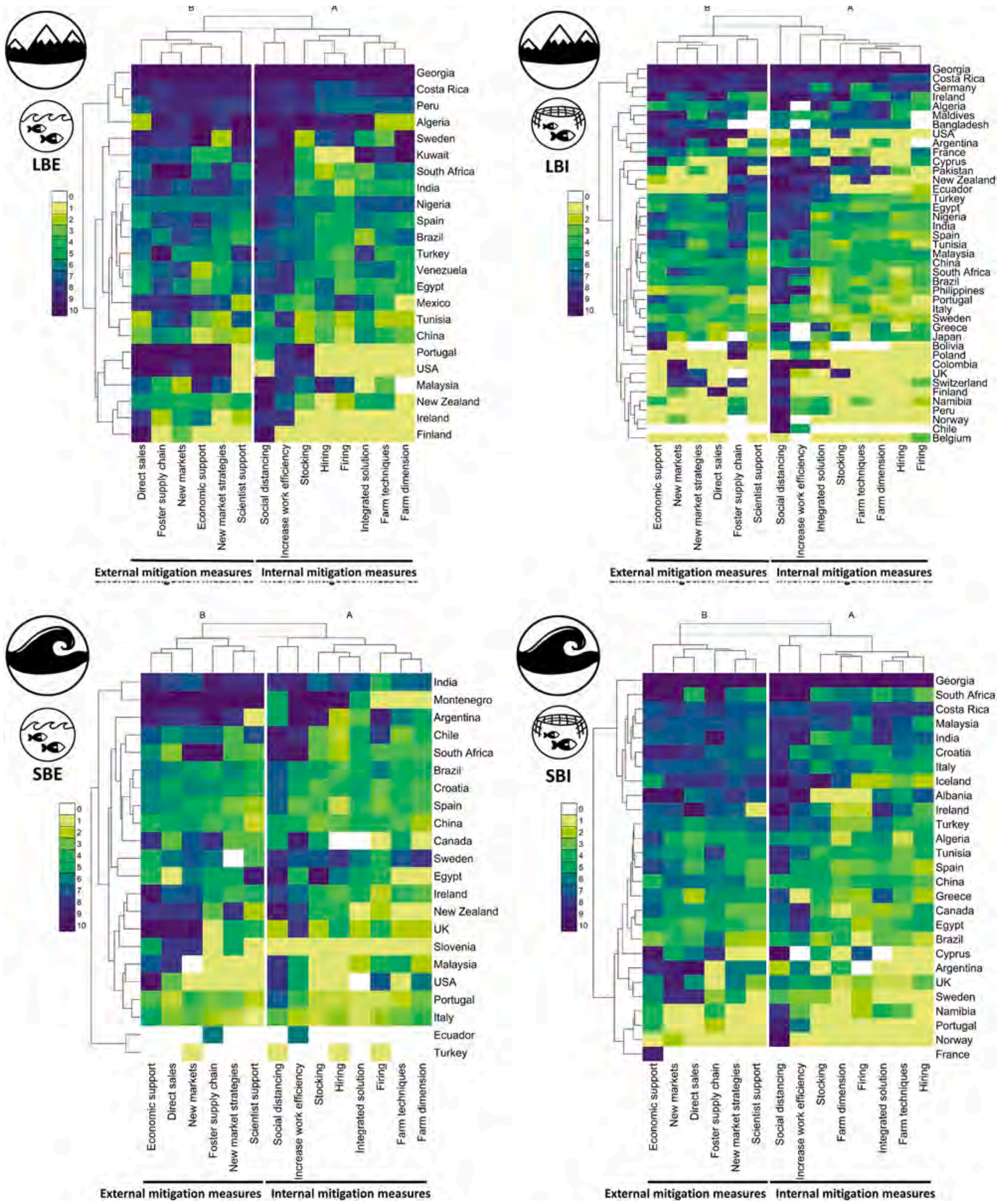

Fig. 5. Heatmaps representing data on the adoption of internal and external mitigation measures (scaled from 1 = no adopted loss at all, to 10 = very high adopted). Internal mitigation measures social distancing, increase work efficiency, hiring, firing, integrated-multi trophic solutions, change in 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 shown per farming strategy (LBE = Land-based extensive, LBI = Land-based intensive, SBE = Sea-based extensive, SBI = Sea-based intensive) with and without Integrated Multi-Trophic Aquaculture (IMTA).

not significant, regardless of whether or not IMTA was used (mixed ANOVA test, factor “farming strategy” df = 3, p = 0.236; factor “IMTA” d = 1, p = 0.625; “Interaction farming strategy / IMTA” df = 3, p = 0.154). There was also variation in job loss among farming strategies in different countries (Fig. 2). The highest percentage occurred in the LBE (35%), while the lowest was recorded at LBI (59%). Loss of jobs was significantly correlated with the farming strategy and was significantly, negatively correlated with 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, the highest loss of job losses was in LBE when compared to the other farming strategies (estimated marginal means tests: LBE *vs* LBI p < 0.0001; LBE *vs* SBE p = 0.0001; LBE *vs* SBI p < 0.004). Lower values of job loss were reported by farmers who incorporated IMTA (Estimated marginal means tests: IMTA *vs* no IMTA p = 0.013).

Stakeholders working both at land- and sea-based systems reported major difficulties and associated economic losses related to the “distribution / logistic” and “market” stages of the aquaculture PFSC, specifically with “transportation restriction” and difficulties in introducing products to domestic and “international markets” (Fig. 3). PCA performed on a multivariate dataset of answers related to the “hatchery” stage showed that the examined variables were significantly correlated with PCA ordination (PC1 explained 56.28% and PC2 19.40% of the total variance, respectively; Fig. 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 axis 1, and more specifically the use of IMTA and extensive aquaculture were associated with major difficulties in the juvenile, fry and raw materials supply and with insurance and auction licences respectively, which was also confirmed by personal comments from some of the interviewed farmers (Table 3; Figs. 3, 4). When performing PCA ordination on multivariate datasets of answers related to “Production / transformation” (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 in the production / transformation stage, the respondents reported the imbalance by farm maintenance costs and farm revenues, operational constraints and higher labour costs (see more comments in Table 3; Fig. 3). With regard to the market stage, respondents reported higher economic losses associated with liquidity shortages and excessive falls in prices (Table 3; Fig. 3).

Participants from all the surveyed farming strategies recognised social distancing and the related working shift as the most commonly adopted internal mitigation measures, followed by an increase in work efficiency. For LBE and SBE operations, stocking was indicated to be the third most commonly adopted mitigation response, followed by hiring and firing, while the adoption of integrated solutions and changes in farming techniques and extent of operations were less commonly used. Growers from LBI and SBI operations placed a higher importance on integrated solutions and changes in farming techniques and dimensions compared to firing (Fig. 5). A PCA performed on a multivariate dataset of answers related to “internal mitigation measures” revealed that the examined variables were significantly correlated with PCA ordination (PC1 explained 41.45% and PC2 13.35% of the total variance, respectively; Fig. 4). “IMTA” ($\chi^2 = 20.51$, df = 1, p < 0.001) was significantly correlated with PCA scores of axis 1, and more specifically the presence of IMTA was associated with a higher score for 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 farming techniques (PC1 0.798, p = 0.001), increased work efficiency (PC1 0.771, p = 0.001), reduction of farm dimensions (PC1 0.716, p = 0.001), and firing (PC1 0.627, p = 0.001). Specifically, several stakeholders made detailed comments describing their experiences in adopting “changes in farming techniques”, “integrated-multi trophic

Table 3
Selected comments reported by interviewed stakeholders, quotations 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	*“We are encountering difficulty in quality control of fingerlings before shipping, and more in general difficulty in getting fingerlings for fattening”.*
Philippine	LBI	noIMTA	*“The restrictions brought about by the COVID-19 lockdown resulted in materials and other pond inputs being not readily available or could not be transported to the pond areas. Regular inspections and consultation 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”.*
Nigeria	LBI	noIMTA	*“I had to afford more high production costs due to more feeding needed to maintain fishes”.*
Ecuador	SBE	noIMTA	*“I had to afford robberies for non-official surveillance”.*
Production / transformation level of the aquaculture PSFC			
Sweden	LBI	IMTA	*“No market but continue costing for electricity, water, heat, feed so fish can survive”*
Portugal	SBE	noIMTA	*“Seasonal personnel could not be contracted, leading to significant operational constraints, higher costs and extreme workload for existing personnel”.*
Italy	LBI	noIMTA	*“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”.*
Market level of the aquaculture PSFC			
Portugal	LBE	IMTA	*“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”.*
Croatia	SBE	noIMTA	*“70% of the sales depend on the touristic season (we supply the high-end markets (hotels/restaurants etc), 30% and less is for the domestic market, the closure of HoReCA channels and local markets is the main reason of economic loss”.*
Turkey	LBI	noIMTA	*“Imbalance in supply-demand and excessive fall in prices”.*
Internal (farm scale) adopted mitigation measures to cope with COVID-19 disruption			
China	SBE	IMTA	*“I'm increasing the level of mechanization of offshore production, increasing the use of advanced equipment to reduce dependence on people”.*
India	LBI	IMTA	*“I'm planning for low density to avoid risk”.*
Turkey	SBI	noIMTA	*“I'm trying new aquaculture species, producing low-cost products”.*
Egypt	LBE	noIMTA	*“I'm dividing the harvest into different periods”.*
China	LBI	noIMTA	*“I'll increase varieties with high added value, and improved survival rate”.*

(*continued on next page*)

Table 3 (*continued*)

Country	Farming strategy	IMTA/ noIMTA	Comment
Italy	SBI	noIMTA	*"I will test the introduction of new species such as sea urchins, sea cucumbers, oysters, etc.".*
External preferred mitigation measures to cope with COVID-19 disruption			
China	SBE	IMTA	*"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".*
Italy	SBI	IMTA	*"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 Productors Organisations at the level of representation in a homogeneous way to other countries, a National Communication Plan on the benefits of farmed fish such as safety, traceability, freshness, inclusion of companies in accelerators, improved access to credit".*
Italy	LBI	noIMTA	*"We are destinating our products to pet food".*
China	LBI	noIMTA	*"I suggest strengthening the industry emergency system".*
India	LBE	noIMTA	*"I suggest creating awareness of the health benefit of shrimp consumption through celebrities. Maintain BMC (Broodstock Maturation Center) cannot depend upon brooder supply chain from other countries to import".*
India	LBI	noIMTA	*"Increase the use of Artificial Intelligence will be highly helpful during lockdown to monitor the farms during pandemic times".*
Italy	SBI	noIMTA	*"Incentivize the purchase of farmed fish, finance the activities they produce in a sustainable way and IMTA".*
Croatia	SBE	noIMTA	*"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".*
Greece	SBI	noIMTA	*"I suggest financial contribution for the maintenance of unsold biomass and for extra airfreight costs".*
Brazil	LBI	noIMTA	*"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".*
Brazil	SBE	noIMTA	*"I propose a relief from tax obligations and contribution to Social Security, until the restoration of commercial normality, especially in the operation of restaurants".*

solutions", and "reduction of farm dimension" (see Table 3, Figs. 4 and 5).

External mitigation measures showed a very heterogeneous pattern of preference across farming strategies (Fig. 5). For LBE operations, direct sales were identified as the most important aspect, followed by the opportunity to foster the supply chain, seeking new markets, requesting economic support and exploring new marketing strategies. For LBI, SBI and SBE operations, direct economic support was identified as the top mitigation approach, followed by direct sales, new market development and new market strategies, and the opportunity to foster the supply chain at sea-based systems. Support from scientists showed 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 this variable significantly correlated with PC1, which explained 50.51%, while PC2 explained 15.19% of the total variance, respectively (Fig. 4). "IMTA" ($\chi^2 = 8.50$, df = 1, p = 0.003) was significantly correlated with PC1, and more specifically the presence of IMTA was associated with a 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), and foster supply chain (PC1 - 0.484, p = 0.001). When asked to indicate their preference for external mitigation measures to be adopted in the future, most stakeholders expressed their preference for "new market strategies" and "foster the supply chain" by providing more extensive comments on the need for "economic support" (see Table 1, Figs. 4, 5).

4. Discussion and conclusion

Our rapid global assessment allowed us to identify specific circumstances that inhibited or created difficulties for stakeholders in their efforts to adapt to the pandemic-induced challenges across the four surveyed farming strategies. Collated data allowed us to describe the effects of the COVID-19 outbreaks propagating along the four analysed stages of the aquaculture PFSC. This analysis identified the primary causal factors of supply shortage (*e.g.,* shortage and higher price of raw material at the hatchery stage; absence of stocking infrastructure at the production stage; transport interruption at the distribution stage) and shrinkage of demand (*e.g.*, food industry and market closures at the market stage) as causing negative impacts. These indicate lack of resilience threatening the aquaculture sector and its potential to contribute positively to increasing global demands for protein (FAO, 2020d). The limited options to transport products represented the weakest link of the aquaculture production pipeline across the four surveyed farming strategies, with farmers who paid more for transport being underpaid the most for their products. Both transport restrictions and increases in transportation costs were identified as common causes 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 material supply and price increase. The market stage was the second most vulnerable link facing severe disruptions due to the closure of local, national and international markets as well as the stopping of the HoReCA channels (*i.e.,* Hotels, Restaurants and Catering industry). Impacts to this latter channel resulted from sudden and prolonged lockdowns, which propagated forward disruption and was the main cause of demand shrinkage.

The widely reported economic distress propagated both ways along the aquaculture PFSC and across the four analysed stages. Economic loss associated with insurance coverage (*i.e.,* difficulty / insolvency or blocking / abandonment by insurance companies) on the initial hatchery stage, generated a key source of financial instability, as farmers can only produce when they have access to financing. As a primary consequence, not surprisingly, the request for economic support was the most important external mitigation measure identified by respondents. Financial sustainability is essential for stakeholders of the FSC and has been reported among the top risk mitigating strategies for PFSC (Cullen, 2020; Kumar et al., 2021).

Following definitions of the fundamental trade-off between FSCs efficiency and resilience by Christopher and Peck (2004), evidence from our global assessment confirmed that aquaculture PFSC - at the surveyed shock stage of the COVID-19 pandemic - failed to maintain the three elements to achieve resilience: 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 more horizontal collaborations, 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 different SCs more in general. Contingencies, as well as new opportunities in the market and business environment, should be catalogued, communicated, and exchanged among stakeholders. This will allow clustering of their logistical 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 have been essential mitigation measures to contain the spread of COVID-19, and not surprisingly were reported as the most widely adopted internal mitigation measures by survey participants across all the farming strategies. Since aquaculture depends on a PFSC characterised by operations that require a lot of human interactions with physical contact, curtailment of human interactions might have been one of the primary causes of job losses.

The collated information allowed the detection of the potential buffering characteristics of IMTA on some surveyed components of economic distress, for example on job losses. IMTA, a promising system in buffering anthropogenic driven shocks (Chopin et al., 2001; Sarà et al., 2021) and showing economic and ecological resilience by increasing the diversity of farmed species (*i.e.,* farmed species having various trophic levels and functional diversity; Troell et al., 2014; Knowler et al., 2020), seems to confer larger resilience also to production efficiency at the local scale. The diversified production of products by IMTA offers more than one or two market options and appears to allow farmers to utilize still active sales channels, thereby circumventing roadblocks in some steps of the PFSC as shown by the adopted internal, and preferred external, mitigation measures respectively. While surveyed stakeholders from all the farming strategies expressed less interest in hiring as an internal mitigation measure onsite, farmers using IMTA expressed more interest in adopting hiring as an 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, a key response to disruption risk, and preferred a more flexible business model as an integrated solution that increased work efficiency. This preventing them from sacrificing too many farm assets (*i.e.,* changes in farming techniques) and preserved the human dimensions of resilience (*i.e.,* firing was a less adopted mitigation measure). Among external mitigation strategies, farmers applying IMTA expressed interest in the exploration of new market strategies and direct sales, scientific support and supply chain promotion, contrary to farmers not applying IMTA who expressed a higher preference for direct economic support from government agencies. Farmers working with IMTA showed higher levels of proactiveness preferring tools typical of "Flexible Business Models" which are considered as one of the best mitigation strategies to cope with disruption risk mitigation in PFSC (Kumar et al., 2021). The one area where IMTA showed lower resilience was in difficulties obtaining juveniles, fry and other raw materials, *i.e.,* the hatchery stage of the supply chain. Therefore, aquaculture based on IMTA appears to suffer more on the first stage of the PFSC. Efforts to shore up the resilience of IMTA-based aquaculture operations should pay close attention to this aspect of the PFSC.

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

The patterns reported by stakeholders in this rapid assessment constitute a snapshot of the various impacts of COVID-19 pandemic on the aquaculture PFSC at the beginning of the pandemic (first shock phase) and impacts 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 facilitate resilience in SCs, to capture the full social and economic effects of shocks, and to mitigate external situations (*e.g.,* lockdowns) and policy measures (*e.g.,* rapid support of decision-making in a crisis). The lack of baseline information, information flow, transparency, accuracy, management and speed of information have been recognised as maximising the vulnerability of FSCs to risk and shock by several authors (Vlajic et al., 2012; White et al., 2021). In this context, starting from our collated evidence - reflecting spatial and temporal constrains typical of a rapid assessment - a knowledge baseline should be built to the highest spatial and geographical resolution level possible, considering both more resilient and organised responses from the developed countries and the labour-intensive and less organised responses from the developing countries (Kumar et al., 2021; Onuma et al., 2020; Love et al., 2021). A future comprehensive - collaborative, multisectoral, and transdisciplinary - knowledge baseline also needs to consider all the potential farming strategies as highlighted by our assessment which allowed us to see geographic clusters of responses (with countries from the Global South such as South Africa and India suffering more economic distress). 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 suggest the need for more system- and SC stage-based, tailored measures, and which warns against a "one-size-fits-all" approach. Unless national recovery strategies of the aquaculture PFSC and the associated financial efforts are tailored to specific stages and SC stages, (International Monetary Fund https://blogs.imf.org; The World Bank, 2020) they are unlikely to be effective.

To avoid wasting the opportunity to change the future direction of the aquaculture sector (Love et al., 2021) we believe that future reactive (*i.e.,* absorb, react, restore) and preventive (*i.e.,* learn, build robustness *sensu* Tendall, 2015) shock-based reaction actions - also resulting from any future pandemics (Love et al., 2021) - should thus include studies of stakeholder perception, key elements to ensure the engagement in transformations over which resilience thinking can be built (Folke et al., 2010).

Vietnam and Indonesia were not included in our rapid assessment, a limitation of this study since both are globally important aquaculture producing countries, although the online survey was distributed to both countries, no responses were received (the circulation of the survey was based on co-authors volunteer effort).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

MCM and GS conceived the study and led the project at all stages. All authors contributed to the execution of the study, participated in circulating the questionnaires throughout their respective national and international networks. MCM and GS with MB, ML, ST, LC, GM coordinated data collection, graphical outputs and statistical analyses. MCM, BH and GS drafted the manuscript, and all authors participated in editing the final revisions.

Competing interests

The authors declare no competing interests.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2021.10.014.

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