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Editorial: Degradation, conservation and ecological restoration of seagrass beds under intensifying global changes

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Editorial on the Research Topic
Degradation, conservation and ecological restoration of seagrass beds under intensifying global changes

Global changes (including warming, ocean acidification, and intensified human disturbances) have profoundly impacted marine environments, threatening foundational species and their critical habitats (Hoegh-Guldberg and Bruno, 2010). Addressing these compounded pressures requires an enhanced understanding of marine ecosystems alongside intensified protection and restoration efforts.

Seagrasses, a group of foundational marine species, are widely distributed along tropical and temperate coastlines, where their meadows support essential ecosystem functions (Unsworth et al., 2019b). These meadows, one of the three primary nearshore ecosystems, provide habitat, food, and nurseries to numerous marine species (Costanza et al., 1997). Moreover, they contribute to water quality by enhancing sediment deposition and removing excess nutrients (Dennison et al., 1993), while their role as carbon sinks helps mitigate climate change (Fourqurean et al., 2012). It is estimated that 19% of the surveyed seagrass area has been lost since 1880, with individual meadows declining globally at a rate of 1–2% per year (Dunic et al., 2021), driven by both natural and anthropogenic factors, including physical disturbances, sediment and nutrient runoff, invasive species, algal overgrowth, and warming waters (Waycott et al., 2009). These threats have catalyzed a global push to conserve seagrasses, aiming to reduce their loss and strengthen their ecosystem functions. The success of the efforts relies on the knowledge exchange and integration of scientific research into conservation/restoration practices, aiming to develop more effective restoration techniques that promote the resilience of seagrass ecosystems and their services.

Our aim for this Research Topic in Frontiers in Marine Science was to bring together studies that improve the understanding of the mechanisms underpinning seagrass degradation and ecological responses to environmental change, as well as the technological approaches that can enhance restoration success. This Research Topic includes nine scientific papers (one review and eight original research articles) covering diverse species from temperate to tropical waters. The main focus was on the assessment of ecological impacts of environmental stressors, adaptive physiological responses to climate change, advances in restoration techniques, ecological restoration benefits, and microbial contributions to restoration success.

Seagrass degradation drivers

Despite their critical ecological roles sustaining biodiversity and ecosystem functions, seagrasses are experiencing significant global degradation (Duarte et al., 2025; Jones et al., 2025). Long-term observations highlight anthropogenic activities as primary drivers. While some of these activities (e.g., oyster aquaculture) may have minor effects on seagrass meadows, at least in the short-term and at small geographic scales (Rubino et al.), others can result in detrimental changes of the seagrass ecosystems in the long-term (Green et al., 2021). For example, in Bohai Bay, Tangshan, extensive alterations in *Z. marina* meadows occurred between 1974 and 2019 due to land reclamation. Partial recovery followed the construction of artificial "longshore sandbanks" after 2012, but meadows remain threatened by fishing, dredging, and aquaculture activities (Xu et al., 2021b). Similarly, the increase in anthropogenic heavy metal pollution (e.g., copper and cadmium) has negative effects on seagrass meadows by suppressing the growth and photosynthesis of these marine plants. This effects can vary among species and populations depending on their specific sensitivities and tolerances (e.g., *Z. marina*: copper EC_{50} = 28.9 μM; *Ruppia sinensis:* copper EC_{50} = 50 μM), and the interactions with other environmental stressors (e.g., elevated temperatures) (Gu et al., 2021; Qiao et al., 2022).

Natural environmental changes can also represent ecological challenges that further compromise meadow stability (Unsworth et al., 2012). For instance, natural biochemical changes in the sediments of seagrass meadows (e.g., accumulation of sulfides), can interact with temporal changes in other environmental drivers (e.g., elevated temperature), impacting the performance (e.g., photosynthesis and growth) of seagrasses. While short-term removal of the stress allows recovery, the prolonged exposure can result in irreversible mortality (Zhang et al., 2024). Similar negative effects can be observed in response to natural environmental changes in oxygen availability and irradiance, in which low oxygen conditions under low light can trigger severe photosynthetic impairment and metabolic alterations (Zhang et al., 2021). The scale of the effects of natural environmental changes on seagrass meadows depends on the magnitude and intensity of the changes. For example, natural extreme events such as the super Typhoon Lekima, nearly eradicated 1031.8 ha of *Z. japonica* in the Yellow River Delta, accompanied by substantial losses of organic carbon (>35%) and nitrogen (>65%) in the top 35 cm of sediments. The long-term detrimental effects of this extreme event together with the absence of seeds and overwintering shoots prevented natural recovery of the seagrass populations (Yue et al., 2021a).

Anthropogenic-driven climate change is another major threat to seagrass ecosystems, altering their ecological dynamics at a global scale. For instance, ocean warming, which is associated to the increase in atmospheric CO_2, has shifted the geographic distribution of seagrasses (*Z. marina*) in the Northeast Pacific (eastern China). Such ecological alterations are further exacerbated by the influence of anomalous extreme temperatures (e.g., marine heatwaves), resulting in drastic declines in the survival and functioning of these marine plants (Xu et al., 2022a; Pei et al.), despite their short-term capacity to regulate the oxidative stress associated to elevated temperatures (Pei et al.). Elevated atmospheric CO_2 can also alter the carbonate chemistry of the seawater resulting in ocean acidification. Contrary to ocean warming, ocean acidification has shown positive effects promoting seagrass growth. However, these beneficial effects cannot offset the functional impacts of heat-induced stress (Wang et al.).

Indirect anthropogenic environmental changes can also result from biological sources in which biotic stressors, such as algal blooms and invasive species, represent important ecological challenges that threaten the stability and distribution of seagrasses. In the Swan Lake lagoon, large meadows of *Z. marina* (199–232 ha), have been impacted by the rapid expansion of green tides of *Chaetomorpha linum*, enhancing the ecological competition for resources (e.g., space and light) (Xu et al., 2019a). Similar competition with invasive plants (e.g., *Spartina alterniflora*) has resulted in the suppression of seagrass growth and the contraction of *Z. japonica* habitats in the Yellow River Delta (Yue et al., 2021b).

Collectively, seagrass degradation results from anthropogenic pressures, natural disturbances, biological invasions, and climate change, involving light limitation, physical disturbance, chemical stress, and metabolic imbalance, which often act synergistically to accelerate decline and reduce resilience (de Fouw et al.). Therefore, future management must simultaneously alleviate local stress and adapt to global change to maintain ecosystem resilience.

Seagrass restoration

Restoration predominantly relies on transplantation and seed-based approaches. Transplantation, while potentially damaging donor beds and resource-intensive, offers relatively high survival and remains the most widely applied method. However, with restoration scaling to hundreds of hectares in China, overreliance on donor beds creates a "destructive-restorative" paradox. Seed-based restoration minimally impacts donor populations and enhances genetic diversity, making it a promising future strategy. Seed- and seedling-based approaches have emerged as a key focus for sustainable, large-scale restoration.

Seed-based methods offer potential for large-scale implementation but face high failure rates and technical bottlenecks (Unsworth et al., 2023; Unsworth and Rees, 2025). Seed selection and storage are critical: high-quality *Z. marina* seeds with >72% integrity can be obtained via saline flotation (>1.20 specific gravity) and maintained at 0°C with nanosilver or copper sulfate treatment, preserving 80–90% viability (Xu et al., 2019b). Long-term storage at 0°C and 40–50 psμ salinity can potentially extend viability up to 17 months, providing a foundation for seed banks (Xu et al., 2020).

Environmental conditions (including burial depth, water depth, salinity, and temperature) critically influence germination and seedling establishment. Field experiments show optimal emergence for *Z. marina* at 2 cm burial depth (21.33 ± 9.30%), while 10 cm prevents germination (Xu et al., 2021a). Freshwater favors germination (up to 88.67%) but compromises seedling morphology and survival; salinity >20 psμ is required for stable establishment (Xu et al., 2016). Various techniques, such as mudball sowing (Xu et al., 2022b), bag fixation (Unsworth et al., 2019a), nutrient supplementation (Unsworth et al., 2022), and seed injection (Govers et al., 2022), demonstrate practical potential. For example, bag sowing achieved 94% mature plant emergence, though storm-induced sediment burial poses risks (Unsworth et al., 2019a).

Regional applications reveal species- and site-specific differences. In the Yellow River Delta, optimal burial depth varies with sediment type (sand 4 cm, silt 2 cm), and *Z. japonica* seed source affects performance (Yue et al., 2024). Transplantation studies on *Z. pacifica*, *T. hemprichii*, and *E. acoroides* further illustrate interspecific and regional variability. For instance, *E. acoroides* in Hainan exhibits 90% survival, outperforming *T. hemprichii* (Shen et al.), while *Z. pacifica* restoration on the US west coast is highly dependent on light, wave exposure, and dissolved oxygen thresholds (Sanders et al.). Rhizosphere microbial communities also influence seedling resource allocation, highlighting the need to integrate microbial factors into restoration planning (Randell et al.).

Ecological benefits

Restored meadows rapidly enhance benthic biodiversity, approaching natural meadow levels (Gräfnings et al.). Long-term monitoring indicates gradual increases in sediment carbon storage and microbial diversity, although short-term carbon sequestration gains are modest (Xu et al., 2025). Across 228 Southeast Asian restoration cases, moderate depths (2–4 m), adequate light, and low-to-moderate energy environments optimize success, with vegetative transplantation yielding the highest survival rates (Thorhaug et al.).

Future directions

With the increasing frequency, magnitude, and duration of global change, research on seagrass degradation mechanisms, management, restoration, and ecosystem function assessment is increasingly urgent. The studies summarized herein contribute critical insights into seagrass ecology, identify knowledge gaps, and highlight new directions. Future research should integrate climate change and anthropogenic pressures, advance precision management, innovate restoration techniques—including mechanization to improve efficiency—quantify carbon storage and ecosystem services, and leverage interdisciplinary approaches and predictive modeling to support sustainable management. We anticipate that this field will attract broad scientific interest, uniting researchers with diverse and complementary expertise to collectively advance seagrass conservation and restoration.

Author contributions

SX: Writing – original draft. RU: Writing – review & editing. JG-E: Writing – review & editing. YZ: Writing – review & editing.

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