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Editorial: Impacts of climate change on seaweeds

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Editorial on the Research Topic

Impacts of climate change on seaweeds

Climate change is drastically altering the composition and abundance of seaweed-dominated ecosystems throughout our oceans. Ocean warming and associated intensifying marine heatwaves (Wernberg et al., 2016; Bunting et al., Trautmann et al., Gendall et al., Khen et al.), ocean acidification (Koch et al., 2013; Comeau and Cornwall, 2016), and deoxygenation (Altieri et al., 2021) can all impact the physiology of seaweeds and the ecological roles that they play. Ocean warming can cause long-term shifts in the ranges of seaweed species, usually in the form of range retractions at warm edges and expansions at cool edges (Straub et al., 2016). Marine heatwaves can elicit acute heat stress in seaweeds, drive subsequent mortality, and result in phase shifts from one ecosystem type to another (Wernberg et al., 2016, 2024). Ocean acidification causes the slow transformation of ecosystems from those dominated by coralline algal substrate to those characterised by a variety of turfing seaweeds or microalgae (Cornwall et al., 2024). Increasing intensity of ocean deoxygenation and frequency of acute localized events will likely exacerbate the effects of localized threats, but the effects of deoxygenation on seaweed communities remain poorly understood compared to other climate change-linked stressors (Altieri et al., 2021). Additionally, increased sedimentation caused by land use changes and increased storm frequencies brought on by climate change (termed ‘coastal darkening’), is also an important stressor of seaweed communities (Blain et al., 2021). Increased sedimentation can interact with other stressors (e.g., temperature) or act on its own to alter the composition and function of seaweed-dominated ecosystems (Wernberg et al., 2024). To better predict and project how seaweed-dominated ecosystems will fare in the future, we require extensive further evidence regarding how the effects of climate change will manifest on seaweeds of all types across temperate, tropical, and polar regions.

Ocean warming is likely to have extensive impacts on the physiology and ecology of seaweeds. Trautmann et al. examine the impacts of ocean warming on the kelp *Laminaria digitata* in the Arctic during the winter months. They test the hypothesis that ocean warming during the Polar Night would reduce survivability due to increased metabolism

and resource consumption under a period of complete darkness. They found a reduction in energy stores, an increase in metabolic rates, and a decline in various biochemical compounds under winter warming. Despite a reduction in physiological health, specimens that underwent warming remained in relatively healthy condition, indicating that winter warming may not necessarily cause a significant decline in *L. digitata* populations in the High Arctic, at least in the near future.

Wu et al. investigated the combined effects of ocean warming and eutrophication on the competition dynamics between two bloom-forming seaweed species, *Ulva prolifera* (green tide) and *Sargassum horneri* (golden tide). The results show that while both seaweeds thrive with increasing temperatures and nutrients up to 25 °C, both had rapid declines in growth, pigment concentration, and photosynthetic activity at 30 °C. Furthermore, under eutrophic conditions, *Ulva prolifera* outcompeted *Sargassum horneri*, particularly at higher temperatures. Collectively, these results suggest that ocean warming and eutrophication, associated with climate change, will facilitate the dominance of green tide blooms.

Zhang et al. assessed the photosynthetic growth response of the rhodophyte *Gracilariopsis lemaneiformis* when exposed to four different nutrient conditions (full factorial high and low N and P) and two temperatures (20 and 23 °C). They found photosynthetic and growth rates of this species generally only increased by higher levels of both nutrients (N+P), but that there were minimal effects of temperature.

Bunting et al. assessed how marine heatwaves of differing intensities and durations impacted sporophytes of the giant kelp *Macrocystis pyrifera* in a laboratory experiment in Aotearoa New Zealand. They find that increasing both the duration (from 3 to 6 weeks) and intensity (from 18 °C to 20 or 22 °C) of marine heatwaves act to reduce the growth of *M. pyrifera*. Moreover,

temperatures over 22 °C were found to have particularly strong negative impacts on growth, as this was the only temperature treatment to cause mortality, especially in the 6-week duration treatment. This indicates marine heatwaves above 20 °C will be especially problematic for this species *in situ*.

Understanding the drivers of kelp forest stability under ocean warming requires long-term, spatially explicit datasets. Multiple papers in this Research Topic develop such datasets using satellite-based remote sensing and uncover patterns of change in kelp forests across Western Canada. Despite its extensive ~26,000 km coastline, the trajectories of Western Canada's kelp forests have remained largely unknown until recently, even with clear evidence of localised climate impacts (Schroeder et al., 2020; Watson et al., 2021; Mora-Soto et al., Starko et al., 2024; Wernberg et al., 2024).

Gendall et al. combined archival charts with satellite imagery to reveal century-scale changes in *Macrocystis* forests of Haida Gwaii, including a persistent loss in the early 1970s likely driven by ocean warming. This is one of the earliest examples of climate-driven kelp loss globally (Wernberg et al., 2024). These declines were isolated to the warmest parts of the region, with nearby areas remaining stable. Mora-Soto et al. extend this perspective to bull kelp (*Nereocystis luetkeana*) in the Salish Sea, demonstrating that recent warming caused major kelp losses in the warmer, inner parts of the region. Notably, these declines occurred during the 2014–2016 marine heatwave, which had extensive impacts on kelp along the west coast of North America (Starko et al., 2025). However, cooler areas were much more stable and did not experience these same declines, similar to the findings of Gendall et al. Finally, Man et al. focus on kelp forest dynamics in the Broughton Archipelago and report high persistence of canopy kelps from 1984–2023, suggesting this cool region may serve as a climate refuge.

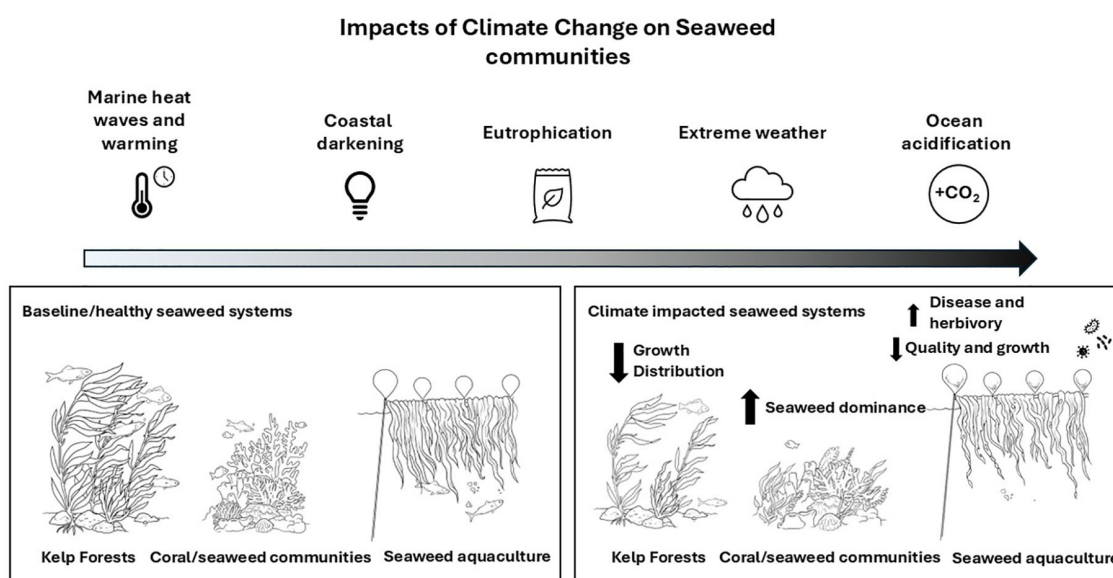


FIGURE 1

Impacts of climate change on seaweed ecosystems reviewed in this Research Topic. Importantly, ocean warming and marine heatwaves will have large consequences for kelp forest and coral/seaweed ecosystems, as well as seaweed aquaculture. The effects of temperature will also be highly modified by local contexts and drivers, such as nutrient and sediment levels.

Khen et al. assessed 11 years of benthic seaweed cover on the coral reefs of Palmyra Atoll in the tropical central Pacific. In addition to identifying that seaweed communities were dominated by calcareous taxa on the fore reef and by fleshy taxa on the reef terrace, they also found that marine heatwaves associated with El Niño years (2009, 2015) dramatically altered seaweed abundances. Fleshy seaweed tended to dominate reef communities after these periods of warming, while calcifying green seaweeds in the genus *Halimeda* declined. Palmyra Atoll's relatively pristine reefs, provide an opportunity to understand long-term patterns in seaweed community dynamics in the absence of direct local human impacts.

Climate change will not only impact seaweed ecology, but also impact their utility in aquaculture. Veenhof et al. provide a summary of climate change related challenges to this industry, contrasted by the various opportunities that seaweed aquaculture presents to enhance ecosystem resilience. The primary challenges experienced are those caused by changes to physical factors (such as ocean warming and acidification), an increase in extreme weather events, and a heightened prevalence of disease and herbivory (particularly by invasive species). To overcome these challenges, Veenhof et al. present the following recommendations: a) by selecting for restoration and aquaculture sites that balance climate change impacts and species responses; b) utilising genetic advancements to inform selective breeding and hybridization, microbiome manipulation, and priming strategies; and c) progressing aquaculture towards approaches that maximize both restoration and cultivation.

Liu et al. examines challenges in *Neopyropia yezoensis* (laver) cultivation in Jiangsu Province, China, focusing on the challenges it faces due to climate change. Warming sea temperatures, extreme weather, and high-density cultivation lead to crop failures, diseases, intra-specific competition and economic losses. The paper proposes strategies for sustainable, climate-resilient development, such as cultivating heat-resistant alternatives like *N. haitanensis*, relocating cultivation to cooler regions, integrating multi-trophic aquaculture systems (IMTA), and aligning the industry with carbon credit markets to improve future ecological and economic outcomes. These measures aim to ensure long-term productivity while mitigating environmental impacts.

Collectively, these studies emphasise the importance of local environmental conditions in mediating seaweed responses to ocean warming (Figure 1). This underscores the need for locally tailored conservation and management strategies to protect these vital ecosystems. Local variability in temperature extremes, ocean acidification, nutrient concentrations, and seasonality will all influence the response of seaweeds to ocean warming and marine heatwaves. This editorial highlights an urgent need for more experimental and observational work that tests the role of multiple environmental drivers on seaweed ecology and physiology.

Author contributions

CEC: Conceptualization, Investigation, Supervision, Visualization, Writing – original draft, Writing – review & editing. DMB: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. COB: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. MDJ: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. SS: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing.

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