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NOTE

The Synergistic Impacts of Anthropogenic Stressors and COVID-19 on Aquaculture: A Current Global Perspective

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ABSTRACT

The rapid, global spread of COVID-19, and the measures intended to limit or slow its propagation, are having major impacts on diverse sectors of society. Notably, these impacts are occurring in the context of other anthropogenic-driven threats including global climate change. Both anthropogenic stressors and the COVID-19 pandemic represent significant economic challenges to aquaculture systems across the globe, threatening the supply chain of one of the most important sources of animal protein, with potential disproportionate impacts on vulnerable communities. A web survey was conducted in 47 countries in the midst of the COVID-19 pandemic to assess how aquaculture activities have been affected by the pandemic, and to explore how these impacts compare to those from climate change. A positive correlation between the effects of the two categories of drivers was detected, but analysis suggests that the pandemic and the anthropogenic stressors affect different parts of the supply chain. The immediate measurable reported losses varied with aquaculture typology (land vs. marine, and intensive vs. extensive). A comparably lower impact on farmers reporting the use of integrated multitrophic aquaculture (IMTA) methods suggests that IMTA might enhance resilience to multiple stressors by providing different market options under the COVID-19 pandemic. Results emphasize the importance of assessing detrimental effects of COVID-19 under a multiple stressor lens, focusing on areas that have already locally experienced economic loss due to anthropogenic stressors in the last decade. Holistic policies that simultaneously address other ongoing anthropogenic stressors, rather than focusing solely on the acute impacts of COVID-19, are needed to maximize the long-term resilience of the aquaculture sector.

KEYWORDS

SARS-CoV-2 pandemic; supply chain; food insecurity; climate change; multiple stressors; vulnerability; stakeholder perceptions; socio-ecological systems

1. Introduction

The COVID-19 pandemic broke out in late 2019 and continues to spread across the planet. As of the middle of 2020, more than 81 million people have been infected globally with deaths exceeding well over one million, and numbers continue to increase (https://covid19.who.int/). While it is still impossible to estimate exactly what the ultimate total economic damage from the global COVID-19 novel coronavirus pandemic will be, economists agree that it will have severe negative impacts on the global gross domestic product (GDP). Economic costs of the COVID-19 pandemic for 2020 are estimated to be at least 2.4% of the GDP for the most major economies, resulting in an unprecedented fiscal policy response of, to date, close to 11 trillion USD worldwide. This response represents a mobilization of economic resources from local, regional and national governments, including funds for maintaining the continuity of the global food supply (International Monetary Fund https://blogs.imf.org). Food sectors such as agriculture, fisheries and aquaculture have already reported severe economic impacts and job losses due both to reduced production capacity, as well as disrupted supply chains (FAO and CELAC 2020). Potential disruptions to food production and supply chains remain of imminent concern as food insecurity, like the virus, will disproportionately affect vulnerable populations (Gregory et al. 2005).

In parallel, the year 2020 has been forecasted to be among the hottest years on record (https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health) and the impacts of climate change continue largely unabated. The World Health Organization estimates that annual excess deaths due to climate change will exceed 250,000 in the next decade, while a recent report by the World Wildlife Foundation estimated annual economic losses of 479 billion USD by 2050 and a cumulative loss at about 10 trillion USD, between 2011 and 2050 (Roxburgh et al. 2020).

The ecological, social and economic impacts of the pandemic and their interactions with ongoing anthropogenic-driven changes are still unfolding (Baker et al. 2020), but they offer an opportunity to explore the perceived impacts and effectiveness of resilience strategies in addressing multiple stressors of both climatic and non-climatic origin (O'Brien et al. 2004).

Here, these concepts were examined with a focus on global aquaculture, recognized as one of the fastest growing sources of protein globally (FAO 2020a). Interpreting how multiple stressors are likely to affect key stakeholder perceptions among aquaculture systems is not straightforward. The COVID-19 pandemic has (nearly) simultaneously impacted (either directly or indirectly) much of the world's population, as have measures to limit or slow the spread of the virus. In stark contrast, the impacts of anthropogenic stressors such as climate change on terrestrial food production sectors are often perceived not as a constant "pressure" (i.e. chronic/press stressor), but instead as a series of short term, local or regional pulses (i.e. extreme events such as those generated by heatwaves, droughts, fire and floods, heterogeneous in space and time; Harris et al. 2018). Anthropogenic-driven stressors typically manifest themselves as asynchronous and heterogeneous; different locations around the globe experience climate-driven stressors that vary in type, magnitude and frequency (Pelham 2018). For example, while one region may be experiencing drought, another, sometimes at the same time, may suffer from floods; coastal environments experience sea level rise, which has no direct effects on inland populations. In part because of these asynchronies, coordinated adaptation strategies to bolster resilience to environmental threats in food production sectors is difficult (Kaufmann et al. 2017). Many terrestrial farmers, in particular those from Low-Income, Food-Deficient Countries (LIFDCs) and Small Island Developing States (SIDS) work in the most vulnerable regions characterized by the highest values of Global Climate risk index 2020 (e.g. Southeast Asian countries). They experience detrimental effects to their livelihood, while many in developed nations are reluctant to acknowledge climate-related impacts (Prokopy et al. 2015). Far less is known of the perceptions of the aquaculture sector to anthropogenic stressors including climate change, and while several studies have been conducted at local and national scales, none have been implemented on a global scale (Dubey et al. 2017).

Aquaculture represents the fastest growing industry in the fish and shellfish production sector and is recognized worldwide as among the most sustainable options for improving food security and eradicating poverty (Barange et al. 2018) tackling at least 7 out of 17 United Nation Sustainable Development Goals (UN SDGs; Hambrey 2017). It also is among the most vulnerable to climate change (Froehlich et al. 2018; Sarà et al. 2018). Aquaculture practices are not confined to any one place and exist everywhere there is water: in contained facilities on land, in freshwater ponds and lakes, and in marine waters both under intensive (e.g. species cultivated at high densities in artificial cages or tanks with feed added by growers) and extensive (e.g. species cultivated at lower densities in natural and created lakes and ponds, enclosed marine bays, rivers) conditions. In this context, integrated multitrophic aquaculture (IMTA) is recognized as a sustainable form of aquaculture (Alexander et al. 2016). IMTA is a practice that incorporates species from different trophic levels (e.g. not only herbivorous bivalves or carnivorous fish cultivated alone but several species representing different trophic levels being farmed together) that results in reduction in organic and inorganic wastes and their impacts. The increased resilience of IMTA to external threats, while hypothesized, has seldom been tested empirically (IFAD 2014).

There is thus a critical need to determine the potential effects of the COVID-19 pandemic on socioecological and economic dynamics of the aquaculture sector. Understanding the magnitude of the perceived negative impacts of pandemic control measures and of climatic and other anthropogenic stressors on aquaculture production on a global scale should be a priority. Such an understanding can guide capacity building and regulations associated with sustainable development (SDGs, Agenda 2030) for a faster response in future scenarios.

2. Questionnaire structure and global distribution strategy

To investigate the perceptions of COVID-19 effects on stakeholders operating in the aquaculture sector (both land- and sea-based) a global web survey based on a semi-structured questionnaire was launched (study approved by the Ethical Committee at the University of Palermo, UNPA-183-Prot. 767-05/05/2020 n. 1/2020 29/04/2020).

The semi-structured questionnaire (see Appendix, supplementary material) was designed with the primary objective to collect stakeholder perceptions on two main questions:

1. *Could you please indicate if there was an economic loss (direct or indirect economic loss) in your farm due to COVID-19?*
2. *Among the following environmental causes that have brought socio-economic loss in your farm in the last decade, which was more negative with respect to that caused by COVID-19?*

Data were also collected regarding type of aquaculture systems, country, nation and role in the farm.

The semi-structured questionnaire was translated into 14 languages (English, Italian, Spanish, Chinese, Croatian, Portuguese, Arabic, Hebrew, Turkish, Swedish, Greek, Maltese, Divehi, Albanian). 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. Specific questions were designed to rapidly assess the perceptions of global aquaculture stakeholders – specifically people involved in production at the farm or within the company – of the direct or indirect economic loss associated to COVID-19 and related control measures (i.e. lockdown and social distancing) scaled from 1 = no economic loss at all, to 10 = very high economic loss (Appendix, supplementary material). The reported economic impact due to COVID-19 was divided into four categories: no loss, low (2–4); moderate (5–7) and high (8–10). Respondents were also asked if they had previously experienced any impacts from anthropogenic-driven changes in last decade that had led to greater economic losses than those from the current COVID-19 pandemic. The anthropogenic stressors (more than one could be chosen) included: heatwaves, hypoxia/anoxia, harmful algae, local pollution, storms, diseases caused by bacteria, viruses and parasites affecting target species, sudden changes in salinity, flooding and eutrophication. Farmers were also asked about their use of IMTA and compared this information with the perceived economic loss of either COVID-19 or anthropogenic stressors.

The semi-structured questionnaire was 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 coauthors to serve as focal point, or rather to promote the compilation of the survey among their communication and dissemination channels linked to aquaculture sector. To ensure that the data collected were representative of the reactive phase of the emerging COVID crisis, the web survey distribution had a duration of three weeks, while the COVID-19 pandemic was still fully active in most countries (5–29th May 2020). While we are aware that respondents were experiencing different stages of the pandemic during the survey, we decided to keep the survey active during a short temporal window to both facilitate a rapid assessment and to avoid including any later, post-pandemic stages. Replies were coded as a function of geographic position of the farms and the typology of aquaculture (land vs. sea-based, and intensive vs. extensive). The survey reached 54 countries across five continents (Figure 1).

Data were analyzed with multivariate techniques (permutational analysis of variance and principal

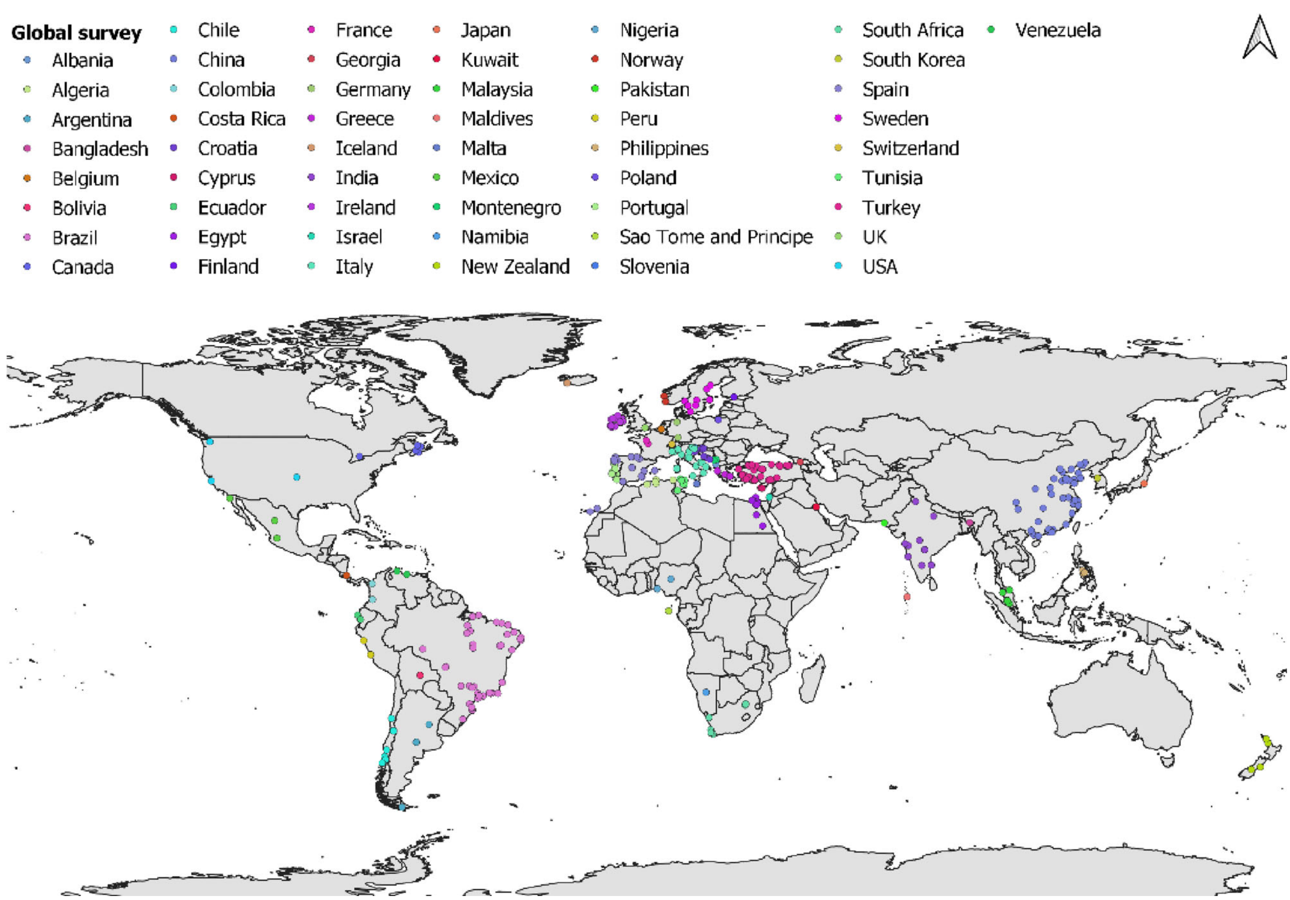

Figure 1. Countries covered by the global web survey (launched on 5th and closed on 29th May 2020), colored dots have been grouped per each of the 54 countries reached across the five continents (see legend). Of a total of 585 respondents to our survey, 483 (83%) from 45 over 54 involved countries, reported that anthropogenic stressors had greater impacts than the pandemic. None of the respondents from Bangladesh, Belgium, California, Germany, Maldives, São Tomé and Príncipe, Slovenia, South Korea, or Venezuela reported impacts of anthropogenic stressors that exceeded the impacts of COVID.

component analysis). A 3-way Permutational Multivariate ANOVA (PERMANOVA, Anderson 2001) – performed on a triangular matrix based on Jaccard index – was used to test significant differences between multivariate response data, represented by the presence or absence of each type of "anthropogenic stressors" reported by respondents, and the different levels of the three explanatory variables: "Country," "Type of aquaculture," "Degree of Salinity." The experimental design comprised: factor "Country," fixed with 25 levels, factor "Type of aquaculture," random and nested in "Country," with 4 levels, factor "Salinity," random and Nested in "Country," with 5 levels. Nested design and permutational analysis of variances have been chosen to deal with non-balancing data (Primer V.7 http://updates.primer-e.com/primer7/manuals/User_manual_v7a.pdf).

The visualization of multivariate data was obtained through a principal components analysis (PCA). PCA was performed on similarity matrix based on Jaccard index derived from multivariate presence/absence dataset as described above (Borcard et al. 2011). The first two components accounted for over 50% of the variance (PC1 – 37%; PC2 – 18%). The function "envfit," which fits environmental vectors or factors onto an ordination, was used to graphically display correlation between responded variable and explanatory variables. Redundancy analysis was used to test significant relations between the amount of economic losses, represented by four categories: "no-losses," "low," "medium" and "high," and the type of aquaculture or the country. All the statistical analysis and graphical ordinations were performed using PRIMER6 and PERMANOVA and R [R version 4.0.2 (2020-06-22)]. The R package used were: "vegan" and "stats" (http://www.R-project.org/; http://vegan.r-forge.r-project.org/).

3. COVID-19 and anthropogenic stressors: a global analysis through stakeholder experiences

Of a total of 585 respondents (colour labeled in Figure 1), 483 (83%) reported that anthropogenic stressors had greater impacts than the pandemic, and here responses from that subset were analyzed. This subset represents respondents from 45 countries and did not include farmers from Bangladesh, Belgium, Germany, Maldives, São Tomé and Príncipe, Slovenia, South Korea, or Venezuela. Farmers from China, Turkey, Brazil, Spain, Egypt, Ireland, Portugal, Italy, and Tunisia comprised about 70% of these replies; 13% and 42% of the respondents worked in land-based intensive and extensive aquaculture, respectively, and the rest in marine open water farming, both intensive (21%) and extensive (24%). The low response rate from some countries precludes a detailed analysis on a country-specific basis. Of all respondents, 92% reported being impacted by the COVID-19 pandemic but at the same time 83% also reported impacts caused by environmental stressors such as heatwaves, hypoxia or eutrophication (among other anthropogenic stressors examined). Responses

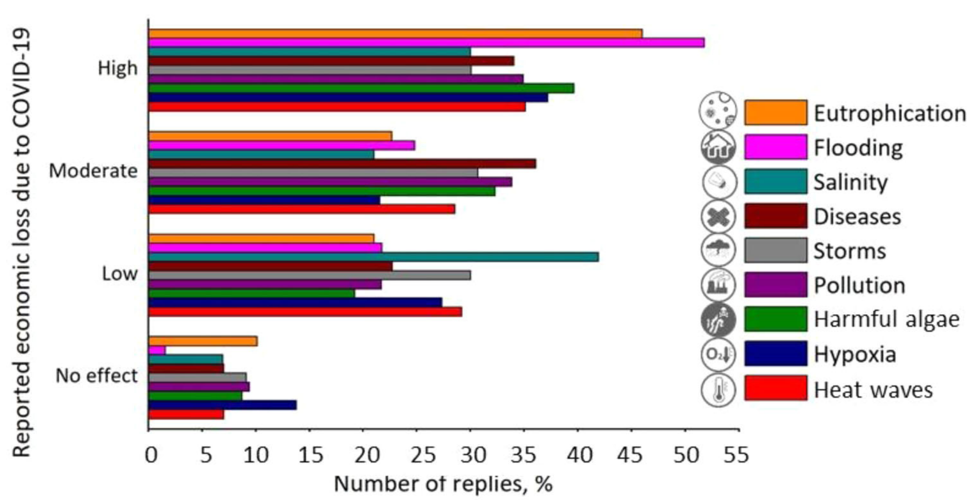

Figure 2. Reported economic loss due to COVID-19 ranked into four categories: no effect (1), low (2–4); moderate (5–7) and high (8–10) with associated experience of any impacts from anthropogenic driven. Respondents were asked to scale the economic loss due to COVID-19 from 1 = no economic loss at all, to 10 = very high economic loss and to report any impacts from anthropogenic-driven changes in last decade recognized to have led to greater economic losses than those from the current COVID-19 pandemic. The anthropogenic stressors (more than one could be chosen) included: heatwaves, hypoxia/anoxia, harmful algae, local pollution, storms, diseases caused by bacteria, viruses and parasites affecting target species, sudden changes in salinity, flooding and eutrophication.

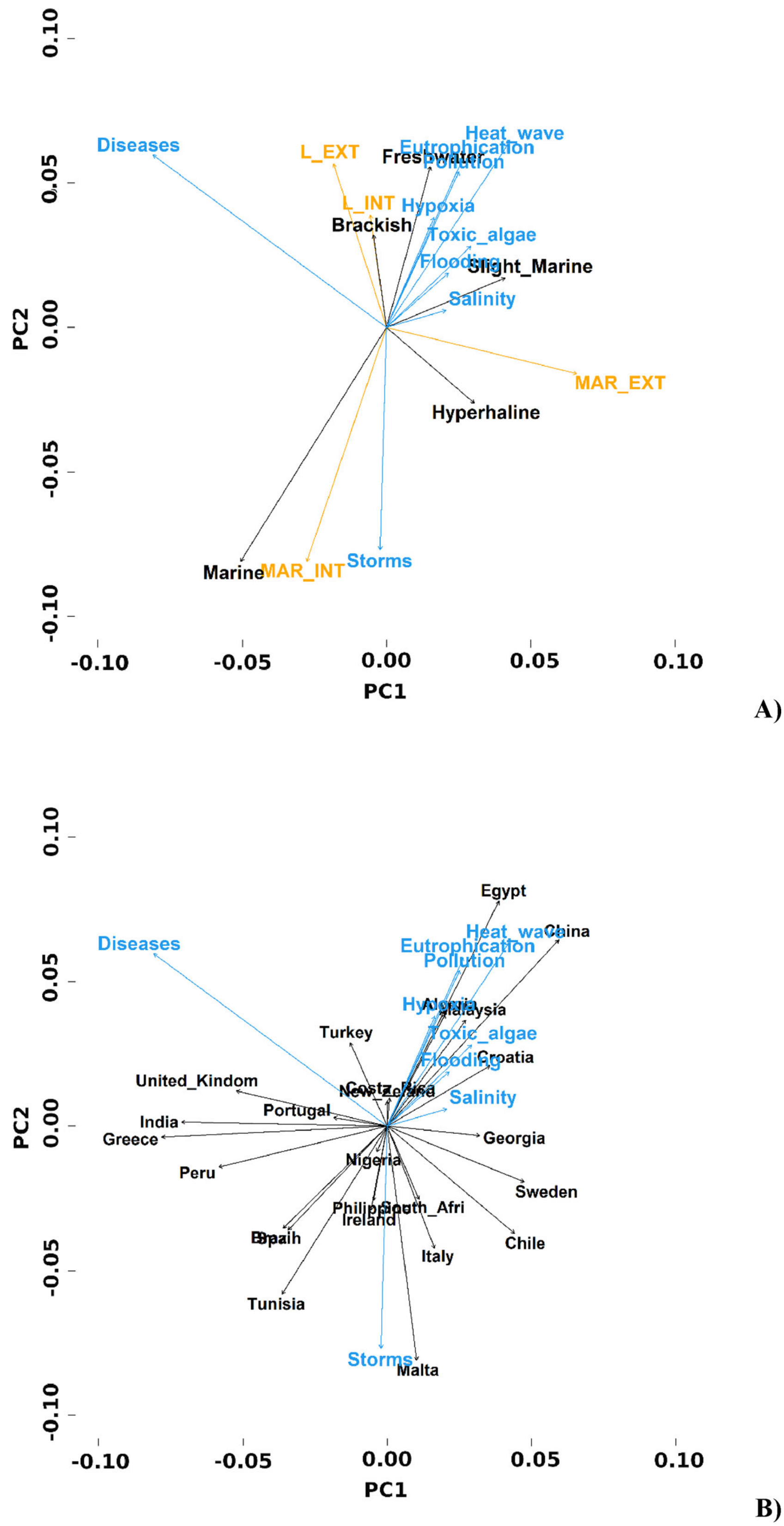

Figure 3. Principal component analysis (PCA) on stakeholder responses on economic-loss perception associated with anthropogenic stressors analyzed (heatwaves, hypoxia/anoxia, harmful algae, local pollution, storms, diseases, sudden changes in salinity, flooding and eutrophication – light blue) depending on the four explored aquaculture systems (land-based intensive L-INT, land-based extensive L-EXT, sea-based intensive S-INT, sea-based extensive S-EXT – orange upper panel – A) and countries (black lower panel – B).

Table 1. PERMANOVA results (SS = sum of squares; MS = mean squares; p = probability; perms = 0 number of permutations) (ns = no significant difference; *difference at $p < 0.05$; **difference at $p < 0.01$; ***difference at $p < 0.001$).

Source	*df*	SS	MS	Pseudo-*F*	*P* (perm)	Perms	*P* (MC)
Country (Co)	21	1.12E + 05	5320.1	1.405	0.018	999	0.006**
Typology (Co)	42	1.39E + 05	3317.7	1.3765	0.106	999	0.006**
Salinity (Co)	47	1.53E + 05	3263.3	1.3497	0.116	998	0.004**
Typology (Co)×salinity(Co)**	22	49103	2231.9	0.78615	0.938	997	0.961ns
Residuals	248	7.04E + 05	2839.1				
Total	391	1.30E + 06					

Table 2. Countries for which respondents reported to have previously experienced any impacts from anthropogenic-driven changes - in last decade - that had led to greater economic losses than those from the current COVID-19 pandemic (significant values are reported) (ns = no significant difference; * = difference at $p < 0.05$; ** = difference at $p < 0.01$; *** = difference at $p < 0.001$).

Significant Factors	Country	PC1	PC2	r^2	p
Salinity, flooding, harmful algae, hypoxia, pollution, eutrophication, heat waves	Algeria	−0.41115	−0.91157	0.0124	0.057 ns
	China	−0.64939	−0.76045	0.0528	0.001***
	Croatia	−0.80307	−0.59589	0.011	0.087 ns.
	Egypt	−0.42291	−0.90617	0.0496	0.001***
	Malaysia	−0.56045	−0.82819	0.0143	0.041*
Diseases, storms	Brazil	0.65119	0.75892	0.0158	0.035*
	Greece	0.99562	0.09349	0.0378	0.002**
	India	0.99979	0.0207	0.0303	0.003**
	Peru	0.95605	0.29321	0.0228	0.006**
	Spain	0.61872	0.78561	0.0153	0.036*
	Tunisia	0.46729	0.8841	0.03	0.005**
Storms	Chile	−0.76742	0.64115	0.0226	0.006**
	Italy	−0.37399	0.92743	0.0138	0.050*
	Malta	−0.13977	0.99018	0.0437	0.001***
	Sweden	−0.93799	0.34666	0.0163	0.026*
Diseases	United Kingdom	0.98232	−0.18719	0.018	0.02

to these interactive crises tend to differ; unlike the pandemic, climate-related effects are usually heterogeneous in space and time and manifest themselves more indirectly via threats such as heat waves, drought or flooding that act from regional to local scales. Among anthropogenic stressors, transient (i.e. pulse) disturbance factors of purely climatic origin (i.e. heatwaves, storms and floods) accounted for 33.3% of replies, while pervasive (i.e. press) local and regional factors (i.e. hypoxia, pollution, harmful algae, eutrophication, salinity changes) represented 66.7% of replies. Overall, farmers who reported no economic loss due to COVID-19 (∼7% of respondents) also reported a lower frequency of anthropogenic factors affecting their activities in the last decade (Figure 2). Farmers reporting an economic loss due to COVID-19 over all other levels (low, intermediate and high) also reported a significant increase in the occurrence of anthropogenic effects on their activities. Among them, flooding and eutrophication were most frequently reported among farmers affected by the highest COVID-19 economic loss, while diseases and salinity increase were most frequently reported among farmers affected by moderate and low economic loss, respectively. Principal component analysis (PCA) showed globally that diseases, hypoxia, pollution, eutrophication and heatwaves were perceived as more detrimental in land-based systems, while impact of storms was reported as a more relevant issue in the sea-based intensive systems. Salinity increase, flooding and harmful algae were reported to be more detrimental in sea-based extensive systems (Figure 3A; Table 1). A significant difference across the covered countries is evident (Figure 3B). Salinity increase, flooding, harmful algae, hypoxia, pollution, eutrophication and heat waves were recognized as a source of economic loss greater than COVID-19 in China, Egypt and Malaysia while diseases and storms were perceived as more damaging in Brazil, Greece, India, Peru, Spain, Tunisia, Chile, Italy, Malta and Sweden (Table 2). Figure 4 details the levels of economic loss due to COVID-19 and anthropogenic effects by country and aquaculture typology. Whereas extensive, land- and sea-based aquaculture was seemingly the most vulnerable, intensive practices were able to partially buffer the effects.

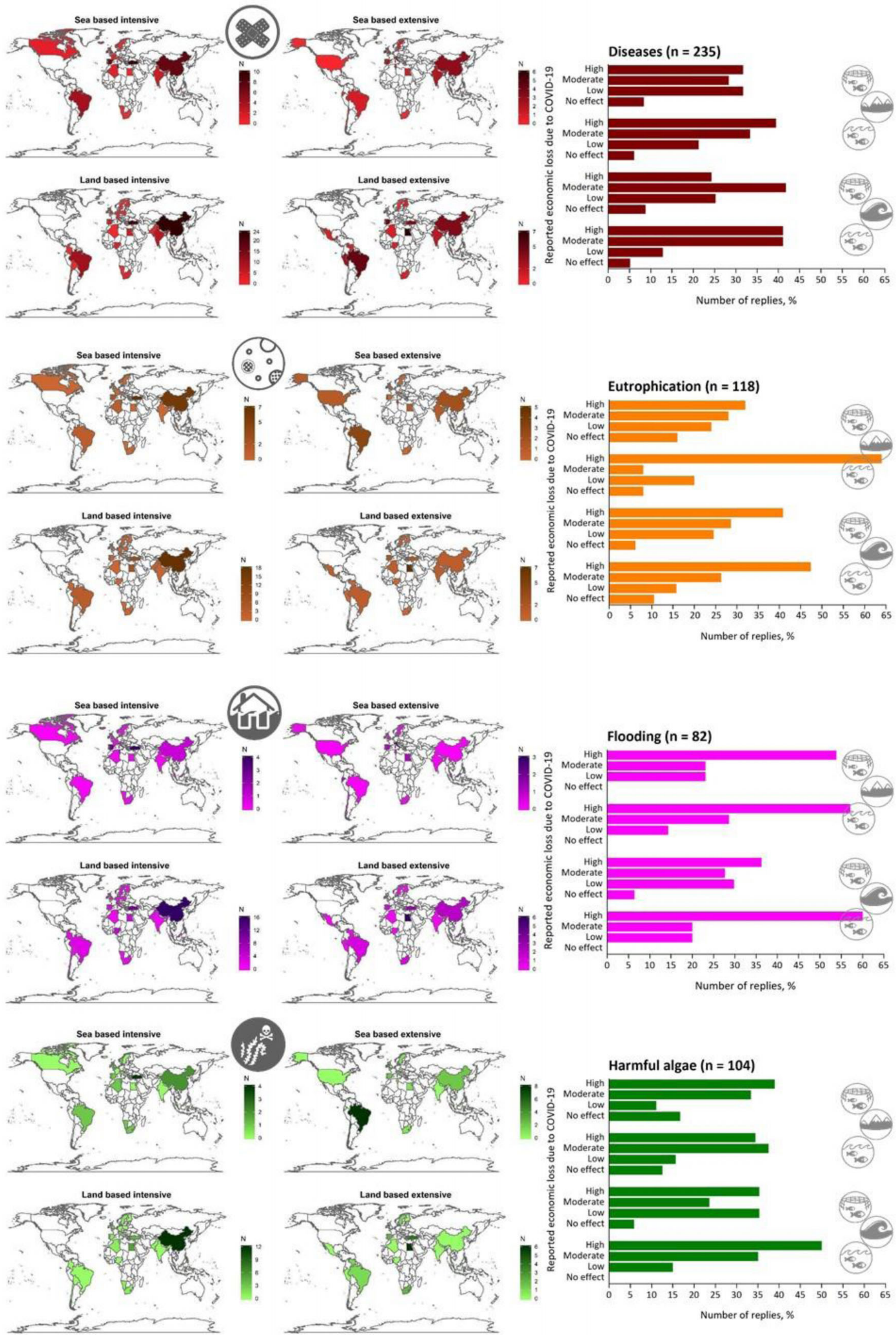

Figure 4. Anthropogenic stressors (number of occurrence, *N*) reported as by respondents, respectively mapped per each of the four explored aquaculture systems (land-based intensive, land-based extensive, sea-based intensive, sea-based extensive), per each surveyed country perceived as more negative with respect to COVID-19 in the last decade (right side). On the left side, histograms with the percentage of replies per each stressor were reported as combined with economic loss due to COVID-19 categories: high, moderate, low, no effect.

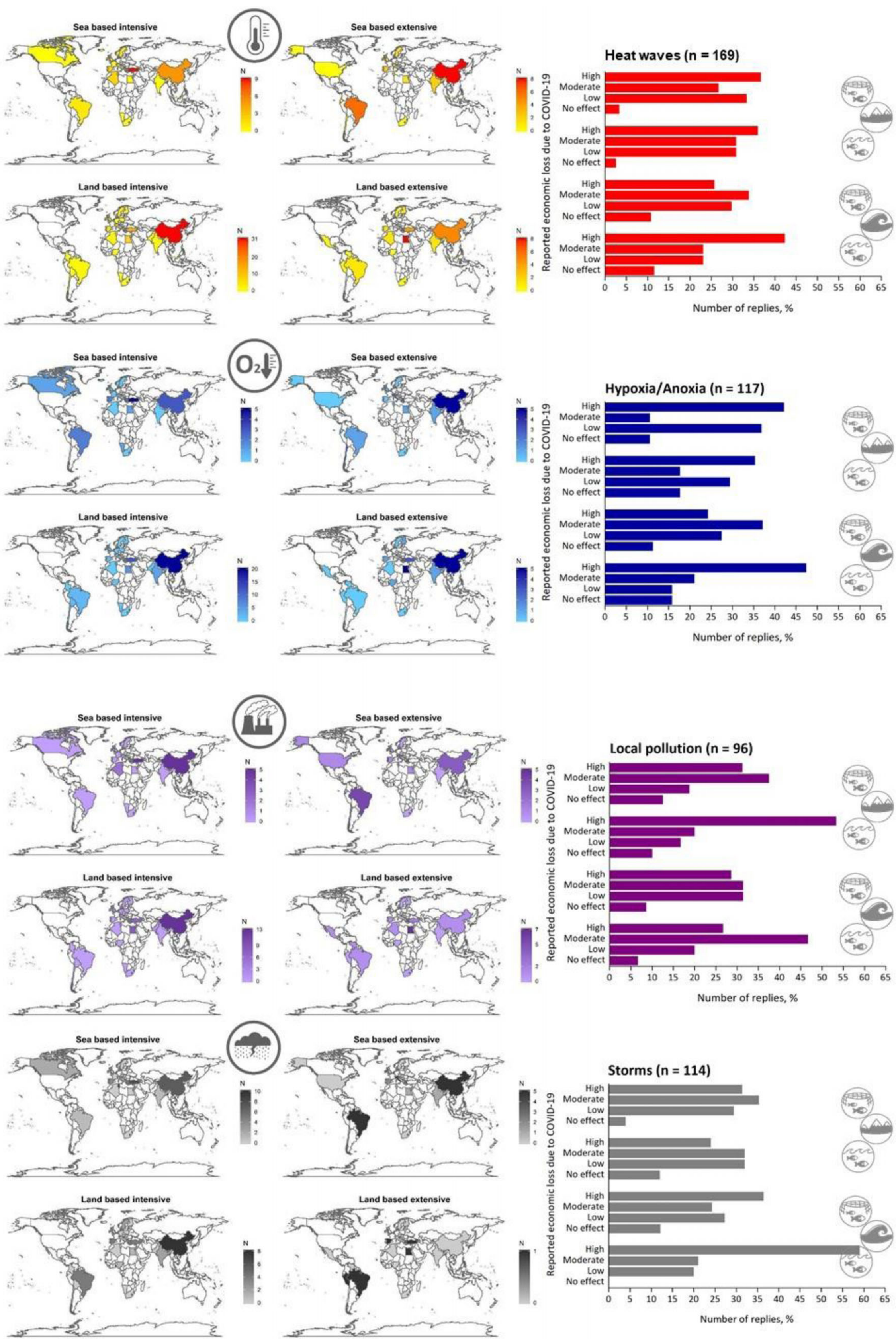

Figure 4. Continued.

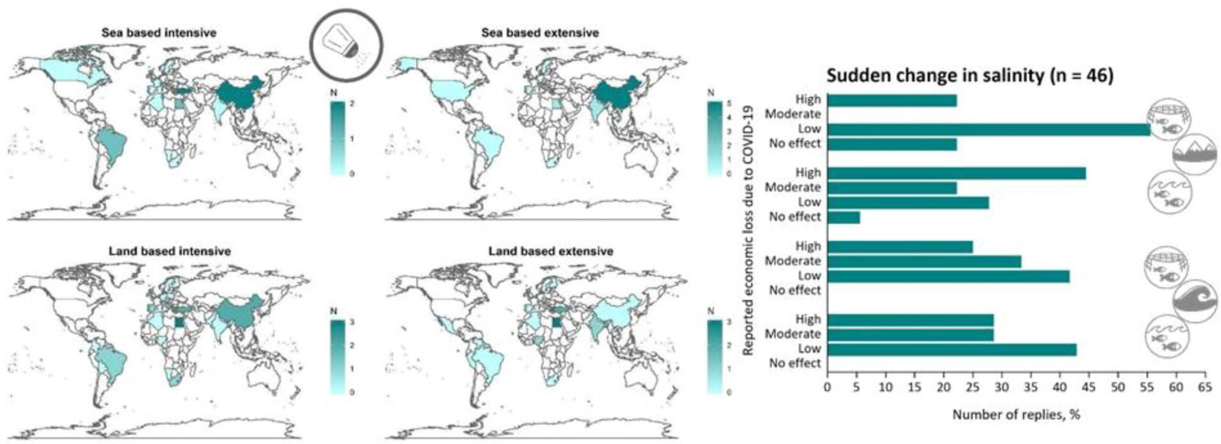

Figure 4. Continued.

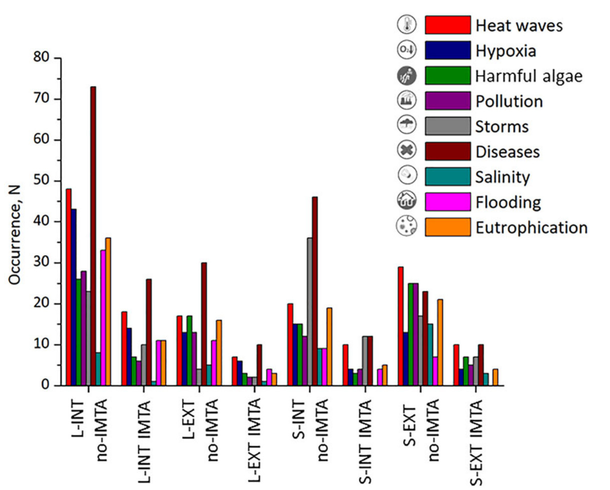

Figure 5. Anthropogenic stressors (number of occurrence, *N*) reported as by respondents, respectively per each of the four explored aquaculture systems (land-based intensive L-INT, land-based extensive L-EXT, sea-based intensive S-INT, sea-based extensive S-EXT) in presence (IMTA) and absence of integrate multitrophic aquaculture (no-IMTA).

Some of the respondents reported: "It [COVID-19] has no significant effect compared to local pollution (as ammonia increase)" (Egypt); "It is a serious necessity to determine the industrial and environmental pollution on bacteria and microorganisms in the water" (Turkey); "The recurring drought of the past 3 years has had a more serious effect" (Italy); "The rainy season drops sharply and the dry season is too high!" (China).

In addition, overall, when IMTA was used, data suggested that there was a tendency to dampen the detrimental effects of COVID-19 (Figures 5 and 6), with IMTA reducing the impacts of organic and inorganic waste in aquatic environments.

Results show that where anthropogenic-driven changes are negatively impacting aquaculture food production sectors, a further crisis such as COVID-19 pandemic amplifies economic losses and food in security. These results align with current ecological theory explaining how multiple stressors can affect a socioecological system's responses (Crain et al. 2008). In general, the crisis due to the COVID-19 pandemic adds a further stressor to already locally suffering, vulnerable, aquaculture systems (Froehlich et al. 2018). A recent FAO (2020b) report showed a greater percentage of COVID-19 economic loss associated with the first and final links of the supply chain (raw material provision, product transport and sale). COVID-19 affects the aquaculture supply chain by limiting, for instance, the ability to supply food to consumers due to closed markets and restaurants (HORECA – hotels, restaurants, cafes/catering sector), disrupting the logistics associated with transportation (both raw materials and final products) and increasing border restrictions (FAO 2020b). In contrast, anthropogenic stressors such as climate change and pollution, more likely drive economic loss on the intermediate links, i.e. the health status, growth and survival rate of cultivated organisms (and thus on the production) (Weatherdon et al. 2016; Peck et al. 2020) (Figure 6). Thus, the COVID-19 pandemic is adding further vulnerability to already stressed socioecological systems (Bennett et al. 2020; FAO 2020b) by acting on different stages of the supply chain. In this context, any possible management practices to enhance the resilience of aquaculture food systems must occur across the production, transformation and stages of the supply chain, if they are to help aquaculture to cope with future pandemic crises. A holistic, multiple stressors-based view that can decrease the vulnerability of the aquaculture sector by also safeguarding the intermediate links of the supply chain (e.g. production,

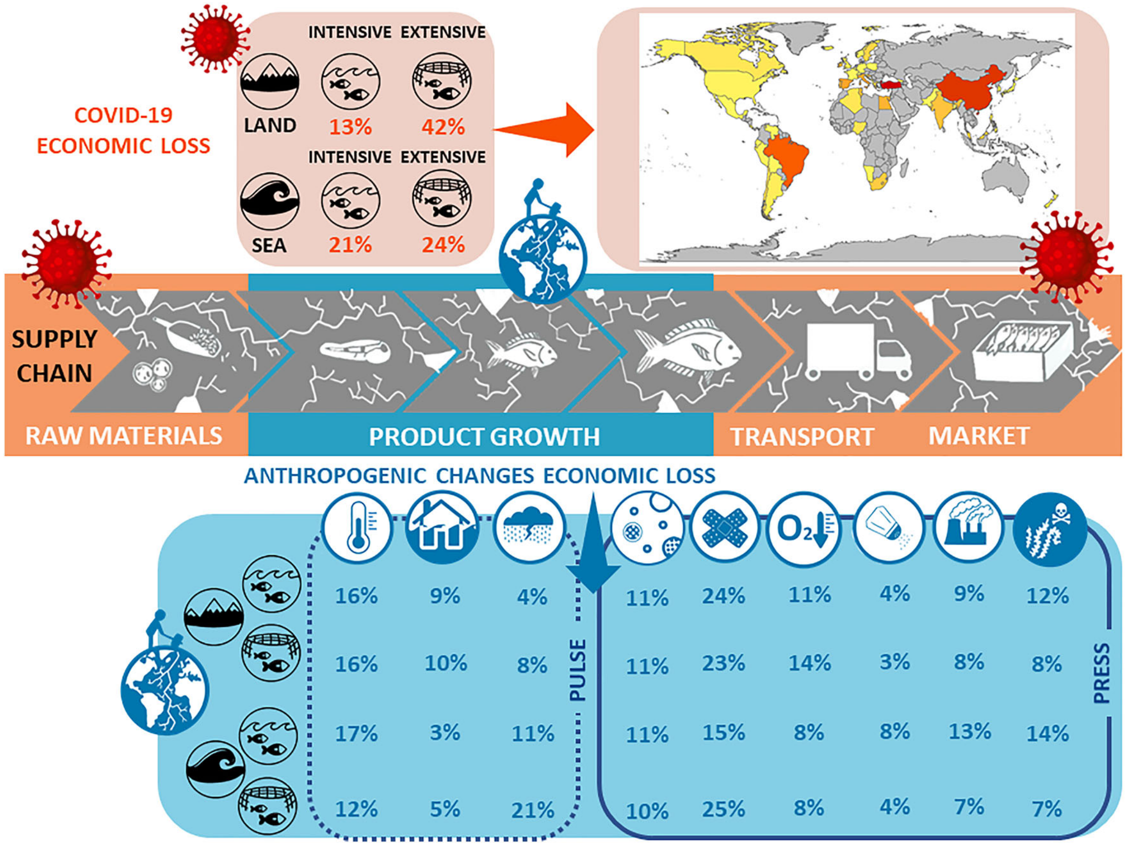

Figure 6. Graphical representation of the double trouble of aquaculture systems COVID-19 and anthropogenic stressors interactions through the supply chain.

maintenance, growth), and not just those directly affected by the pandemic is needed (e.g. market). The potential role of IMTA in buffering the effects of anthropogenic stressors on aquaculture loss is already described in literature from the last two decades (Shpigel and Neori 1996) and its value under pandemic emerged among some of the respondent comments, i.e. "It is recommended to increase the use of advanced equipment and integrated approaches (IMTA) to reduce dependence on people" (China) and "Focus on prevention, increase varieties of species (IMTA), increase species with high added value, and improve survival rate" (China).

Generally, farmers cultivating more than one species using IMTA protocols, also reported fewer economic impacts due to COVID-19. By contrast, sectors with monoculture practices (i.e. large, biomass-dense systems with a monodirectional energy input) (Bardach 1997) and few marketed products were more vulnerable. Increasing the number of species under IMTA conditions results in a more diverse ecological system that is more resilient as it is more able to cope with anthropogenic stressors and different market demands (e.g. diversification of product lines to fill alternative markets) (Worm et al. 2006; Loreau and De Mazancourt 2013, 25), something to consider when planning future recovery policy in context of both post COVID-19 and anthropogenic resilience.

4. A need for multiple stressors-based recovery plans

Unlike pressing anthropogenic stressors (which can have a slower onset and are global) and pulse disasters (which have a rapid onset but are localised), the very rapid onset and global nature of COVID-19 pandemic has caught the aquaculture sector (and everyone) off-guard, and affected production and supply in ways that had not been predicted or anticipated. The industry sector, and especially aquaculture, should be better equipped to deal with a world subjected to growing global crises. Synergies of COVID-19 and anthropogenic stressor effects can be critical in terms of both detection and policy responses. The main lesson learnt from the COVID-19 pandemic is the importance of taking rigorous, strict and fast disaster-risk management approaches to adapt to a novel sudden shock condition and to safeguard life. In the near future, as economic aid becomes available to rebuild economies, it will be time to act. The crisis offers an invaluable opportunity for decision makers and stakeholders to improve communication skills, logistics and connectivity among them to generate more secure farms, to promote food services and a framework for a long-term sustainable aquaculture industry for local people and regional economies. COVID-19 provides a unique opportunity to unite stakeholders, managers and policy makers around what is perceived as a common threat (global pandemic). The policies issued in the next months, could have the added benefit of enhancing resilience to other stressors such as climate change that, otherwise, may exacerbate the crisis and make recovery more difficult and expensive.

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