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Editorial: Restoration of coastal marine ecosystems

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Editorial on the Research Topic
Restoration of coastal marine ecosystems

At the COP 15 summit in Montreal in 2022, the United Nations adopted the Kunming-Montreal Global Biodiversity Framework (GBF; United Nations Environment Programme, 2022), which includes the ambition to protect 30% of the Earth's land, ocean, coastal areas and inland waters by the year 2030. The so called "30 by 30" initiative for conservation management includes measures for active ecosystem restoration of degraded habitats. Hence, a specific target in the GBF is to effectively restore 30% of the degraded ecosystems by the year 2030. Following this ambition, the period between the years 2020 and 2030 has been proclaimed as the UN Decade for Ecosystem Restoration (United Nations Environment Programme, 2021).

Ecosystem restoration started in the terrestrial realm, where nowadays, restoration efforts such as reforestation can be implemented at a multi-millions' hectare scale (De Jong et al., 2021). In contrast, restoration of most marine ecosystems is at present executed only at pilot scale (Bayraktarov et al., 2020). Today, the magnitude of successfully implemented marine restoration projects ranges from a few hundred hectares for seagrasses (Van Katwijk et al., 2016) and oyster reef habitats (Bersoza Hernández et al., 2018) to a few hundred square meters for coral reefs (Boström-Einarsson et al., 2020), respectively. Restoration at larger scales to unfold the desired ecological effects is an important target across all degraded marine habitats and is currently being addressed by roadmaps, e.g. for macroalgal (kelp) forests (1 million ha and 4 million ha by 2040; Eger et al., 2023) and by international networks[1] e.g. for biogenic reefs and oyster habitats (Pogoda et al., 2020). The large difference in the spatial scale of intervention between terrestrial and marine ecosystem restoration could limit the possibilities to achieve the targets of the 30 by 30 initiative. In a perspective on restoration of coastal ecosystems that was published at the start of the UN Decade for Ecosystem Restoration, Waltham et al. (2020) identified a series of uncertainties that complicate the planning for large-scale coastal restoration and impede predictions on the outcomes of such restoration measures. Uncertainties included 1) insufficient

1 https://noraeurope.eu

availability of successful showcases; 2) the scalability of the approaches used for marine restoration; 3) a lack of business cases associated with marine restoration, and 4) unpredictable effects of climate change. In this Research Topic on Restoration of Marine Coastal Ecosystem, we present new insights on the most recent achievements in marine ecosystem restoration four years after the start of the UN Decade for Ecosystem restoration with reference to the four uncertainties mentioned above.

The present Research Topic "Restoration of Marine Coastal Ecosystems" comprises 21 articles that cover a wide range of topics and ecosystems: 19 articles discuss restoration aspects that are specific for the targeted ecosystem. These ecosystems include macroalgal forests, seagrass beds, estuarine wetlands, oyster reefs, and (sub)tropical coral reefs and represent cases from four continents (Figure 1). Findings per ecosystem type are introduced below and include successful showcases that prepare for further planning and upscaling of restoration efforts. Two articles cover overarching topics that apply to all coastal marine ecosystems. In a perspective paper, Ter Hofstede et al. discuss five principles to be taken into account when engaging industrial partners in marine restoration. Engaging industry by adopting industrial techniques and infrastructure is an effective route towards scaling up restoration. In particular, landscaping activities, such as the installation of scour protection in offshore windfarms, offer opportunities for large-scale ecosystem restoration. Another overarching topic in marine restoration, reviewed by Corinaldesi et al., is the role of microbiomes. Changes in microbial communities associated with foundation species targeted for restoration can impose threats to restoration success. As such, microbiome analysis can be used as an indicator to monitor the health of restored species and communities. Furthermore, manipulation of the microbiome by the provisioning of probiotics that enhance specific microbiome-related functions can be explored as a new tool for marine restoration. Probiotics have been applied successfully to promote seedling growth in macrophytes (Malfatti et al.) and to increase heat resilience in tropical corals (Peixoto et al., 2022), thus confirming the potency of this novel approach.

Estuarine wetlands

Estuaries are extremely dynamic ecosystems, often altered by human activities over centuries. It is sometimes difficult to assess the historic, pristine state before human-induced disturbances and to predict the effects of restoration actions. To assess the suitability for macroalgal and seagrass development of a temperate coastal lagoon in the Baltic Sea, Schernewski et al. managed to estimate the historic benthic cover by these communities as far back as in the year 1890. Their conclusion that this lagoon may historically have been eutrophic and turbid, not allowing macrophyte to cover more than 36% of the lagoon seafloor, shows governmental restoration targets were overambitious. The desired value for water quality (turbidity) would exceed the historical, natural value. The study by Wang et al. shows unexpected effects of a restoration action in the Liaohe River Estuary Wetland in Northeast China. 5500 aquaculture ponds were removed for a (passive) restoration of the original reed-dominated ecosystem, a system with a high capacity to store carbon. However, in the first years after removal of the ponds, the blue carbon storage decreased rather than increased, due to slow development of the ecosystem towards its original state. The study

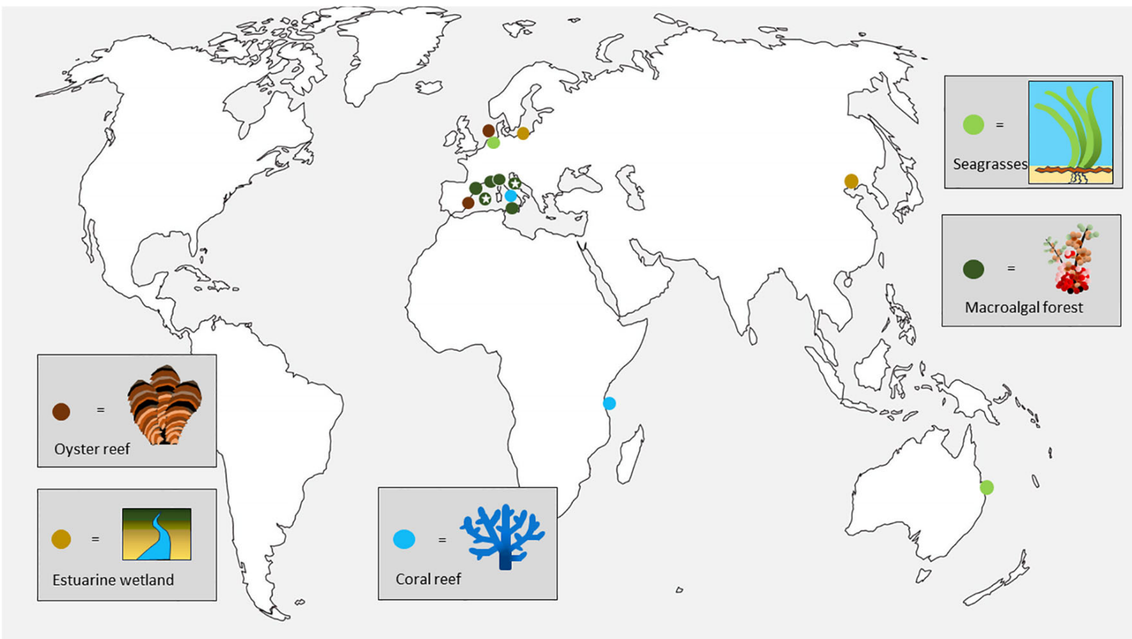

FIGURE 1
World map showing the ecosystems and locations investigated in this Research Topic. Locations with a star represent sites where multiple studies have been executed. World map retrieved from www.freeworldmaps.net.

includes an assessment of the potential impacts of climate change on the recovery of the ecosystem. Sea level rise is expected to induce a change in dominance from reed to seepweeds in this estuary, which may further affect its blue carbon potential.

Seagrasses

Seagrass restoration can either be based upon transplantation of shoots from donor populations or upon the use of seeds. When opting for transplantation, the self-reinforcing character of seagrass beds should be considered. Shoots will easier establish themselves when hydrodynamic forces have already been attenuated by adjacent seagrasses. To facilitate the return of an European eelgrass (*Zostera marina*) population in a highly dynamic coastal area (the Dutch Wadden Sea), Rehlmayer et al. applied root-mimicking structures that improved early survival of transplanted shoots with 67%. Long-term survival of the shoots was less successful, indicating that the selection of sites and source populations needs to be further investigated and optimized. The second option for seagrass restoration, based on seeds, requires knowledge on factors determining flowering of seagrasses. Lekammudyanse et al. investigated the influence of tidal exposure time, season and shoot density on flowering of the Australian eelgrass *Zostera muelleri* during two subsequent years. They found that flowering density increased with exposure time, which is in line with the general principle that flowering is associated with stressful conditions. Seasonal peaks in flowering were observed at both sites studied. Although these trends were consistent over the two years, the difference in absolute numbers of flowers differed substantially per year. These findings will facilitate seed-based eelgrass restoration in tropical Australia and beyond.

Macroalgal forests

A significant proportion of this Research Topic is devoted to the restoration of Mediterranean macroalgal forests. 11 articles show that integrated approaches considering multiple biological and ecological aspects can lead to successful regeneration of threatened or degraded ecosystems. A review on macroalgal restoration shows that upscaling is mainly compromised by a lack of understanding of the drivers of decline of the targeted ecosystem, which impairs the selection of appropriate restoration sites (Verdura et al.). Smith et al. managed to elaborate a decision framework for Mediterranean *Cystoceira* forests, largely based upon the progress reported in this Research Topic. Technological progress includes the earlier mentioned microbiome-based improvement of seedling growth (Malfatti et al.) and an optimized protocol for timing of collection of these early life-stages (Rindi et al.). New ecological insights highlight the potentially inhibitory role of grazers on macroalgal recovery (Monserrat et al.), the benefit of macroalgal forests for development of other ecoengineering species such as the vermetid snail *Dendropoma cristatum* (La Marca et al.) and the importance of foundation species in early ecosystem rehabilitation (Bianchelli et al.). A comparative study on passive (Fanelli et al.) and active (Bianchelli et al.) restoration of macroalgal forests historically degraded by pollution showed that both approaches can complement each other and should not be considered as a dichotomy. Ten years of monitoring of a restored macroalgal forest (Galobart et al.) once more evidenced the importance of long-term monitoring of ecosystem restoration. Functional diversity (species and traits) recovered to levels equaling or even surpassing the non-perturbated reference sites and highlight the potential for upscaling. Gaps in the path towards upscaling include a governance mismatch between bottom-up initiatives and (inter) national policies and the involvement of capital investment (Smith et al.). Climate change may affect restoration success in the future, since both early life stages and adults of some macroalgal species are inhibited by high temperatures (De Caralt et al.).

Oyster reefs

Many oyster restoration projects apply the deployment of hard substrates to initiate natural reef development through natural spatfall in substrate-limited areas (Fitzsimons et al., 2020; Chowdhury et al., 2021). In the North Sea, populations of the native European flat oyster (*Ostrea edulis*) have diminished to such an extent that most restoration sites are substrate- and recruitment-limited without the potential for passive recovery. Analogous to seagrass, active restoration of oyster reef habitats and oyster populations could happen through translocation of adult oysters. Considering ecological pressures at donor sites and biosecurity risks for target sites, hatchery-produced oysters seeded on substrate such as oyster shell material are the long-term strategy for large-scale oyster habitat restoration. Bos et al. report the successful translocation of adult oysters from donor populations in Ireland and Norway to five locations in the Dutch North Sea. Oysters grew and reproduced at the translocation sites. To make oyster restoration independent of harvest from donor populations, Hernandis et al. established an oyster hatchery in the Mar Menor area in Eastern Spain. This lagoon is a designated oyster restoration area, but source populations are scarce. The study yielded 680,000 juvenile oysters, originating from nearly 60 million collected larvae. The juvenile oysters will be used for a restoration pilot in the Mar Menor lagoon.

Coral reefs

A case study by Knoester et al. provides results of a successful pilot-scale restoration of tropical coral reefs in Kenya. Active restoration of a completely damaged reef area by outplacing cultured corals on artificial reefs re-established key ecological functions within a time span of only two years. Comparable results were recently reported from in Indonesia (Lange et al., 2024), demonstrating that rehabilitation of coral reef ecosystems can be achieved within a relatively short period of time. Nevertheless, both projects indicated that full recovery of biodiversity up to the level of the natural reference reefs in the targeted areas may require a time span of over 20 years. The project in Kenya showcases both the importance of stakeholder involvement (the restoration work being executed in collaboration with local communities) and the importance of long-term monitoring to realize the restoration objectives. However, the future endurance of the current reef restoration actions is predicted to become largely compromised by climate change (Knowlton et al., 2021). Hence, continuation of these projects should include measures to improve the heat resilience of the re-introduced corals. Heat resilience also played a role in the study by Roveta et al. on the Mediterranean reef building coral *Cladocora caespitosa*. These authors translocated a population of this endangered species from an artificial substrate that was threatened by demolition. Translocation was successful with over 80% survival, but dropped after the occurrence of a marine heat wave.

Concluding remarks

As of now, the UNEP target of restoring 30% of degraded marine coastal habitats by 2030 is difficult to achieve. Intensifying and upscaling restoration across all habitats is an obligatory action. Significant progress towards upscaling is reported in this Research Topic on the Restoration of Coastal Marine Ecosystems. Technically, our current capabilities to restore seagrasses, macroalgal forests, oyster reefs and coral reefs allow for planning and implementing large-scale marine habitat restoration. For many regions and habitat types, site selection remains a challenge especially when considering user conflicts and climate change scenarios. Especially, coral reef and seagrass restoration science must provide a profound understanding of specific restoration potentials and strategies to increase the resilience of affected systems. It is important to note that the potential for successful restoration of different marine habitats, as well as information for optimization and adaptation of restoration measures, are strongly tied to efficient and long-term monitoring. Marine restoration is often still predominantly driven and funded by science, and NGOs, and thus of limited extension. Government acts are needed to expand the spatial scales of intervention. The first of its kind, EU Nature Restoration Law aims to restore at least 20% of the EU's land and sea areas by 2030, and all ecosystems in need of restoration by 2050 (European Commission, 2022), which may facilitate this scaling. Seconded by designated marine compensation measures, such as oyster reef habitat restoration to compensate for offshore wind and cable construction in the North Sea, the required larger investments and the engagement of commercial and industrial partners will also be fostered. In this way, future planning for scalability will also emphasize business cases associated with marine restoration, which were not yet addressed in most of the contributions to this Research Topic.

Author contributions

RO: Visualization, Writing – original draft. RD: Writing – review & editing. AD: Writing – review & editing. BP: 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.

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