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Editorial: Immunity and disease of aquatic organisms under the combined impact of anthropogenic stressors: mechanisms and disease outcomes

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Editorial on the Research Topic
Immunity and disease of aquatic organisms under the combined impact of anthropogenic stressors: mechanisms and disease outcomes

Anthropogenic activities have high impact on the world's ecosystems and are strong drivers of environmental change. Modifications of habitats to fit the needs of society are causing severe effects including global warming, environmental degradation, biodiversity loss and mass extinction (Ceballos et al., 2015; Ceballos et al., 2017; USGCRP, 2017). Temperature changes are evident (IPCC, 2014) and climate change is fueling extreme weather events worldwide. The impact of warming, acidification and deoxygenation are already having a dramatic effect on the flora and fauna of the oceans with significant changes in distribution of populations and decline in sensitive species (Bijma et al., 2013). These climate-related alterations of aquatic species' ecological conditions often occur in combination with the presence of other anthropogenic stressors, such as pollution (Groh et al., 2022), eutrophication (Chislock et al., 2013), or overfishing (Jackson et al., 2001). The cumulative impact of these multiple man-made stressors can have severe and often unexpected consequences on aquatic organisms (Crain et al., 2008; Shears and Ross, 2010; Segner et al., 2014).

There is strong evidence that the incidence and severity of diseases in both freshwater and marine environments are increasing, and this increase appears to be related at least in part to the cumulative impacts of multiple anthropogenic stressors (Johnson and Paull, 2011; Burge et al., 2014; Miller et al., 2014; Adlard et al., 2015; Rohr and Cohen, 2020; Byers, 2021; Hutson et al., 2023). The relationship between environmental stress and disease of aquatic organisms can involve diverse mechanisms and processes, but a major driver appears to be the impact of the stressors on immunity (Jacobson et al., 2003; Martin et al., 2010; Rollins-Smith, 2017; Palmer, 2018). Immunity is a convergence point for many environmental stressors, hence, changes in immune performance can be at the root of emerging disease. For instance, exposure to persistent organic pollutants has been shown to cause immunosuppression in aquatic species (AMAP, 1998; Letcher et al., 2010; Suzuki et al., 2020), and contaminant-induced immunosuppression has been suggested to be a contributing factor to disease-dependent mortality in several marine mammal and fish species infected with various pathogens (Jepson et al., 1999; Ross, 2002; Maule et al., 2005; Arkoosh et al., 2010; Rehberger et al., 2017; Desforges et al., 2018). Likewise, changes of ambient temperature are known to influence the immune system particularly of ectothermic aquatic organisms, what has been shown to lead to altered defense capacity against infectious pathogens [e.g., (Bailey et al., 2017; Traylor-Knowles and Connelly, 2017)]. Overall, there exists strong evidence that man-made stressors, alone or in combination, can compromise the resistance of aquatic organisms to pathogens, thereby contributing to the emergence of infectious diseases. For a better understanding of the relation between environmental change and disease, it is essential to provide knowledge if, and how, the immune system of aquatic organisms responds to multiple stressor exposure, and if and how this translates into an increased occurrence and severity of infectious diseases.

The present Research Topic aims to advance our understanding of the avenue from environmental change (driver) to altered immunity (mechanism) resulting in modified health or disease (outcome) of aquatic organisms. The contributions to the Research Topic shed spotlights on the continuum from environmental stress via immunity to disease. The contribution of Nardi et al. focuses on the interactive effects of environmental stressors – more specifically, temperature change and cadmium exposure -, on the immune system of an aquatic species, the Mediterranean mussel *Mytilus galloprovincialis*. Currently, there exists no systematic understanding how organisms respond to combinations of stressors of different quality and intensity, i.e. if the stressors act antagonistically, additively, or synergistically. Hence, it is important to broaden our knowledge base on this subject. Bivalves are well-suited study organisms for this type of research, as they are important indicator species for environmental and anthropogenic stressors. The findings of Nardi et al. suggest that the concomitant occurrence of thermal stress and toxic metal stress could elicit interactive and negative effects on the immune system of *Mytilus galloprovincialis*.

The work by Krasnov et al. investigates two important aspects of the role of environmental stressors in the causation of disease. Firstly, the authors examine the impact of hypoxia on the immune system of Atlantic salmon (*Salmo salar*) during development. During ontogeny, immune structures and functions experience major modifications, and these changes in the endogenous factors may modulate the immune response to exogenous factors. While this fact is rather basic, its importance for assessing environmental impact on immunity and disease of aquatic organisms is often missed. Secondly, Krasnov et al. evaluate whether the stressor-induced alterations of immune parameters translate into an altered immunocompetence of salmon against pathogens. The complexity of the immune system makes it challenging to select appropriate exposure and effect parameters, and to evaluate the significance of the selected parameters for the overall fitness and immune competence of the organism. Measured parameters may not influence the outcome of infection, and more importantly, adverse effects of stressors may only be detectable after immune system activation, and not in the resting immune system of a noninfected host. The findings of Krasnov et al. provide evidence that hypoxia at early life stages induced sustained effects on the immune system with increased expression of immune genes and attenuation of their downregulation during smoltification. However, these changes did not improve survival of fish after challenge with *Moritella viscosa*.

The contributions of Ling et al. as well as McCracken et al. attract attention to another often neglected aspect in the linkage between environmental stress, immunity and disease: the role of the microbiome. The microbiome is susceptible to environmental change, and it influences the immune and health status of the host organisms. This intimate relationship provides avenues through which environmental impacts on microbiome homeostasis directly or indirectly may cause disease. McCracken et al. provides an example, where microbial dysbiosis, i.e. changes in the microbiome community composition, preceded signs of sea star wasting disease in wild populations of *Pycnopodia helianthoides*. Microbiome composition was also shown to be vital in the health of brown seaweed *Saccharina japonica*, where Ling et al. found that the epimicrobiome shifted with progression of the seaweed bleaching disease.

The two concluding contributions of this Research Topic focus on the ecological implications of environmentally induced disease of aquatic species. Salazar-Forero et al. highlight how strongly pathogen and disease dynamics in wild populations depend on environmental conditions. The authors show that winter storms strongly affected pathogen dynamics with significant pathogen increments in the sea urchin species *Diadema africanum* and *Paracentrotus lividus*. Hence, the driver underlying the recurrent pathogen-induced sea urchin mass mortalities in the Canary Islands appears to be the changes of the environmental weather conditions. Tallam and White, finally, suggest to use disease parameters as universal indicators of estuary ecological status or health. The advantage of the disease parameter is that it provides an integrative indicator of ecosystem health rather than a stressor-by-stressor assessment. As already pointed out by Segner et al. (2014), the issue that matters is how the biological or ecological receptors respond to the combined presence of the anthropogenic stressors. Tallam and White have reviewed 22 years of literature. They found that as indicators of both general ecosystem health and of multiple other stressors, diseases play a disproportionally significant role in the face of climate- and anthropogenic-related stressors. While the review focused on estuaries, it is likely that disease is a valuable indicator to assess the health of other ecosystems as well, providing essential markers that should be monitored and modelled further.

Author contributions

AL: Conceptualization, Project administration, Writing – original draft, Writing – review & editing. EH: Conceptualization, Writing – review & editing. HS: Conceptualization, Writing – review & editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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