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Angel Borja,
Technology Center Expert in Marine and Food Innovation (AZTI), Spain

*CORRESPONDENCE
Neusa Martins
nemartins@ualg.pt

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Editorial: Opening the black box of kelps: Response of early life stages to anthropogenic stressors

Neusa Martins[1]*, Melinda A. Coleman[2,3], Thomas Wernberg[3,4] and Michael Y. Roleda[5,6,7]

[1]Centre of Marine Sciences (CCMAR), CIMAR Associated Laboratory, University of Algarve, Faro, Portugal, [2]New South Wales Fisheries, Department of Primary Industries, National Marine Science Centre, Coffs Harbour, NSW, Australia, [3]University of Western Australia (UWA) Oceans Institute and School of Biological Sciences, University of Western Australia, Crawley, WA, Australia, [4]Institute of Marine Research, His, Norway, [5]Division of Biotechnology and Plant Health, Norwegian Institute of Bioeconomy Research (NIBIO), Ås, Norway, [6]Biomarine Resource Valorisation, Division of Food Production and Society, Norwegian Institute of Bioeconomy Research (NIBIO), Bodø, Norway, [7]The Marine Science Institute, College of Science, University of the Philippines, Quezon City, Philippines

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Editorial on the Research Topic

Opening the black box of kelps: Response of early life stages to anthropogenic stressors

Kelps form marine forests along world's coastlines, providing valuable ecosystem goods and services, either directly as a source of food or medicinal products, or indirectly as biogenic habitats or carbon sink agents (Teagle et al., 2017; Wernberg et al., 2019). However, kelp forests are currently under threat due to anthropogenic climate change with latitudinal range shifts and large-scale declines at a global scale (Smale et al., 2019; Wernberg et al., 2019). Most studies on the impact of anthropogenic stressors on kelps have focused on the macroscopic sporophyte stage of the haploid-diploid life cycle (Schiel and Foster, 2006; Veenhof et al., 2022). However, the microscopic stages considered as the "black box" of kelps due to the complexity of studying them *in situ*, have been suggested to play a crucial role in the persistence of populations that experience sporophyte mortality after large-scale disturbances (McConnico and Foster, 2005; Barradas et al., 2011) as they can persist as "seed bank" analogues under adverse conditions (Hoffmann and Santelices, 1991; Veenhof et al., 2022). This Research Topic is a collection of 8 articles contributing to opening the "black box" of kelps by providing greater insight into how microscopic life stages of kelps are affected by anthropogenic climate change, helping to predict the persistence of these foundation species and therefore the fate of ecosystems and coastal communities. These studies highlight that the response of kelp early life stages to stressors can be strongly dependent on the population and thermal history.

Contributions

Among the consequences of anthropogenic climate change, sudden and anomalously warm thermal events known as marine heatwaves (MHWs) are increasing in frequency and duration globally (Oliver et al., 2018) and have drastically impacted ecosystems everywhere (Smale et al., 2019). Strasser et al. investigated the effect of MHWs on gametophyte survival and their reproductive success during recovery in four populations of *Laminaria ochroleuca*. The MHWs delayed gametogenesis and the highest MHW of 27°C caused more than 50% of gametophyte mortality in all populations. However, inter-population variability in gametophyte thermal resilience and reproductive success during recovery was found along the distribution range, with the northernmost (cool) population showing greater thermal sensitivity.

Using a common garden approach, Becheler et al. simulated conditions along the coast of Chile and Peru in the laboratory to enable reciprocal transplants of *Macrocystis pyrifera* gametophytes. They found that gametophyte performance was dependent on the thermal treatment and region, with gametophytes from marginal populations showing lower fertility than those from the intermediate region. The gametophyte performance during a simulated MHW was also investigated and although all gametophytes survived, the physiological vigour was negatively impacted across regions with the southernmost (cool) gametophytes being the least resilient.

Schimpf et al. found similar gametophyte upper thermal tolerance across several populations spanning the NE Atlantic distribution range of *Laminaria digitata*, with no gametophyte survival at 25°C and a uniform upper survival temperature of 24°C. Additionally, all female gametophytes remained in a vegetative state in thermal treatments >20°C and only the females recovering from 20-23°C developed eggs and sporophytes. However, populations had adapted to their local thermal conditions, as the gametophytes from the two southernmost (warm) populations had higher reproductive success during post-heat recovery compared to the northernmost (cool) gametophytes.

These studies provide evidence that kelp microscopic stages can be negatively affected by warming, but their tolerance responses are not uniform across distribution ranges, revealing adaptation to local thermal regimes. Liesner et al. demonstrated the beneficial effects for offspring thermal resilience of crossbreeding genetically distinct *L. digitata* populations with different thermal phenotypes. These results highlight the potential of outbreeding to generate more resilient strains for kelp aquaculture and restoration (Coleman et al.).

The response of kelp early life stages to anthropogenic stressors was recently shown to also be modulated by thermal history (Liesner et al.). Further evidence of the influence of thermal history within and across life cycle generations in *L. digitata* was provided by Gauci et al. Gametophyte cultivation at cold temperature promoted gametogenesis, recruitment and thermal tolerance of offspring sporophytes at extreme temperatures compared to a warm thermal history. These results show that increased temperatures may severely affect *L. digitata* persistence in trailing-edge populations.

Anthropogenic climate change can also have indirect effects and might lead to complex interactions in the way other stressors such as grazing, impact kelp microscopic stages (Veenhof et al., 2022). Veenhof et al. showed that a turf-associated gastropod micrograzer reduced the coverage and abundance of *Ecklonia radiata* gametophytes, but the gametophytes were able to survive ingestion, developing into sporophytes after secretion. However, the gametophytes did not fully recover from grazing under future warming scenarios, suggesting reduced kelp forest resilience in coming decades.

Furthermore, the review by Edwards provides an overview of how several other anthropogenic stressors (e.g., nutrients and declining salinity, increasing irradiance and sedimentation) affect the survival, growth, and reproduction of kelp microscopic life stages and how they can persist during periods of unfavorable conditions, contributing to the resilience of kelp forests. The potential of using microscopic stages in kelp forest conservation and restoration was also highlighted in this review.

The natural recovery of degraded ecosystems can be challenging even after the removal of the environmental stressors (Lotze et al., 2011), therefore successful restoration strategies are urgently needed to combat the kelp forests decline. The potential of the novel technique 'green gravel' for *E. radiata* restoration in Western Australia where natural kelp forest recovery has failed was assessed by Alsuwaiyan et al. The sporophytes successfully developed attached onto the gravel as well as in the surrounding substratum providing a vector of material dissemination onto the underlying habitat enriching depleted ecosystems.

Perspectives

Overall, this Research Topic extended our knowledge of how key biological processes associated with kelp early life stages are impacted by anthropogenic climate change. However, further studies are still required to fully understand the "black box" of kelps, such as research focusing on the beneficial interactions between kelp gametophytes and their associated microbial communities, since it may provide a novel technique for improving kelp resilience to climate change (Veenhof et al., 2022). Future studies should also consider responses of cryptic early life history stages to multiple environmental drivers not only of global significance but also of local consequence (e.g., eutrophication and heavy metal contamination; Leal et al., 2018) using improved experimental design that can simultaneously manipulate e.g., as much as five stressors that primarily control organismal physiology (Boyd et al., 2016), the competitive interactions and facilitation between kelp gametophytes and other species that might vary with environmental changes (Zacher et al., 2019; Eger et al.). This Research Topic has demonstrated that the microscopic stages of kelps are sensitive to anthropogenic stressors, and opening the black box of these critical life stages may well hold the key to help secure kelp forest in the future.

Author contributions

NM designed this Research Topic. All authors have contributed to this work and approved the manuscript for publication.

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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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