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REVIEW PAPER

Integrating multiple stressors in aquaculture to build the blue growth in a changing sea

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Abstract Fisheries currently represent the main source of animal protein intake worldwide, although catches of most commercial species are at or beyond maximum sustainable yields. Increasing production would require an excess of exploitation levels and aquaculture is expected to become crucial in sustaining a growing seafood demand. Nonetheless, many threats are expected to affect aquaculture and the increased production must evolve in a way that minimizes environmental and socio-economic impacts. The claimed sustainable development of human activities at sea (blue growth and economy) seeks for new joint analyses and solutions at (trans-)national systemic level should be planned and applied. To meet a sustainable development, both production and management approaches should evolve. Here we propose a conceptual framework to integrate a "downscaling approach" based on functional features of cultivated organisms to accommodate multiple stressors in setting sustainable development standards to design adaptive solutions fitting with the management of marine space.

Keywords Aquaculture · Multiple stressor · Climate change · Downscaling · Sustainable development · Marine spatial planning

Introduction

The harvesting and cultivation of fish and shellfish has greatly contributed to the development of coastal Mediterranean societies. In turn, these activities have influenced and shaped local cultures, boosting socio-economic innovations that are still rooted in traditions and activities linked to fish and shellfish industries (Sarà, 1998). According to the World Bank, global food demand from aquatic systems will reach $\sim$ 150.000 million tons in 2030, with an increase of 27% compared to 2010 (FAO, 2014) and fisheries in combination with aquaculture are called to sustainably meet the needs of a growing global population. Although fisheries currently represent the main source of animal protein (17% of the world protein comes from fish; FAO, 2014) for over 1Bn people worldwide,

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catches of most commercial species are at or beyond maximum sustainable yields at least in the Mediterranean basin (Colloca et al., 2013) with documented direct effects on both seabed communities and fish biological traits (Mangano et al., 2017). Thus, increasing production may require a paradigm shift in fisheries (and consumer attitudes) towards less selective balanced harvesting with a concomitant decrease in exploitation at higher trophic levels (Jacobsen et al., 2014; Burgess et al., 2015). Under this scenario, aquaculture is expected to become crucial in sustaining a growing seafood demand (FAO, 2016) and, more challenging, to increase a more integrated production by minimizing environmental and socio-economic impacts with a more sustainable use of the marine resources. In this regard, “old” challenges, such as the detrimental effect of organic enrichment of the surroundings (Modica et al., 2006; Grigorakis & Rigos, 2011; Sarà et al., 2011), the diffusion of pathogens and augmented virulence promotion as well as harmful algae blooms (HABs), must be coupled with “new” ones, such as the effect of cultivable species on local biodiversity and the reduced consumer acceptability of aquaculture products with respect to wild conspecifics (Grigorakis & Rigos, 2011; Johnson & Volpe, 2016). To date, only local-scale solutions resulting from the effort of single scientists or regional administrators have been applied (McDaniels et al., 2006; Soto, 2008). In a new context of worldwide sustainable development of human activities in the sea, the so-called blue growth and economy, new joint analyses and solutions to multiple stressors’ interactions at (trans-)national systemic level (sensu Allan et al., 2013) should be planned and applied (see Sustainable Development Goals, SDGs; http://www.un.org/sustainabledevelopment/sustainable-development-goals/).

Thus, to cope with the potential increased seafood demand and simultaneously taking into account the need to meet SDGs, both production and management approaches should evolve addressing solutions to monitor, model and minimize the impacts of many factors—social, economic and environmental (sensu Lu et al., 2015). New solutions based on the knowledge of “cause–effect mechanisms” seem the most reliable path to deal with new challenges such as multiple stressors. Here it is our intention by borrowing some concepts from ecological theory and climate change modelling (Fowler et al., 2007; Flint & Flint, 2012) to provide an attempt to set the pace in addressing SDG standards and the related monitoring and evaluation procedures. Thus, we (i) briefly discuss the role of multiple stressors in threatening SDGs and consider why the single-stressor-per-time perspective cannot work to tailor management strategies at a broader scale, (ii) propose a predictive management approach based on a downscaling approach and lastly (iii) explore possible tools and recipes to plan future aquaculture management strategies.

Multiple stressors: the “new” recognized but still underestimated threat

The worst threat for a sustainable aquaculture development derives from interaction among stressors (i.e. multiple), including rising temperatures, changes to ocean circulation and mixing, eutrophication, ocean acidification, ocean deoxygenation (i.e. the global trend of decreasing oxygen as a result of ocean warming and increasing stratification), coastal hypoxia (i.e. low-dissolved oxygen environments due to increased organic enrichment and nutrient levels) and pollution. Multiple stressors, co-occurring in time and space, increasingly expose marine aquaculture organisms and ecosystems to simultaneous impacts (sensu Matzelle et al., 2015). The recognition of the differential manifestation of any individual stressor is fundamental when considering the scale at which they can be managed or mitigated (Murray et al., 2014). Indeed, global stressors (e.g. acidification) tend to change slowly over long periods of time, although their intensity and effects can be contingent on local conditions. Local stressors, instead, are often manifest as rapid changes over shorter, more defined spatial and temporal scales, for example the excess of nutrients and the organic enrichment generated in aquaculture. Interactions among stressors transversally generate unexpected effects from local to global scale (Helmuth et al., 2014). This makes the search for sustainable aquaculture development goals more challenging, complex and variegated. While the synergistic effects that different stressors can have on marine organisms and ecosystem provision of goods and services are currently poorly understood, to consider the effect of a single-stressor-per-time on biological and ecological responses is misleading and generates unrealistic conclusions (Crain et al., 2008; Gunderson et al., 2016). Nonetheless, the vast majority of management strategies currently proceed on a single issue-specific basis, with little consideration for the relationships and feedbacks between multiple stressors (Hall et al., 2013). This represents a significant limitation in the current approach as it reduces the ability to cope with real challenges linked to the use of marine resources and is now recognized as the main limitation of the ecosystem management approach (Hughes et al., 2005). It is evident from the literature that little effort has been made to connect multiple stressors to get a complete view of the involved phenomena (Arends et al., 1999; Afonso et al., 2008; Eissa & Wang, 2015; Morash & Alter, 2015; Tromp et al., 2016). Even if the growing interest and application of ecosystem-based approaches to marine resource management has made cumulative impacts from multiple stressors, a focal topic in marine conservation and management (Halpern et al., 2007; Leslie & McLeod, 2007; Crain et al., 2008), the literature on multiple stressors in an aquaculture context is still deficient.

Although it is recognized that multiple stressors can interact to generate complex detrimental effects on individual functional performances, up to population level, there has still been a pressing question of scientific research in ecology and conservation for almost the last two decades (Breitburg et al., 1999; Sala et al., 2000; Zeidberg & Robison, 2007). Such effects can be much more severe than those promoted by any single stressor, as reviewed for both marine and freshwater ecosystems (Crain et al., 2008; Ghedini et al., 2013; Ban et al., 2014; Gunderson et al., 2016). In terms of their impacts on organisms, multiple stressors can be viewed as having additive, antagonistic or synergistic effects (Fig. 1; Crain et al., 2008; Ghedini et al., 2013; Gunderson et al., 2016). The explanation of why a single-stressor approach may generate unrealistic conclusions is simple and essentially connected to biological first principles driving the ecological functioning. Considering mechanisms, the Sokolova et al.'s (2012; Fig. 2a, b) model provides a clear mechanistic physiological ground to increase our understanding of when, where and how multiple stressors alter functional performances of marine organisms. What is important is the total physiological impact of stressful conditions (i.e. the total amount of exposure time to stressors—sensu Miller et al., 2011—along the cultivation cycle) in terms of the energetic expenditure required to return to homeostasis (Gunderson et al., 2016; Harley et al., 2017). For each species, there are specific thresholds at which a particular environmental variable becomes stressful (Sokolova et al., 2012). If the stress threshold is passed, the energy required to overcome the stress event increases with increasing stress intensity (Sokolova et al., 2012). Nonetheless, organisms are constantly having to readjust to their homeostatic baseline and among the most challenging question is how do we differentiate between normal tolerance, the point beyond which an environmental parameter can be considered stressful, and the point where there is a gross and distinct physical response to a source of stress. However, this is only one side of the coin. The timing of environmental stressor events and fluctuations (sensu Miller et al., 2011) in their magnitude are also important for our understanding of how organisms respond to changing conditions. What is important to investigate is the temporal juxtaposition of exposure to two or more environmental variables (stressors), i.e. if the temporal relationships among different variables are in or out of phase (ad litteram Gunderson et al., 2016). Timing is important in addressing the type and strength of multiple stressor interactive effects and it drives the approach to stress thresholds, from which the bio-ecological responses ultimately depend on. Gunderson et al. (2016) presented a model to predict the time-dependent multistressor effects in situations when additive, antagonistic and synergistic physiological responses are most likely to occur. They pointed out that the impact of multiple stressors depends critically on the intensity and timing of each stressor.

In Fig. 3, we built a hypothetic schematic cascade of events—essentially centred on the functional performance response of a generic farmed species—to clarify the multiple stressors' interaction based on literature evidence (sensu Mangano & Sarà, 2017a). For instance, the action of a global driver (*e.g.* increasing temperature due to climate change increasing the likelihood of heat waves, etc.) may synergistically generate at least two different effects (sensu Nagelkerken et al., 2016): (1) indirect—on habitat quality through the alteration of local chemical and physical conditions (e.g. coastal hypoxia, Diaz & Rosenberg, 2008; sensu Connell et al., 2017) that may derive, for instance, from the impairment of the bio-ecological functioning of local fouling community (e.g. through a reduced filtration rate by suspension

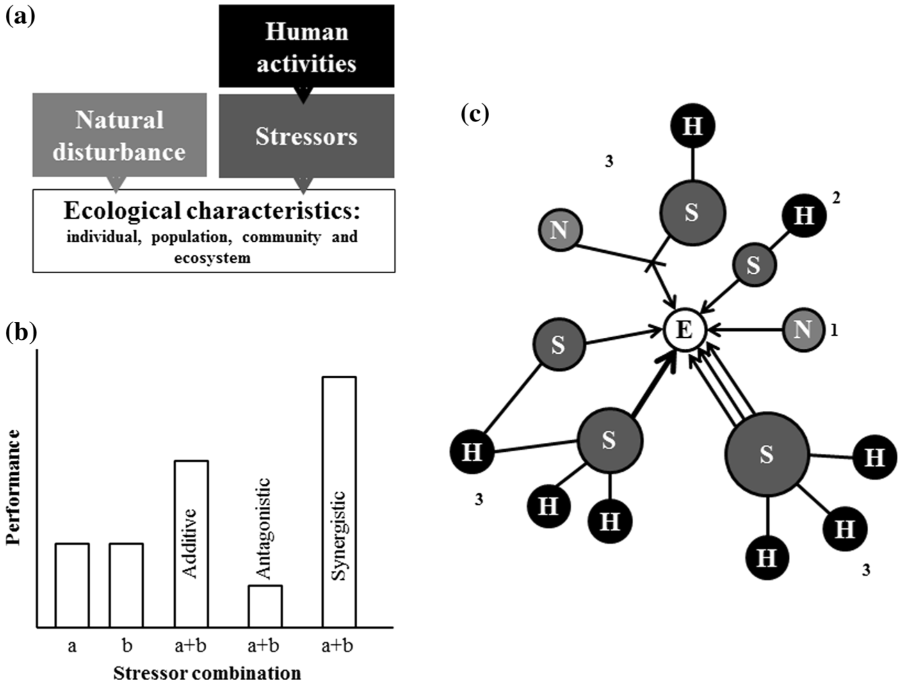
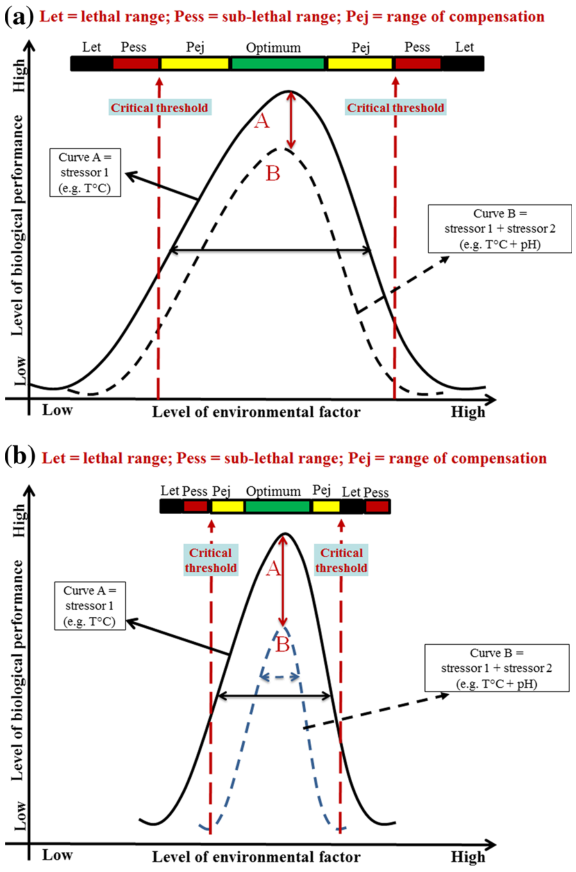


Fig. 1 **a** Schematic of multiple stressor chain. Generic human activities generate stressors (each human activity can generate one or more stressors) exerted on the ecological characteristics (sensu Knights et al., 2013); additionally natural disturbance can impact. **b** Conceptual diagram of possible interactive effects of multiple stressors (*a* and *b* represent two stressors). Multiple stressors can interact producing three main effects: additive, independent interaction; antagonistic, interactive interaction with performance decrease; synergistic, interactive interaction with performance increase (from Gunderson et al., 2016, modified). **c** Conceptual network of multiple cumulative effect pathways affecting the ecological characteristic (white circle, E). Different human activities (black circles, H) generate one or more stressors (grey circles, S); natural disturbance (light grey circles, N) can also interact. *1* Natural disturbance effects only; *2* Independent effect, a single human activity produces a single stressor; *3* Additive effect of multiple stressors with different interaction pathways

feeders that usually are the most abundant component of macrofouling communities; Lacoste & Gaertner-Mazouni, 2015; Floerl et al., 2016); (2) direct—through the impairment of functional traits (Sarà et al., 2014) of cultivated organisms such as reaching stress thermal thresholds or altering behaviour in cages (e.g. feeding rate, swimming rate, cage-space use, etc.). A second stressor (e.g. lowering salinity due to successive sudden runoff events) may worsen fish conditions in cages.

Another well-known example comes from shellfishes and can be based on the contextual (synergistic) action of local and global stressors generating less predictable scenarios. Local effects such as organic enrichment and excess nutrients interact with global factors such as increasing water column stratification due to global warming. This may result in enhancing eutrophication which would be detrimental for aquaculture (sensu Nixon, 2009). Eutrophication can produce toxic algal blooms (HABs; Hallegraeff, 1993; Anderson et al., 2002) and local oxygen depletion zones (Cloern, 2001) with subsequent shellfish harvest closures (Dyson & Huppert, 2010; Ajani et al., 2013).

In both examples, a synergistic effect among local and global stressors is likely to occur, and therefore pinpointing the sources of nutrient stressors may be tricky as nutrients may be discharged from a number of non-point and point sources, including sewage outfalls, agriculture and coastal development. However, in most aquaculture activities where an artificially simplified ecological system is built which implicitly prevents the possibility that biodiversity (viz. higher complexity) can act as a buffer against disturbance (Isbell et al., 2015), the described cascade of events will always end with a tangible and ultimate influence on cultivated animals, under both intensive (e.g. fish) and extensive conditions (e.g. bivalves). The



◀**Fig. 2** **a** The conceptual framework based on the energy-limited tolerance to stress to assess the effects of multiple environmental stressors (Sokolova et al., 2012; modified). Solid lines refer to a single environmental factor/stressor situation (stressor 1, e.g. increasing temperature), and dotted lines refer to a combined exposure to multiple stressors (stressor 1, e.g. increasing temperature + stressor 2, e.g. hypoxia, hypercapnia or pollution) that can negatively affect the scope for growth of a given cultivated species and thus narrow the tolerance window for another environmental factor/stressor (e.g. temperature). The level of the biological performance of an organism is proportional to the available aerobic scope and diminishes (red arrow) as an organism transits from the optimum to pejus, pessimum and then lethal range. The shape and the symmetry of the curves (black arrow defining the width of curve) can change depending on the nature of the stressor and depend on species. Thus, for some stressors (such as temperature or salinity) the relationship between the level of the stressor and the organism's performance follows a bell-shaped curve, which may also be skewed (Angilletta, 2012). As a result, there are lower and upper pejus (Pej), pessimum (Pess) and lethal (Let) ranges for these factors. For other stressors (such as pollutants, toxins or acidification), the optimum lies near the zero level of the stressor such as that shown by curve B. This framework can be theoretically applicable to any stressor that negatively affects the scope for growth of an organism and has been experimentally tested for a number of combinations of stressors. Nevertheless, this type of response is highly species specific **b** and then any species cultivated has its own tolerance limits and can cope with environmental variability generated by the effect of multiple stressors according to its species specificity. The total amount of exposure time to stressors is crucial to understanding how stressors affect functional and biological performances

ultimate effect will be evident on both growth rate and animal welfare; according to the most relevant and commonest strategies, when external constraints prevent individuals from acquiring energy from food, they start to divert energy from both reproduction and growth to ensure maintenance of somatic tissues (see Kooijman, 2010 for some variants of this strategy). Thus, depending on the habitat quality, the resulting lack of energy intake will lead to a reduced amount of allocated energy to growth (sensu Kooijman, 2010; Sheridan & Bickford, 2011) which is the primary trait that should be maximized in aquaculture systems (sensu Fig. 4).

From here, it is easy to derive a complete picture to explain (i) how multiple stressor effects and timing on cultivated organismal responses may affect sustainable development of aquaculture and (ii) to suggest how to manage the effects of multiple stressors in terms of mitigation and possible adaptation. The resulting potential biotic repercussions of synergistic effects between long-slow global stressors and short-rapid local stressors on aquaculture growth rates and habitat quality can be translated into a wide spectrum of socio-economic impacts ranging from financial losses to adaptive shifts in local cultures and loss of community traditions (sensu Selim et al., 2016; Bundy et al., 2016).

"Downscaling to bottom-up": a fundamental ecological step for a predictive management approach

To develop a proactive approach, we need robust, reliable and realistic predictions of when, where and how stressor synergies will affect functional performances of farmed species. However, science still has limited ability to provide realistic inferences of future dynamics in complex systems such as those expected when multiple anthropogenic pressures, outside of historic norms, act synergistically. We propose the

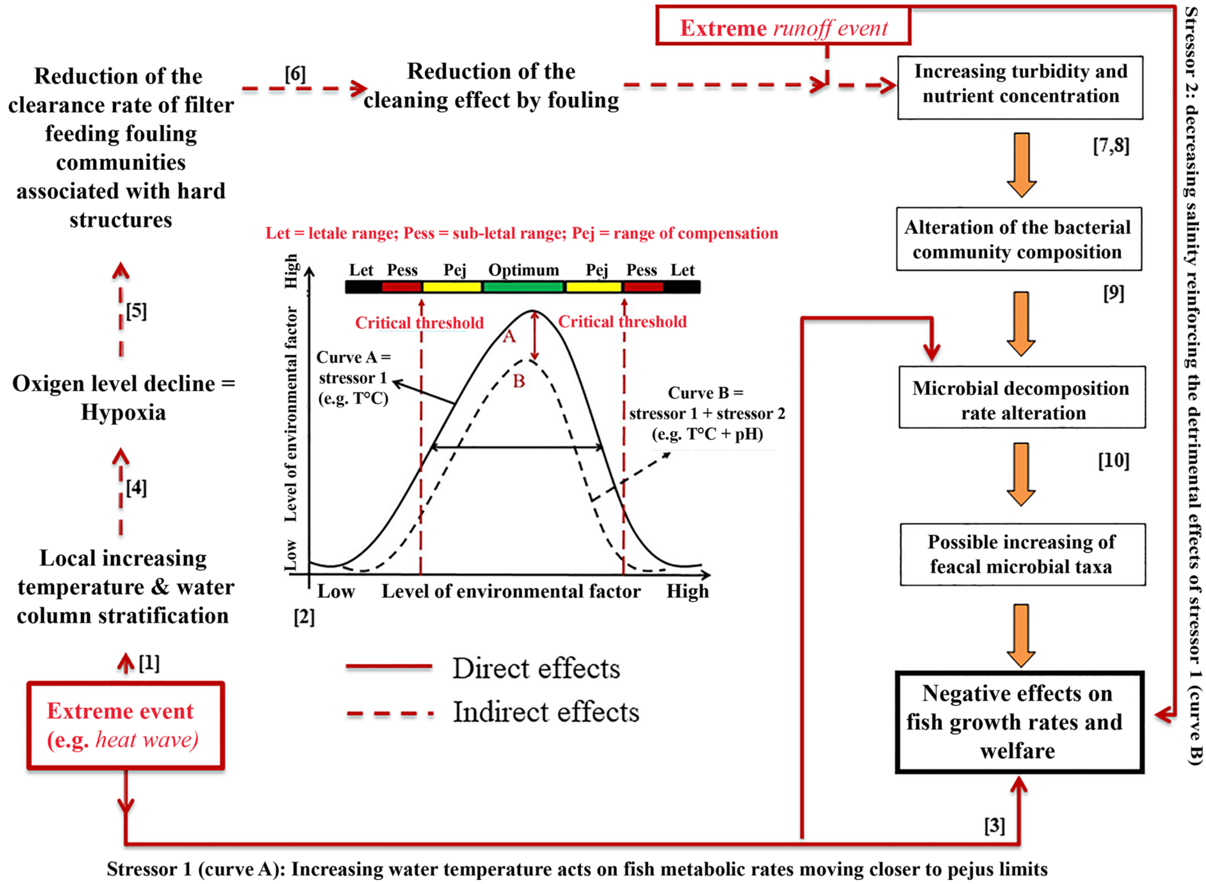


Fig. 3 Schematic cascade of effects (multiple stressors) that can generate from an unexpected succession of extreme climatic events (first a longer extreme heat event and later an extreme runoff event). Biotic responses are essentially centred on the Sokolova et al.'s (2012) functional response model. An indirect effect on habitat quality is triggered by the heat wave generating the alteration of local chemical and physical conditions (e.g. coastal hypoxia) that derive from bio-ecological functioning impairment of local fouling community (e.g. through a reduced filtration rate of the encrusting suspension foulers). A direct effect of impairment on functional traits of cultivated organisms with related attainment of the thermal stress thresholds. Both the effects culminate in alteration in fish metabolic function and behaviour in cages. A second successive occurrence of extreme runoff reinforces the effect of heat wave indirectly through a further local increasing turbidity and nutrient concentration and directly affecting the fish metabolism by lowering local salinity. Although most of cultivated organisms are halo-tolerant, this successive event occurs when fish may be already stressed by the exposure to first stressor. (Numbers in boxes indicate main references used to depict this process: [1] Nagelkerken et al., 2016; [2] Sokolova et al., 2012; [3] Sarà et al., 2014; [4] Diaz & Rosenberg, 2008; [5] Floerl et al., 2016; [6] Sarà et al., 2007; [7] Lacoste & Gaertner-Mazouni, 2015; [8,9] Sarà, 2007a, b; [10] Kalantzi & Karakassis, 2006)

development of a reliable predictive model based on biological fundamental characteristics, i.e. the Functional Traits (FT; sensu Schoener, 1986; Sarà et al., 2014) of any cultivated species as possible solution. As required, at scales relevant to national management, the development of FT-based approaches (sensu Kearney & Porter, 2009) can allow the generation of "mechanistic species-" and "site-specific predictions" of costs and benefits in order to increase the chance of success to get the appropriate sizes of aquaculture facilities.

Aquaculture is the ideal sector in which to develop "functional trait-based predictive models" relying on current bioenergetic theories (e.g. Dynamic Energy Budget [DEB]; Kooijman, 2010; Sarà et al., 2012, 2014). In aquaculture as also in most intensive terrestrial cultures, the effects of biotic interactions (e.g. competition for space and resource and prey–predator relationships) are controlled through

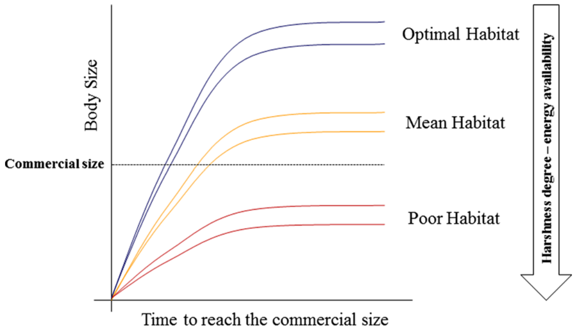


Fig. 4 Theoretical impacts of stressful environmental conditions on growth rate, size at maturity and commercial body size (two lines reported for each habitat indicate slow- and fast-growing fishes; sensu Stearns, 1992)

cultivation practices. Predictive FT models based on current bioenergetics allow the inclusion of environmental variability and multiple stressor effects into growth predictions and the amount of total releases in terms of carbon and nitrogen by cultivable species, under both intensive and extensive Integrated Multi-Trophic Aquaculture (IMTA; Sarà et al., 2012). Thus, a detailed mechanistic knowledge (Sarà et al., 2014) of (i) how changing environmental conditions due to synergistic effects (sub-local, local and regional *per* global) affect the magnitude of functional traits in each species and (ii) how functional traits in turn affect the flow of energy (from food) through the organisms driving growth allocation rates is crucial to build realistic predictions in a multiple stressor context by simulating different scenarios (e.g. Kearney et al., 2012; Sarà et al., 2013; Matzelle et al., 2015; Carrington et al., 2015). A spatially contextualized mechanistic model (e.g. DEB) can easily allow to quantify growth rate and the amount of egested products as a function of food amount and local ambient temperature. A coupled deposition model (Cromey & Black, 2002; Gentry et al., 2017) implemented with local hydrodynamics can generate scenarios of local impact. The combination of these two types of information essentially based on spatially contextualized cause–effect relationships (i.e. mechanistic and functional-based) is the key to increase the ability of decision makers of when, where and how the relationship between time to reach the optimal commercial body size (benefit) and the consequent environmental effects on the surroundings (costs) can be optimized and to consequently produce management strategies tailored to target species. Additionally, the Sokolova et al.'s (2012) framework (Fig. 1a, b) will allow us to accommodate multiple stressor effects that will generate a tendency to optimize loss. A similar approach will help both stakeholders and policy makers to recognize the occurrence of synergistic effects and the disproportionately large benefit of acting simultaneously across a number of stressors, rather than on single stressors individually.

From threat mapping to action: tools and recipes to plan future aquaculture management strategies

Intensive aquaculture is essentially based on monoculture (i.e. large biomass-dense system with a mono-directional energy input; Bardach, 1997). Monoculture relies on a bio-ecologically low diversified system as it is essentially focused on a single species. From an ecological point of view, low diversity and low complexity lead to scant capacity to be resilient against multiple stressors (Adams & Ham, 1996; Worm et al., 2006; Loreau & de Mazancourt, 2013) and this brings as a main consequence an increase in vulnerability of aquaculture systems (Brugère & De Young, 2015). The monoculture is implicitly at odds with new and modern management strategies, the objective of which is "to enhance resilience of natural and human-managed systems to multiple environmental stress and to enhance ecosystem services provided by intact communities…" (ad litteram Bernhardt et al., 2013).

Although the role of Integrated Multi-Trophic Aquaculture (IMTA) is still being refined, it seems to offer a promising sustainable aquaculture tool for the future, and a potential provider of ecological, economic and social benefits (Chopin, 2015). Based on integrated food production systems where the components are integrated in ecosystem health, the IMTA systems build on species integration from various trophic levels (e.g. benthic invertebrate as sea-urchins, sea-cucumbers, polychaetes, seaweeds, etc.), each providing different ecosystem functions and services (Clements & Chopin, 2016). As with other articulate and biodiverse systems where increased biodiversity can enhance the resilience of marine ecosystems and communities to stressors (Peterson et al., 1998; Worm et al., 2006; Levin & Lubchenco, 2008; Isbell et al., 2015), IMTA could contribute to the mitigation of climate change effects (e.g. ocean acidification, Clements & Chopin 2016) as a result of a buffering effect exerted from its components (sensu Loreau, 2010; MacDougall et al., 2013; Isbell et al., 2015). Overall an increased diversity can translate to a maximization of resource use from trophic webs, can balance the risk associated to climate change effects and related stochastic variation of environmental variables on ecosystem functioning and can reduce the shifts in occurrence of ecosystem processes as invasiveness and spread of pathogens (Naylor et al., 2001; Murray et al., 2014). Therefore, investigations into the role of IMTA in promoting ecological resilience are needed to investigate the effects on crossed multiple stressors disentangling the bio-buffering components to allow the implementation of proper future mitigation strategies (Bernhardt & Leslie, 2013). Nonetheless, as recently pointed out, the "commercial operationalization of this practice in the offshore environment is relatively new and faces challenges with efficiency and economic scaling …" (ad litteram Gently et al., 2017). The potential effectiveness of IMTA may depend on some environmental constraints (e.g. background nutrient levels, food availability and hydrodynamics sensu Troell et al., 2009), technological development (to cope with the global change, e.g. more robust, automatized cages equipped with pressure and temperature sensors, suitable to both resist in case of more intense wave energy and submerge in case of increase of sea surface temperature "heat wave" events), and the species integration and diversification needs (possible negative effects of co-cultivation, e.g. disease transfer, contaminant's bioaccumulation).

Diversified aquaculture systems are imperative also from an economic perspective to increase profitability and competitiveness producing an economic diversification that maintains high levels of environmental sustainability and promotes societal acceptability (http://www.un.org/sustainabledevelopment/sustainable-development-goals/).

Clearly, if a synergistic effect involves global components that need international priority (e.g. climate change effects), the focusing on reducing local stressors may allow us to address a set of small-scale and short-term actions that can maintain the resilience of marine systems and may prove effective at reducing synergies with global stressors (Wooldridge, 2009; Ghedini et al., 2013).

Further research should be directed in the way, for example, to promote the improvement in food quality (e.g. reduction of fishmeal; dietary supplements probiotics and prebiotics) in order to ameliorate species growth rates and to reduce the effect on habitat quality deterioration (Vergara et al., 1999; Fontanillas et al., 2013); to set hormones that confer tolerance against different stressors (Gesto et al., 2016) and natural products to enhance the immune response of fish, minimizing the risk associated with the use of chemical products such as anaesthetics (Barata et al., 2016), vaccines, antibiotics and chemotherapeutics (Dawood & Koshio, 2016); to enhance the biotechnologies in control diseases (sensu Eissa & Wang, 2015); to design new technologies to increase the IMTA efficiency and the monitoring of multiple stressor effects (e.g. biosensors); to promote participatory processes to produce and fund large databases of farmed species biological (functional) traits (e.g. Riviere et al., 2015); and to explore the power of systematic reviews (Mangano et al., 2015, 2017a, b), evidence-based atlas for sustainable development (sensu McKinnon et al., 2015) and threat and action maps (sensu Tulloch et al., 2015) as the most useful tools to assess the effects of multiple stressors and effectiveness of management measures. All these measures, progressively updated and improved, could help transform the work of addressing global challenges into a rigorous management strategy including local stressors (Klinger & Naylor, 2012). Even if during the last decade the evolution of Marine Spatial Planning has become a crucial tool to develop ecosystem-based use and management strategies for the marine environment, to date, only a few frameworks have provided guidelines to facilitate integrated, strategic and comprehensive planning in relation to all activities taking place in marine areas. Marine spatial planning has arisen in response to specific social, economic and environmental problems that recognize the full array of ecosystem interactions and human uses, rather than considering single issues in opposition to a previous management view dominated by individual economic sectors (e.g. ship channels, disposal areas, military security zones, concession for mineral extraction, aquaculture sites, marine protected area; Young et al., 2007; Douvere, 2008; Katsanevakis, 2011). The capacity to accurately predict the optimal cultivable species and the best practices to adopt and the most suitable marine spaces ("suitability maps", Allowable Zone for Aquaculture—AZA), together with the breadth of aquaculture activities' impacts on the nearby environment ("threat maps" Allocated Zone of effect—AZE), have to date represented the best tools for planning aquaculture activities (Sanchez-Jerez et al., 2016). Therefore, in the future these useful tools should be incorporated within a transparent and repeatable Structured Decision-Making Process (SDMP sensu Tulloch et al., 2015) in order to allow both better planning and better conservation decisions. In planning future aquaculture management strategies, future generations of stakeholders, policy makers and scientists should recognize the need to produce additive scoring approaches for multiple threats, incorporating not only ecosystem vulnerability (sensu Halpern et al., 2008), but also the socio-economic values in order to provide cost-effective conservation decision. The cross-border nature of the sea and related resources will require careful consideration of political, cultural and economic contexts and also recognition of human welfare as an important component and the need to minimize income loss to local coastal communities depending on the exploitation of marine resources.

New transparent and iterative approaches, basically grounded in decision theory (Gregory et al., 2012), may be developed to cope with constraints on human activities by producing alternative management actions (e.g. Gimpel et al., 2015) that would (i) examine outcomes, measurable attributes and values, (ii) assess trade-offs between different actions and (iii) help avoid the mismatch of objectives to finally promote the production of cost-effective decision making.

By "listing actions" more than threats as proposed by the SDMP as suggested by Tulloch et al. (2015), we will focus resources toward actions that encourage positive biodiversity or socio-economic outcomes. Determining relationships, for example between human perception of aquaculture activities (Kaiser & Stead, 2002; Mazur & Curtis, 2008), space availability, outcomes and money invested, production and impact, will be vital for selecting cost-effective actions (Carwardine et al., 2012). The solution would be the adjustment of the national and regional legislative frameworks to encourage the development of IMTA practices (Alexander et al., 2015) which may allow more sustainable exploitation levels in terms of balance between conservation needs and socio-economic interest, towards a ground-breaking *Blue Growth* development.

In conclusion, several steps should be followed to produce analyses and solutions to reach Sustainable Development Goals in aquaculture:

(i) to promote the combination of several different explanations of patterns and processes following a multi-disciplinal and proactive ecosystem-based approach of marine resources;
(ii) to produce short-term predictive models based on a multispecies integration analysis of biological data, food webs, environmental and human pressures' layers;
(iii) to develop models of vulnerability detection based on multiple stressor interactions (including climate change) and indicators to apply as early warning systems;
(iv) to develop tools to check both the monitoring and the effectiveness of management measures (mitigation, adaptation and protection);
(v) to develop monitoring strategies and plans to mitigate the impact of invasive species;
(vi) to revise the status of suitable areas for aquaculture and produce conflict-free maps of maritime use and activities;
(vii) to facilitate the bureaucracy needed to set up IMTA and monitoring strategies of traditional farm systems;
(viii) to guarantee outcomes dissemination and communication between both scientific and non-scientific sectors and involved people creating the awareness that the seafood production has to be integrated with a more sustainable use of marine resources;
(ix) to promote tools for assessing impacts and economic analysis (modelling framework and cost–benefit analysis, CBA) to address externalities that can influence profitability (e.g. disease, climate, cost of feed, packaging and transport, market prices) necessary to prepare and inform stakeholders on the required capital, operating costs involved, the labour input and the profit margins they

might expect to receive given an identified level of risk.

Aquaculture systems are essentially very simplified ecosystems that utilize well-researched species. Thus, they lend themselves to the cause–effect approach in appraising likely interactions of species and environment. The ability of mechanistic models to predict growth responses of organisms in a complex matrix of environmental conditions will represent a useful tool for policy makers considering both the viability of aquaculture operations and their potential cumulative effects on host habitats, supporting the need for a more sustainable use of marine resources in the next future. As climate changes induce a myriad of changes in environmental variables while we continue to face food security issues, we need tools such as mechanistic models that give some confidence in predicting outcomes in previously unknown situations. The opportunity to anticipate the multiple effects due to climate change will help identify flexible management priorities able to adapt to societal variations (Sale et al., 2014).

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Author contributions GS and MCM conceived the original idea and wrote the manuscript; all authors contributed to the development of concepts, paper content and data visualization; all authors reviewed and commented on the final manuscript and revisions.

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