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Overview Article

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Climate change is reshaping seagrass futures: novel environments and opportunities along coastlines and across oceans

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Abstract

Seagrasses are a highly productive ecosystem that supports biodiversity and fisheries, protects coastlines, and buries globally significant carbon stocks. Because seagrasses are increasingly stressed by warmer, darker, and more variable waters, established management strategies may not guarantee future success. Here, we depict a global outlook for seagrass futures by synthesizing how climate and non-climate human pressures may restructure meadow composition, food webs, fisheries, and blue carbon services. Current seagrass range shifts, adaptations, and acclimations to novel environmental conditions preview future states: climate-tolerant species often become dominant post-disturbance, seeds can disperse hundreds of kilometers, and local management can facilitate habitat persistence and large-scale restoration. To boost climate resilience, we propose a three-part framework involving (1) expanding seagrass mariculture and planting, (2) detecting and predicting shifting stressor gradients and species distributions, and (3) managing for seagrasses tolerant of novel environments. Together, these strategies offer proactive pathways for cultivating climate-adapted seagrass meadows worldwide.

Keywords **climate change, stress-tolerance, restoration, submerged aquatic vegetation**

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For seagrasses under climate change, the future is now

Seagrasses are some of the most unique plants in the world, having evolved to a complete underwater existence. Over the last 100 million years of their evolution, these marine flowering plants have colonized, survived, and spread to all but the most polar seas (Les et al. 1997, Short et al. 2007), forming vast underwater meadows that serve multiple vital roles within the coastal seascape. Seagrass meadows are essential fish nurseries that support a fifth of the world's largest fisheries (McDevitt-Irwin et al. 2016, Lefcheck et al. 2019, Unsworth et al. 2019b). They also filter particles to improve clarity of nearshore waters (Orth et al. 2020), and in doing so, reduce human, fish, and coral disease pathogens (Lamb et al. 2017). Finally, they constitute a globally significant carbon stock fueled by productivity that is equal to that of tropical rainforests, mangroves, and marsh ecosystems (Fourqurean et al. 2012, Gomis et al. 2025, Krause et al. 2025). Historically, seagrasses have declined due to human-driven eutrophication, dredging, and filling (Waycott et al. 2009, Turschwell et al. 2021). Now, these foundational coastal habitats face the greater threat of climate-driven marine heatwaves, sea level rise, and, to a lesser extent, ocean acidification (Halpern et al. 2019). Today, 80% of coastal regions adjacent to seagrasses are exposed to high human pressures (Williams et al. 2022), and the global extent of seagrass has declined 19% since 1880, based on monitored meadows (Dunic et al. 2021). The combination of climate change and other human impacts is creating novel environmental conditions not experienced within the recent genetic memory of seagrasses (Williams et al. 2007, Morse et al. 2014). However, seagrasses and seagrass food webs are already responding physiologically, genetically, and ecologically to these novel conditions (Pazzaglia et al. 2021, Zimmerman 2021).

Despite the significant ongoing threats to all coastal ecosystems, progress has been made in the two decades since a global crisis for seagrasses was declared (Orth et al. 2006). Researchers and managers have identified several mechanisms that suggest seagrass meadows can and are adapting to the novel environments of the modern ocean. Seagrasses have genetic and life history adaptations to a range of environmental conditions and employ diverse dispersal and disturbance-recovery strategies that encourage local, regional, and global migration (Kendrick et al. 2012, Kilminster et al. 2015, Orth et al. 2017, Allcock et al. 2022). High-profile examples of successful management continue to grow local and international awareness and support for seagrass conservation: meadows can respond rapidly and enduringly to targeted mitigation of nearby human impacts, and seagrass restorations now constitute some of the most successful coastal restorations around the world (Dolch et al. 2013, Saunders et al. 2013, Sherwood et al. 2017, Orth et al. 2020). ***However, these past victories may not guarantee future successes because our ability to accurately model local and global seagrass futures and to predict appropriate management actions is complicated by emerging unique stressor combinations, shifting species and community ranges, and ongoing changes to the frequency and intensity of extreme disturbances*** (O'Brien et al. 2018, Dunic and Côté 2023, Hensel et al. 2023). This grand challenge for coastal resource management requires scientists and managers to combine theory and current scientific knowledge to imagine the dynamics of future seagrass ecosystems and use these concepts to inform priorities, policies, and actions that help seagrasses keep pace with rapidly changing coastal environments.

Herein, we envision the future dynamics of seagrass meadows, humans, and coastal management under novel environmental conditions (figure 1, box 1). First, we describe how **(1) novel environments are redefining where seagrasses can live**, by reviewing the non-climate and climate-human drivers of seagrass losses and gains and how multi-scale habitat squeezes shift seagrass distributions across space and time. Then, we outline how **(2) future seagrass species, traits, and services may shift along shorelines and across oceans**. Focusing on immediate, near-future, and far-future time scales, we use seagrass physiology, ecology, and biogeography to review the rise in seagrass species with opportunistic life history strategies and the impact of biodiversity under climate change. Then, we predict how dispersal strategies, changing food webs, and bioregional species pools can change future seagrass community structure and facilitate new meadow formation into the near and far future. Lastly, we discuss how climate-driven changes in species dominance and distribution will affect seagrass fisheries and blue carbon. To close, we present a framework depicting the **(3) evolution of restoration and management to generate resilient seagrass futures.** This framework includes three major advancements in scale, diversity, and technology needed to cultivate climate-ready seagrass meadows; remote sensing and early detection of climate novelty for management; and multi-method mapping to track and predict the leading and retracting distributional edges of seagrass change. We finish by outlining how seagrass governance, policy, and economies can innovate to achieve lofty conservation and management goals, for example, those set forth by the Kunming-Montreal Biodiversity Framework and the UN Decade on Ecosystem Restoration (United Nations 2021, Convention on Biological Diversity 2023). With efforts to identify and manage actionable stressors in each bioregion, to target management for resilient species, and to facilitate establishment of newly available habitat, seagrasses may yet have a promising future under global climate change.

Novel environments are redefining where seagrasses can live

Novel physical and biological conditions are simultaneously shifting the ecology that defines seagrass persistence and restructuring the spatial boundaries within which seagrass meadows can survive. Both climate and non-climate stressors are compressing suitable habitat across depth gradients and latitudinal ranges while accelerating the frequency of acute disturbances that interrupt recovery. Understanding how these forces interact across scales is essential for anticipating where seagrass meadows will persist, retreat, or emerge under conditions without historical analog.

Climate and non-climate pressures drive seagrass gain and loss

Table S1 summarizes all major drivers of past and future shifts in seagrass cover, physiology, genetics, food webs, and ecosystem services (see also Short et al. 2007, Grech et al. 2012, Duffy et al. 2022). Throughout temperate and tropical seagrass-dominated coasts, water quality and watershed quality have and will continue to be the primary drivers of local and regional seagrass change. Unsustainable agricultural practices, deforestation, sediment input from land, and wastewater discharge have degraded watershed quality to cause extensive seagrass losses by increasing turbidity, fueling nuisance algal growth, and reducing benthic light availability (Orth

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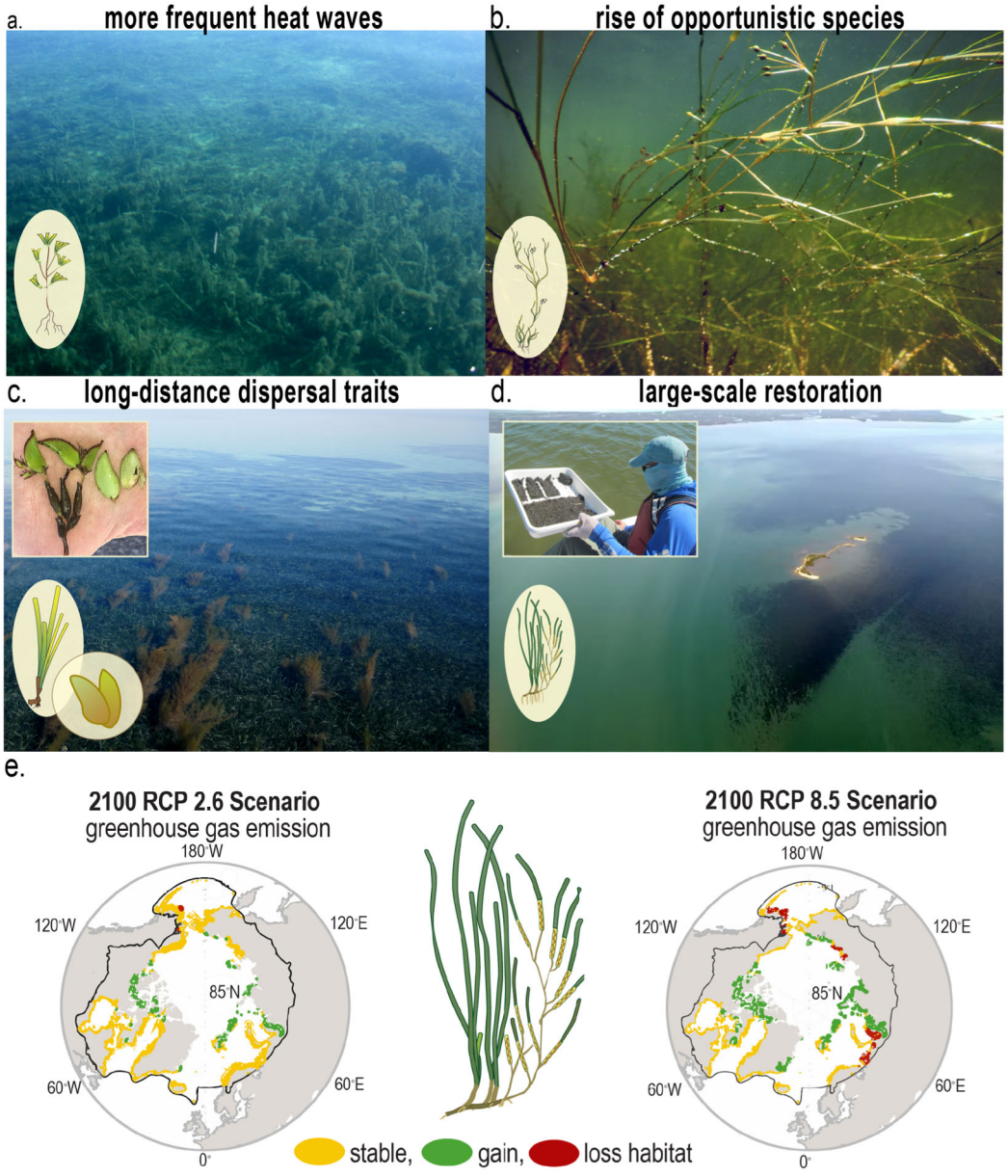
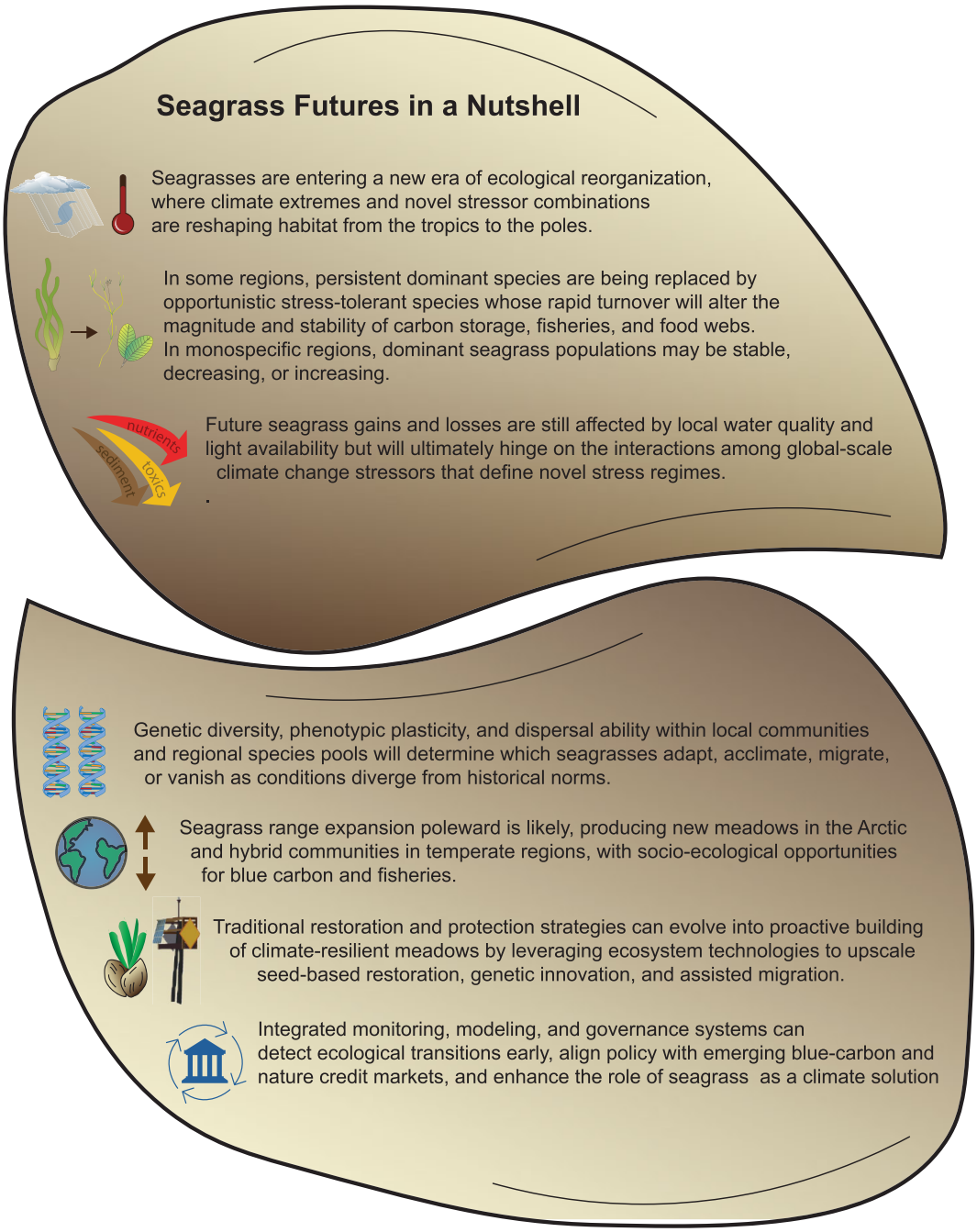


Figure 1. Recent examples that preview the future of seagrasses under climate change. We expect to observe (a) more frequent and intense marine heatwaves, like the 2-month heatwave in Shark Bay, Australia, in 2010–2011 that caused massive die-back of seagrasses such as *Amphibolis antarctica* and led to nearly 9 $TgCO_2$ released to the atmosphere (Arias-Ortiz et al. 2018); (b) the rise of less-studied opportunistic and climate-tolerant seagrasses, like temperature-tolerant *Ruppia maritima* in Chesapeake Bay, USA, that has taken over after *Zostera marina* die-back (Hensel et al. 2023; image by Alison Hall, VIMS); (c) the presence of seagrass species with long-distance dispersal traits in regional species pools, like *Posidonia australis* fruits that can float on currents for over a week, will determine colonization dynamics under climate change (seed image by Adrian J. Hunter Wikimedia Commons); (d) scaled-up seagrass restoration, like the most successful coastal restoration project in Virginia, USA seaside bays that brought back habitat, food webs, and fisheries after 80 years of bare ground (Orth et al. 2020); (e) colonization of new coastal polar habitat, including potentially thousands of km^2 of available Arctic *Z. marina* and/or *Z. noltei* habitat ("stable" and "gain") that will become suitable by 2100 under low (RCP 2.6; left) and high (RCP 8.5; right) emissions scenarios (Assis et al. 2022).

et al. 2006, Grech et al. 2012, Quiros et al. 2017, de los Santos et al. 2019, UNEP 2020, Turschwell et al. 2021). Conversely, targeted local actions to reverse water quality pressures and regulate destructive demersal fishing have fueled seagrass recoveries throughout many bioregions (Turschwell et al. 2021). In particular, reducing stormwater run-off, curbing nutrient loads, and controlling sediment inputs have consistently improved optical conditions and enabled natural (re)colonization (Sheridan 2004, Dolch et al. 2017, Sherwood et al. 2017, Lefcheck et al. 2018, Boesch 2019). When active planting or seeding is implemented with these water quality gains, recovery can be rapid, scalable, and economically efficient (e.g., large-scale seed-based restoration under favorable conditions can yield a massive return on investment (van Katwijk et al. 2016, Orth et al. 2020).

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Box 1: Summarization of the future outlook for global seagrasses under climate change.

Although solutions to these local stressors remain actionable, they now coincide with more frequent and extreme disturbances linked to both global climate change and local human pressures. Mechanical disturbance (e.g., trawling or anchoring), overgrazing, disease outbreaks, tsunamis, hurricanes/cyclones, and ever more extreme marine heatwaves continue to fragment habitat, reduce areal extent, and limit reproductive success (Orth and Moore 1983, Erftemeijer and Lewis 2006, Tsujimoto et al. 2016, Harcourt et al. 2018, Fourqurean et al. 2019, Smith et al. 2024). ***Thus, current environmental conditions already differ fundamentally from those in which most water quality and restoration targets were derived.***

Seagrasses are adapted to a wide range of environmental conditions and natural disturbances, but the frequency and intensity of those disturbances, temperature and light regimes, and CO_2 availability are all changing due to climate change (Halpern et al. 2019, Zimmerman 2021). Within the next century, seagrasses and other ecosystems are expected to experience conditions more similar to 3 million years ago than to the last 300,000 (Burke et al. 2018, IPCC 2023). Under these novel conditions, it will become increasingly difficult to predict how present-day species and ecosystems will respond based on our very recent history of scientific observation and understanding (Wright et al. 2026).

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Seagrass distributions are being squeezed across multiple spatial and temporal scales

Climate and non-climate stressors are jointly reshaping where seagrass meadows can be productive both along shorelines and across latitudes (figure 2). Across short time scales, interacting stressors can combine to create a ***subtidal squeeze*** on local meadows, restricting the range of depths suitable for efficient photosynthesis and complicating meadow-level response to sea level rise (Kairis and Rybczyk 2010, Saunders et al. 2013, Valle et al. 2014). For example, in regions with high coastal run-off, microalgal blooms may block deep light penetration, whereas high temperatures simultaneously render the shallows uninhabitable (Davis et al. 2016, Aoki et al. 2020). Over longer time scales, many seagrass-dominated coasts have some degree of hardened shorelines or coastal infrastructure that prevents local meadows from migrating landward (e.g., through clonal growth or seed colonization) in response to sea level rise, resulting in a ***coastal squeeze*** (Pontee 2013, Williams et al. 2022).

Across latitudinal scales, rising sea surface temperatures are redefining seagrass' thermal landscape. In several western boundary current systems, warming is accelerated by the poleward transport of tropical waters; seagrass-dominated coasts near Japan, the eastern USA, southeastern Africa, and western Australia are experiencing nearshore warming rates nearly three times faster than the global mean (Wu et al. 2012, Wernberg et al. 2013, Vergés et al. 2014). By 2070, seagrasses in the Mediterranean Sea, mid-Atlantic USA, and Southern oceans are expected to experience subtropical thermal regimes paired with temperate patterns of photoperiod, incident light angle, and seasonality (Cui et al. 2021)—*creating completely novel conditions unfamiliar to both resident species and potential climate migrants*. In addition, marine heatwaves are increasing in frequency and duration in many locations globally, leading to decline in seagrass habitat (Lefcheck et al. 2017, Oliver et al. 2018, Smale et al. 2019, Aoki et al. 2021, Wiberg 2023). At the same time, removal of sea ice at high latitudes (e.g., parts of Greenland) has led to local seagrass gains (Marbà et al. 2018). Predicting species' local responses (e.g., resilience) and potential for migration (e.g., range shifts) under these no-analog climate conditions requires extrapolation beyond the bounds of past observations of seagrass responses to environmental change.

Future seagrass species, traits, and services will continue to shift along shorelines and across oceans

In response to the global crisis for seagrass ecosystems, seagrass research has expanded and evolved over the past two decades (Zimmerman 2021). Now, we leverage the most up-to-date research to depict future seagrass community trajectories over three temporal scales: *immediate responses* to novel environments, many of which are already occurring; *near-future responses* that are expected to occur over the next 50 years; and *far-future responses* that are expected to become prevalent into the next century. We close by discussing how two key seagrass-derived services, *seagrass fisheries and blue carbon sequestration*, are expected to respond to novel environmental conditions over time.

Immediate: the rise of opportunistic dominants and the role of biodiversity

Present-day meadow community structure such as life history traits, genetic diversity, and phenotypic plasticity will govern the most immediate seagrass responses to climate change. Historically, persistent genera (*Posidonia, Thalassia, Enhalus*) with long lifespans, deep roots, and slow growth have resisted environmental variability most effectively (Turschwell et al. 2021). Under modern climate conditions, these stable meadows are increasingly reaching multi-stressor thresholds (e.g., marine heatwaves combined with poor water clarity), resulting in massive die-off with limited recovery capacity (Fraser et al. 2014, Lefcheck et al. 2017, Kendrick et al. 2019, Aoki et al. 2020). ***Yet, in many bioregions, die-off of historical dominants does not leave coastlines permanently bare; instead, it enables climate change-driven substitutions to occur.*** Opportunistic and colonizing seagrasses—genera like *Ruppia*, *Halodule*, and *Halophila*—rapidly expand or invade into habitat where they were previously outcompeted (Dolch et al. 2017, Nowicki et al. 2017, Sherwood et al. 2017, de los Santos et al. 2019, Hensel et al. 2023). Many opportunistic seagrass species have long-lasting seed banks, rapid sexual reproduction, or short-distance dispersal traits (e.g., negatively buoyant seeds, rapid clonal growth) that allow swift colonization into newly vacated space following extremes (Marbà and Duarte 1998, McMahon et al. 2014). Thus, community-level diversity in life history and other morphometric properties can enhance regional resilience by stabilizing sediment and supporting biodiversity, consistent with the "insurance hypothesis" documented in seagrass restoration contexts (Williams et al. 2017). As environmental gradients shift, community-level selection will likely favor climate change-tolerant phenotypes, especially in temperate regions where dominant persistent species are near their thermal limits.

Especially important within monocultures or where species diversity is low, existing genetic diversity and pathways that enable rapid within-species adaptation can likewise determine seagrass' immediate responses to novel environmental conditions (figure 2). Higher allelic richness can buffer against disturbance, accelerate recovery, and improve restoration outcomes and ecosystem services (Reusch et al. 2005, Ehlers et al. 2008, Reynolds et al. 2012, 2016). Phenotypic plasticity boosts resilience to variable conditions, as some seagrass species respond to stress by switching between clonal and sexual reproduction or from perennial to annual life histories (Muñiz-Salazar et al. 2005, Hovey et al. 2015, McMahon et al. 2017).

In constantly changing near-future climates, ***epigenetic and transgenerational responses that occur on timescales aligned with environmental change will be especially important in facilitating acclimation across a few generations without requiring shifts in allele frequencies.*** DNA methylation, transgenerational priming, and other non-genetic inheritance mechanisms have been shown to modulate stress responses to heat, light, and salinity in several species by creating physiological "stress memory," including at multiple life history stages (Marín-Guirao et al. 2019, Pazzaglia et al. 2021). Over longer timescales, natural selection may begin to favor genotypes that tolerate low light, extreme temperatures, or episodic disturbance, though the pace of selection remains poorly understood in most populations (but see Hughes and Stachowicz 2004). As warming progresses, opportunistic seagrass dominance could mask initial declines, but genetic changes, acclimation, and genotype sorting may

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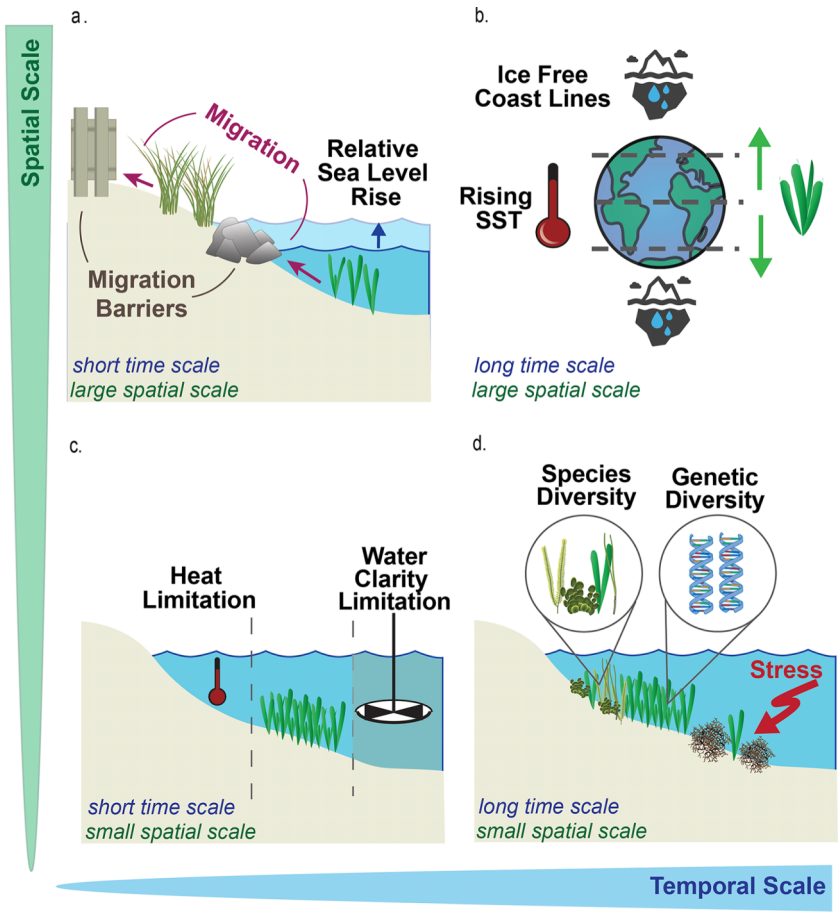


Figure 2. Novel environmental conditions from global change create multi-dimensional shifts and squeezes in seagrass habitat availability. On short time scales along coastlines worldwide (a, top left), sea level rise increases the amount of vertical water column available for growth, but physical migration barriers (e.g., coastal development, sea walls) may restrict migration onto shallow habitats (i.e., "coastal squeeze"). Over long temporal scales across large latitudinal spatial scales (b, top right), rising mean sea surface temperatures and more frequent marine heatwaves will gradually shift the range distributions of temperate, sub-tropical, and tropical species into polar, temperate, and sub-tropical regions, respectively. On short time scales at the scale of individual embayments and estuaries (c, bottom left), coastal darkening from pollution limits the deep edge of meadows, whereas temperature simultaneously makes shallow water less habitable (i.e., "subtidal squeeze"). As climate change continues into the next centuries, unique stressors, extremes, and shifting gradients will reshape current species diversity and shift both community structure and genetic diversity on a local meadow-scale response, with consequences for associated faunal communities (d, bottom right).

produce lagged ecological responses that reshape meadow composition over decadal to millennial timescales.

Near-future: re-assembly of seagrass food webs across latitudes from the bottom up and the top down

Over the next half century, local seagrass meadow structure will be reshaped by climate migrants moving across latitudes in response to shifting environmental gradients and novel conditions (figure 3). ***From the perspective of seagrasses themselves, dispersal ability and adaptive capacity will determine their rate of expansion.*** For example, tropicalization of seagrasses, that is, poleward shifts away from the equator into temperate areas, is increasingly likely in interconnected regions with diverse species pools (Kim et al. 2009, Virnstein and Hall 2009, Hyndes et al. 2016). Migrant success will depend largely on long-distance dispersal traits, such as floating fruits, vegetative fragments, or zoochory (Kendrick et al. 2012). Species that have these traits and are best positioned to migrate and establish in new regions are persistent genera like *Posidonia*, whose fruits float for over a week; *Thalassia*, capable of dispersal distances up to 720 km; and *Enhalus*, projected to expand range in Australia by 500 km by 2100 (Van Dijk et al. 2009, Hyndes et al. 2016). The temperate, globally distributed species *Zostera marina* has also been shown to travel similar distances and through similar mechanisms (Harwell and Orth 2002, Sumoski and Orth 2012). Nevertheless, given patterns in global seagrass diversity, the temperate Pacific will likely host more potential migrants (Hyndes et al. 2016), whereas low-diversity systems such as the temperate northwest Atlantic may exhibit more deterministic shifts (i.e., only a few species available to migrate).

Climate migrants establishing in new habitats will encounter unfamiliar competitors and shifting resource conditions. For example, temperature spikes can cue early flowering and seed abortion in temperate species (Diaz-Almela et al. 2007, Sinclair et al. 2015). In temperate-subtropical transition zones, mid-to-late-century climate change could reverse the early dominance of opportunistic species occurring now if medium-term climate-driven adaptations (or even assisted evolution) produce persistent genotypes capable of reclaiming territory. Poorer competitors, such as *Ruppia* and *Halophila*, might eventually retreat back into shallow fringing areas, whereas the cli-

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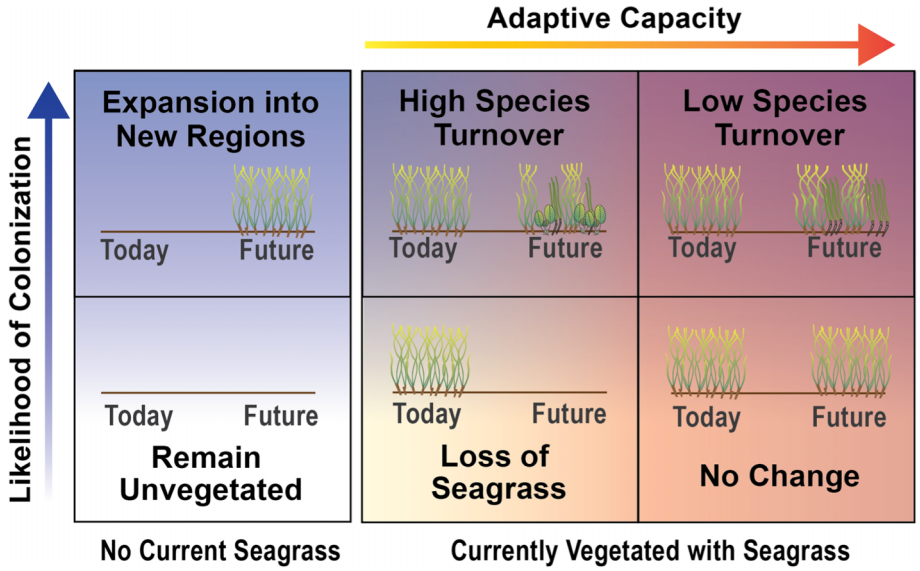


Figure 3. Expected paths of seagrass meadows subjected to future change over time are based on the adaptive capacity (horizontal axis; left/yellow = low adaptive capacity, right/red = high adaptive capacity) and the likelihood of colonization (vertical axis; lower/light blue = low likelihood of colonists arriving, higher/dark blue = high likelihood of colonists arriving). Major changes over time (i.e., from today to future) depend on these two axes and the community structure (low vs. high diversity depicted in cartoons) of today's local seagrass meadows. Although *currently bare regions* (left panel) with no available colonists are likely to remain unvegetated (bottom left), if supporting physical conditions exist in local and global areas with potential colonists (e.g., a protected embayment and the Arctic, respectively), these bare areas may experience seagrass expansion creating new seagrass regions (top left). In regions *currently vegetated with seagrass* (middle and right panels), variation in the adaptive capacity (e.g., phenotypic plasticity, genetic diversity, climate-tolerant traits) of today's community will control future change in seagrass species relative abundance. Without active restoration efforts, meadows with low adaptive capacity and few available colonists (bottom middle) may lose seagrass entirely. Local meadows with high adaptive capacity and few colonists are also likely to remain unchanged (bottom right). As colonization likelihood increases, the level of species turnover (top middle, top right) in the future community is likely to depend on the adaptive capacity of current meadows.

mate migrants adapted to warmer conditions become dominant. Cascading effects from shifting dominant foundation species may include altered nursery habitat for infauna, epifauna, and nekton (Alvaro et al. 2025) and altered carbon stocks (Brenner et al. 2024), but more experimental research and space-for-time surveys are required to predict wide-reaching effects across bioregions (Zimmerman 2021).

Changing trophic interactions will play a central role in future seagrass meadow structure and resilience, as herbivore and predator range shifts are already transforming the landscape of seagrass top-down control. Because successful conservation efforts and climate-driven range shifts have enabled both mobile megaherbivores and omnivorous and/or herbivorous fishes to expand poleward, many seagrass systems will face novel or intensified grazing pressure (Mazaris et al. 2017, Fourqurean et al. 2019, Lefcheck et al. 2024, Cloyed et al. 2025). Regions with limited evolutionary history of large grazers like manatees, dugongs, and sea turtles may lack defenses or stabilizing feedbacks (Kirsch et al. 2002, Fourqurean et al. 2010, 2019). Other regions will experience additive pressures from multiple herbivore guilds, like turtle range expansion into already urchin-grazed meadows (Valentine and Heck 2021), or the tropicalization of herbivorous seagrass fish (Kirsch et al. 2002, Fodrie et al. 2010). Grazer shifts will be especially important within tropicalization zones, as the strength of herbivore control on tropical seagrasses increases with latitude (Campbell et al. 2024).

In parallel, seagrass-associated predator community shifts are already occurring (Fodrie et al. 2010, Fujiwara et al. 2019, Purtlebaugh et al. 2020, Torres Ceron et al. 2023) and are likely to alter dynamics of micrograzers that consume epiphytic algae and maintain light availability for seagrass. Climate-induced changes in predator abundance or foraging behavior (e.g., tropicalization of keystone amphipod predator pinfish *Lagodon rhomboides*; Lefcheck et al. 2024) may suppress grazer populations, weakening algal control and exacerbating light limitation for seagrasses (Heck et al. 2000, Whalen et al. 2013). In many regions, trophic reassembly (i.e., new grazers and shifting predation regimes), variation in defensive traits, and ocean acidification effects will combine to control the trajectory of local seagrass meadows.

Far-future: Unique colonization vectors may vegetate previously bare shallow seas as new habitat becomes available

Projected climate migrant arrival will not only catalyze community and trophic shifts but could also create new meadows in previously uncolonized bare areas. Sea ice retreat and warming waters are predicted to open large areas of potentially suitable Arctic habitat by 2100 (Wilson and Lotze 2019, Murphy et al. 2021). ***The speed and probability of Arctic "borealization"*** (i.e., temperate seagrass migrating into polar waters; Krause-Jensen et al. 2020) ***depend on metapopulation traits of the only two polar-adjacent temperate species with a 150 km dispersal ability***, *Z. marina* and *Z. noltei* (Källström et al. 2008, Valle et al. 2014, Olsen et al. 2016, Assis et al. 2022). Establishment of polar *Zostera* meadows will be shaped by novel selection pressures, including unique dispersal vectors such as northward-shifting fish, waterfowl (and changes in their migratory routes), and floating debris; polar light conditions; prolonged summer daylight; and Arctic-specific disturbances like ice scouring and severe freezes (Jueterbock et al. 2021). The presence of existing eelgrass populations from 63° to

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73°N suggests that it is already possible to realize this species even in areas with near total darkness in the winter (Murphy et al. 2021). However, another form of "habitat squeeze" may occur, as seagrass depth limits become shallower to maintain positive carbon balance, limiting the available area for meadow development. Because application of *Zostera* depth limits from other areas and lower latitudes is not appropriate, habitat suitability models and surveys to determine how much colonizable substrate actually exists is now a priority for forecasting borealization rates (Assis et al. 2022).

Over the centuries and into the next millennia, taxonomic and latitudinal shifts will combine with variability of future light environments to create different rates of change, periods of biotic and abiotic disequilibrium, transitional states, and temporal lags (Blonder et al. 2015). Eventually, these changes may alter broader biosphere-level patterns and processes. For example, retreating sea ice could lead to genetic mixing between Pacific and Atlantic Ocean populations of *Z. marina* that has been isolated for 3.5 million years (Olsen et al. 2004, Duffy et al. 2022). Tall, sparse Pacific seagrass "forests" of *Z. marina* could intermix with short, dense Atlantic "meadows" to create hybrid meadow types with novel ecosystem structures. Additionally, colonization of polar shorelines by seagrasses as sea ice retreats could contribute to changing Arctic albedo, trading white ice for green grass rather than light sand (e.g., Houghton et al. 2012). Overall, these shifts in seagrass structure, function, and associated food webs will persist long after global climate stabilizes, reshaping not only marine ecosystems but also the human communities dependent on seagrass-derived services.

Seagrass ecosystem services into the future: Habitat squeeze and community change will reshape seagrass fisheries and blue carbon

Changes in seagrass meadow extent, connectivity, and community composition are reshaping key services like fisheries and blue carbon storage (Mtwana Nordlund et al. 2016). For fisheries, increased storm intensity and coastal squeeze may reduce catch volume and limit fishing to nearshore waters, disproportionately impacting small-scale fishers in the Caribbean, Southeast Asia, and Oceania (Heck et al. 2021). Because strong cross-ecosystem connectivity improves nursery habitats and supports diverse fishery species, habitat degradation in corals or mangroves may additionally force fish (and fishers) to rely increasingly on seagrasses (He and Silliman 2019, Rogers and Mumby 2019). Although this amplifies human reliance on seagrasses for fisheries, at the same time, climate-driven migrations could create new harvest opportunities and deliver new services to previously unvegetated areas. That is, fish, turtles, mollusks, and crustaceans moving with or ahead of seagrasses will not just restructure food webs (e.g., Mazaris et al. 2017, Lefcheck et al. 2024), but also bring new commercial and recreational fisheries to expansion regions. For example, Arctic colonization by seagrass could provide novel economic and ecological benefits, including new seagrass fisheries and coastal erosion protection in Canada and Russia (Lantuit et al. 2012, Marbà et al. 2018). Lastly, trading vegetated habitat for bare ground decreases fishery output, but community composition shifts may not have negative effects on fishery habitat provisioning (Alvaro et al. 2025).

Changes in climate, community structure, and governance will also affect the future of blue carbon sequestration, an essential seagrass benefit (Mcleod et al. 2011). Seagrass meadows are globally significant carbon sinks; though occupying less than 0.2% of ocean area, seagrasses store between 20–40 Tg in their tissues (Gomis et al. 2025) and 665–1699 Tg of organic carbon in the top 30 cm of their sediments (Fourqurean et al. 2012, Krause et al. 2025). In addition to potential changes in seagrass habitat provisions, changes in carbon services due to shifting seagrass dominance (figure 3) will have wide-reaching effects. Persistent species have tall canopies and substantial belowground biomass, which have historically offered the most stable drawdown of organic particulates and long-term carbon storage. As shifts in relative abundance of persistent and opportunistic—and invasive (e.g., *Halophila stipulacea*)—species occur, area-specific sequestration rates may vary by two orders of magnitude (Lavery et al. 2013, Röhr et al. 2018, Bedulli et al. 2020). Further, the small canopies and shallow root systems of many opportunistic species mean that they store up to 11x less carbon in their tissues than larger persistent species (Gomis et al. 2025). Thus, an era dominated by herbaceous opportunistic seagrasses will come at the expense of long-term magnitude and stability of meadow-scale blue carbon; further, constant sediment resuspension from frequent boom-bust population dynamics may negate high productivity. ***The rise of opportunistic dominants may provide important—but reduced and increasingly temporary—standing stocks of blue carbon.*** To increase seagrass blue carbon conservation, the field needs spatially explicit ecological predictions on when and where seagrass species dominance shifts will occur and better quantitative assessment of climate change effects on global distributions of standing seagrass biomass. For example, a recent analysis has shown sediment carbon stocks to be equivalent between opportunistic species like *Ruppia* and *Halophila* and persistent species, but this finding may arise from these opportunistic species colonizing previously vegetated sediments (Krause et al. 2025). Overall, ecosystem service provisioning by degraded, invaded, or opportunistic seagrass meadows, along with the history of these sites, is a high research priority so that conservation plans and protected areas can manage existing seagrass blue carbon to be climate resilient.

Restoration and management must evolve to generate resilient seagrass futures

Global change is rendering many traditional coastal management strategies obsolete (e.g., diking to create land, hard shorelines, beach nourishment). As climate stressors intensify and conditions diverge from historical baselines, we must shift from reactive, site-specific activities to proactive, effective, and scalable strategies that cultivate seagrass meadows built for the future (figure 4). This approach requires not only new ecosystem technologies and innovative restoration techniques (Unsworth and Rees 2025, Silliman et al. 2026), but also a rethinking of which species are used, how environmental conditions are managed, and where seagrasses are expected to persist or expand. In this section, we outline three major avenues of advancement in scale, diversity, and technology needed to help seagrass managers cultivate climate-ready meadows and keep pace with the novel environmental conditions of the near and far-future.

Advancement 1: Scalable strategies to create, expand, and sustain resilient seagrass meadows. Under ideal conditions, namely clear water, low disturbance, favorable thermal regimes, and intact communities of species with mutualistic relationships with seagrass, seagrass restoration using seeds is considered the most successful and efficient way to revegetate coastal areas for species whose life histories are amenable to this approach (van Katwijk et al. 2016, Orth et

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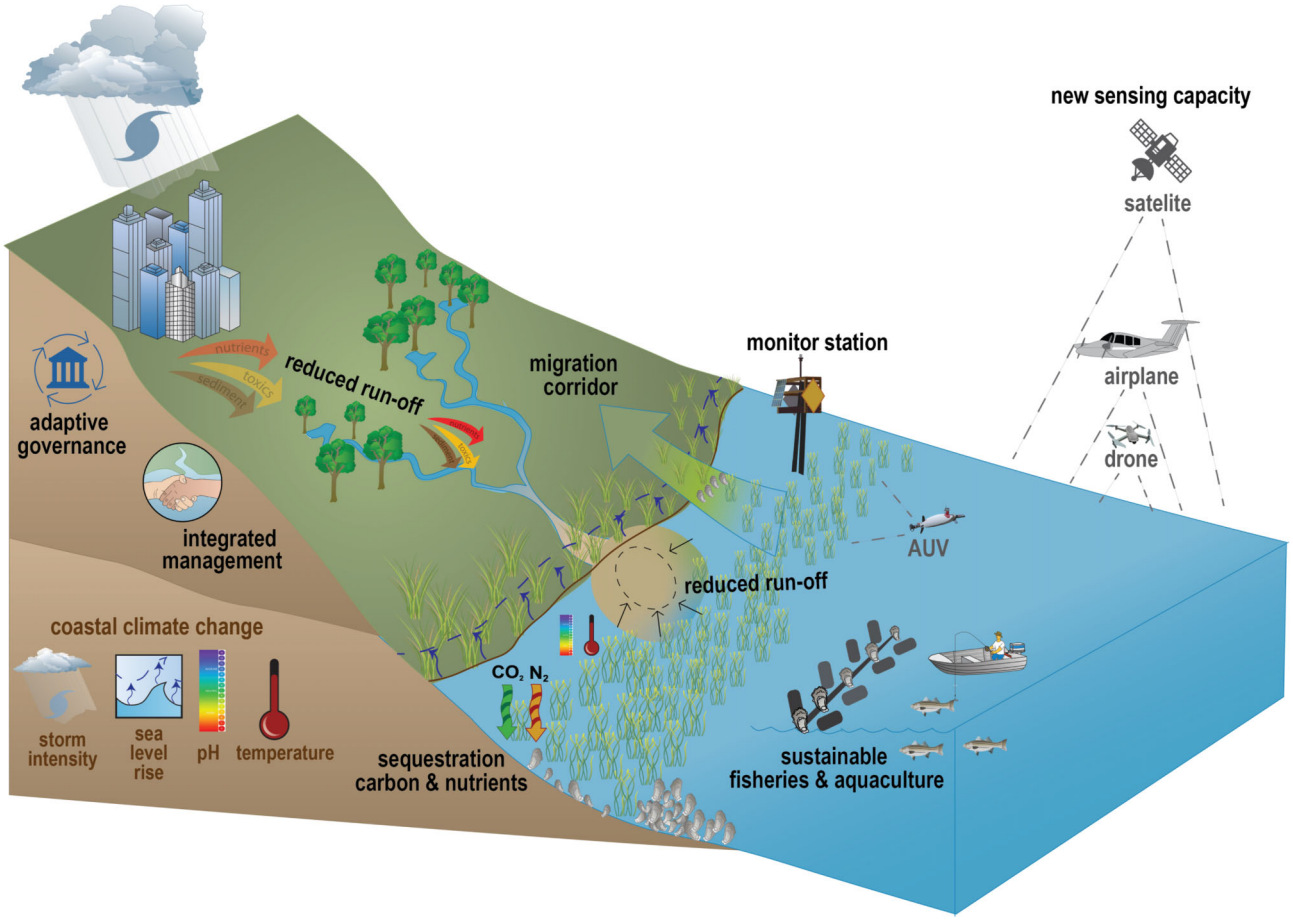


Figure 4. Depiction of a coastline with strong adaptive management plans for seagrasses under climate change effects like increased storm intensity, temperature rise, ocean acidification, and sea level rise (bottom left). Adaptive, future-facing seagrass strategies to specifically identify, analyze, and address critical uncertainties about natural resources require several simultaneous actions. Coastal managers can leverage new sensing capacity to monitor for novel environmental conditions through automated sensor systems and map changes in seagrass distribution, cover, and the physical environment through multiple types of remote sensing and autonomous underwater vehicles. These data can then be used to further develop ocean models and run scenario analyses. Collaborations with local engineers and citizen scientists to create migration corridors and living shorelines can help build cost-effective coastal resilience to sea level rise and storms. Coordinated co-restoration of climate-ready seagrasses and adjacent habitats (e.g., mangroves, marshes, oyster reefs, kelp forests) seeks to simultaneously improve carbon sequestration and nutrient filtration while amplifying sustainable fisheries and aquaculture opportunities. Integrated upstream management of nutrient and sediment inputs and adaptive governance are needed not just to protect existing meadows, but to create conditions that favor a proliferated, proactive *restoration* of lost meadows, active vegetation of bare areas, and cultivation of resilient seagrasses around the world's coastlines.

al. 2020, Valdez et al. 2020, Govers et al. 2022). Watershed and coastal zone management to support both current and future seagrass meadows still begins with managing controllable stressors. Especially in areas at thermal risk, reducing turbidity, nutrient loading, and physical disturbance (e.g., propeller scars, dredging, demersal fishing) is fundamental for both restoration and persistence of current meadows. But positive outcomes are now in doubt because climate change has added stressors that act independently from water quality. Further, climate stressors in large part cannot be managed at the local or regional level and require global cooperation (Lefcheck et al. 2017). As such, water quality improvements alone may not benefit the species most capable of persisting under novel conditions (Hensel et al. 2023, Beck et al. 2024). Most frequently, seagrass restoration interventions to revegetate degraded areas are implemented in isolation from stressor management and at small scales, leading to high failure rates and limited outcomes (van Katwijk et al. 2016, Orth et al. 2020, Valdez et al. 2020, Govers et al. 2022). Without technological investment, a deeper integration of ecological insight into the spatial and temporal variation in environmental stressors, and coordinated governance at multiple levels, past solutions are likely insufficient to meet the challenges ahead.

Expanding local seagrass restoration successes to global scales requires filling intellectual and technological gaps by engineering approaches used widely in agriculture or in terrestrial restoration (Unsworth and Rees 2025). For example, bottlenecks in large-scale planting might be addressable through development of subaqueous drones that inject or deposit seeds into the sediment (Govers et al. 2022, Mei Tan et al. 2023) or aerial drones that enable rapid broadcast seeding over large areas, mirroring forest restoration (Mohan et al. 2021). Other locally successful seagrass restoration techniques require technological advances to upscale. Suspending seagrass reproductive shoots above suitable habitat in buoys (Pickerell et al. 2005) and hessian bags (Unsworth et al. 2019a) can automate seagrass outplanting, and will be most successful if deployed across multiple hectares at

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once (Unsworth and Rees 2025). For often costly and unsuccessful seagrass shoot restoration, large-scale production of biodegradable root mat ecomimics that suppress waves and sediment mobility would allow for outplanted shoots to be spread over bigger and more hydrodynamically active areas (Temmink et al. 2020). In addition, methods to transplant large swaths of sod-based strips of seagrass, rather than individual plants, can utilize positive density dependence and may prove effective in high-energy sites and locations requiring immediate structural stability.

Scaling up restoration efficiency is just a first step, as seagrass restoration must also use species and genotypes that can survive and grow in the conditions to come, not just those of the past. These strategies require greatly expanded restoration research as many regions continue to rely on narrow species pools, particularly *Z. marina*. When historical dominants are near their physiological limits and future environmental conditions are projected to move outside those limits, efforts to restore the historically dominant species are likely to fail. In these cases, management efforts can focus on maintaining vegetated states by restoring the individuals or species that *can* tolerate current stress while the system transitions. Leveraging biodiversity-stability theory through planting fast-growing, climate-tolerant opportunists in tandem with persistent species greatly increases restoration success in high-stress conditions (Hensel et al. 2024). Similarly, applying facilitation theory yields increased success when maintaining positive interactions (e.g., positive density dependence from high-density outplants, co-planting mutualistic bivalves) and avoiding negative interactions (e.g., actively excluding herbivores or bioturbators) (Valdez et al. 2020). Importantly, only a few of the 72 described seagrass species have been used for restoration, and research on the ecology, biology, and restoration of non-dominant seagrass species lags behind the most widely used plants in restoration efforts (van Katwijk et al. 2016). Because species, population, and trait diversity have led to increased restoration success (Reynolds et al. 2012, Williams et al. 2017), experimental seagrass restoration ecology can be used to quantify the role of biodiversity in enhancing short- and long-term resilience. Under novel future conditions, high-diversity planting should stabilize sediments, sustain ecosystem functions, and buy time for long-term adaptation through climate-driven migration or the development of stress-tolerant strains. Seagrass restoration success in novel environments thus hinges on the combination of ecology-based strategies that both improve local physical conditions and leverage seagrass life histories.

Advancement 2: Genetic and microbial tools to catalyze the rise of future-ready seagrass mariculture. To further prepare meadows for future conditions, seagrass restoration science can accelerate its use of genetic tools and creative production strategies. Over the past decade, seagrass genetic research has revealed that adaptive variation, cryptic hybridization, and epigenetic mechanisms can explain restoration success and failure (Reynolds et al. 2012, Nimbs et al. 2024, Moore et al. 2025). Even though genetic engineering has transformed seed-based agriculture and forestry in the face of stressors (Mittler and Blumwald 2010, Harfouche et al. 2011), application to seed-based seagrass planting lags. Recent discoveries provide actionable insights for restoration without transgenic approaches. For example, following agrotech advancements (Wang et al. 2003), seagrass restoration yields may be improved by engineering seagrasses to mass-produce future-proof genotypes with fast initial growth or to express heat shock proteins for resistance and resilience to marine heat waves. Also, discovery of naturally occurring genotypes that reveal a strong connection between genotype and low-light tolerance and of genetic markers that can predict adaptation to extreme light regimes will support the strategic use of clonal materials for restorations (Jueterbock et al. 2021, Moore et al. 2025). Progress in genetically informed restoration will depend on collaboration not only among researchers and managers, but also with private nurseries, biotech companies, aquaculture enterprises, and governments. Thus, seagrass mariculture offers a critical platform for translating genetic and epigenetic knowledge into practice, both by expanding restoration supply chains and advancing adaptive breeding programs. Here, inspiration may come from coral systems, which have experienced much greater heat stress and for which significant technological innovations have been made (Humanes et al. 2026).

Following blueprints from kelp mariculture and shellfish aquaculture (Coleman and Goold 2019), seagrass mariculture systems can be designed to cultivate large quantities of propagules for outplanting while also serving as experimental hubs for selective breeding and assisted evolution (van Katwijk MM et al. 2021). Creating these facilities will allow researchers to grow and test genotypes under controlled conditions, accelerating the identification of traits that enhance resilience to heat stress, low light, or poor water quality. Mariculture operations could also support long-term goals such as developing "super individuals" for Arctic *Zostera* colonization or high-temperature thresholds in subtropical margins. Beyond plant genetics alone, mariculture facilities also provide an opportunity to manage sediment and plant-associated microbial communities that mediate seagrass responses to heatwaves and light limitation (Martin et al. 2018, Fuggle et al. 2023). Inoculation with beneficial microbial assemblages can improve photosynthetic performance and shift rhizosphere composition, whereas disruption of these communities can undermine seagrass resilience under climate extremes (Zhou et al. 2024). These approaches also have the potential to enhance seagrass restoration, as has been shown on coral reefs and terrestrial plant and agricultural systems (Peixoto et al. 2021, Chakraborty and Ramteke 2023). Lastly, when co-located with other sustainable aquaculture practices, like seaweed or shellfish farming, seagrass mariculture may even produce synergistic benefits like enhanced water clarity, nitrogen removal, or mutual habitat provisioning (figure 4). As climate stressors intensify, cross-sector partnerships that integrate genomics, microbial ecology, and mariculture infrastructure can bridge the gap between ecological need and restoration capacity.

Advancement 3: Use assisted migration and strategic planting to overcome colonization lags. As tools for large-scale cultivation and genotype development advance, seagrass management can seek to establish meadows in places where seagrasses will be viable in the future, not just within their historical range. Assisted migration, widely applied in forestry and agriculture (Hoegh-Guldberg et al. 2008), offers a way to overcome colonization lags and avoid prolonged states of bare ground that hinder recovery (van der Heide et al. 2007, Maxwell et al. 2017).

Situations conducive to assisted migration include (1) assisting species at their range-limits into newly suitable areas (e.g., assisting selected or genetically engineered genotypes of *Z. marina* or *Z. noltei* into sub-Arctic and Arctic Canada or Greenland); (2) migrating new species into soon-to-be suitable transitions zones (e.g., assisting *Halodule* north into warming mid-western Atlantic waters); (3) encouraging gene flow of stress-tolerant genotypes into dynamic areas or vulnerable populations (e.g., transplanting temperature-tolerant *Z. marina* from historically hot areas like North Carolina, USA to increasingly warm northern areas like Chesapeake Bay, USA); and (4) establishing

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meadows in isolated coastlines with low colonization potential and genetic exchange due to geography and/or habitat barriers (e.g., low light Georgia coastline acts as dispersal barrier for seagrass to move from Florida to the mid-Atlantic).

In many bioregions, low-hanging restoration success can be achieved by pairing assisted migration with simple coastal engineering interventions (e.g., opening protected embayments or harbors) to increase habitat availability (Valle et al. 2014). These approaches can also combine with targeted use of resilient species or genotypes to help managers recover ecosystem functions more quickly after extreme events. To support this flexibility, expanded seed-based experiments would enable practitioners with a diverse portfolio of restoration options ready to match both ecological conditions and restoration goals.

Together, scaling up seed-based restoration of climate-tolerant species, advancing genetic tools, developing mariculture, and implementing assisted migration represent a shift from reactive restoration to proactive cultivation of seagrass meadows. Rather than restoring to the past, managers can now construct future-adapted meadows that are diverse, flexible, and capable of persisting under changing and less predictable conditions. But building these systems also requires knowing when and where change is happening. As climate stressors intensify and species redistribute, restoration success will increasingly depend on an ability to detect novel conditions early, assess environment-genomic linkages to select genotypes for restoration, and anticipate how species shifts will alter the ecological dynamics of future seagrass meadows.

Early detection of climate novelty forms the new foundation of adaptive seagrass management

Modeling to understand where novel environments are conducive to long-term seagrass persistence requires tools that integrate how multiple stressors interact. Experimental and observational studies of light and temperature effects on seagrass physiology can generate "multi-stressor response surfaces" to capture these dynamics (Murphy et al. 2022, Dunic and Côté 2023). ***By modeling nonlinear performance responses across changing physical conditions, multi-stressor response surfaces can help managers in thermally sensitive regions quantify when and where improving water quality can mitigate cumulative stress.*** For example, *Z. marina* survival thresholds shift dramatically across combined light–temperature gradients, and these multi-stressor response surfaces are helping managers assess how maintaining light availability and sediment stability will support continued growth and photosynthetic function even under warming conditions (Dunic and Côté 2023). In data-rich regions or for well-studied species, combining long-term seagrass and water quality monitoring can improve forecasts by identifying these multi-axis ecological tipping points (Lefcheck et al. 2017). In regions undergoing other aspects of environmental change, multi-stressor response surfaces could be expanded and refocused to include sedimentation, salinity, or wave energy.

Numerical ocean models provide a complementary pathway for identifying ecological thresholds and forecasting future conditions. By resolving interacting physical processes such as circulation, mixing, and stratification, these models help explain the mechanisms driving thermal, chemical, and optical stress in seagrass habitats. When paired with long-term monitoring and species distribution models, numerical ocean models can produce dynamic, spatially explicit forecasts of environmental suitability (Carr et al. 2012, Jabbari et al. 2024). Additionally, numerical model output can be combined with seagrass stress-response models to predict performance across large spatial scales, such as generating high-resolution heat risk maps under both contemporary and future conditions (Wong et al. 2026). Building on these existing spatial tools, emerging initiatives like Digital Twins of the Ocean will further enhance our predictive capabilities by integrating numerical model outputs with broader, real-time ecosystem-level data (Tzachor et al. 2023, Boon 2024). By facilitating complex scenario analyses and "what-if" predictions, Digital Twins of the Ocean offer a framework to help identify tipping points, define "safe operating spaces" for dominant species, and prioritize management actions that delay or avoid ecosystem state change.

Regular monitoring of seagrass extent and species composition is critically important for detecting early evidence of ecological transitions under climate change (Dolch et al. 2013, Orth et al. 2022, Duffy et al. 2026). Many regions of the world are currently unmonitored or monitoring efforts do not occur regularly. In these regions, data deficiencies may miss early warnings of future state shifts. However, even areas with robust regular monitoring programs often fail to quantify relative abundance of different species in the meadows, and so can also miss large-scale shifts in species composition that herald major changes in meadow structure and function (e.g., Hensel et al. 2023). Proactive monitoring of species assemblages and corresponding traits (e.g., tolerances, life history) is critical for both detecting ecological shifts and forecasting future community reorganization.

Track and map the leading edge of change, using data to stay ahead of substitutions and expansions

Advances in imaging, ecological monitoring, and ocean modeling have the potential to allow managers to track species shifts and anticipate future meadow expansion or contraction. Aerial and drone-based mapping capable of detecting changes in species identity and relative abundance can move beyond coarse measures of extent to more ecologically meaningful indicators of meadow condition and ecosystem function (e.g., Essential Ocean Variables, such as seagrass cover and composition (Duffy et al. 2026)). These emerging tools are increasingly complemented by expanded food web monitoring like seine or trawl surveys, epifaunal counts, and drone surveys of megafauna to detect early shifts in trophic structure and habitat quality (Orth et al. 2022, Duffy et al. 2026).

At larger scales, satellite imagery and uncrewed aerial vehicles (UAVs) can identify new colonization fronts, and numerical ocean models can predict future shifts in ocean temperature, currents, and light availability. For example, the northward expansion of *Halodule wrightii* in the mid-Atlantic could be tracked by combining satellite detection (e.g., Landsat, Sentinel-2) with UAV-based species confirmation, then linked to ocean model outputs to project future trajectories (e.g., Dierssen et al. 2003, Williams et al. 2012, Hill et al. 2017). Oceanographic predictions like bottom temperature, stratification, light attenuation, and current direction can serve as inputs to seagrass distribution models and help define physical indices relevant to colonization and persistence. In Arctic regions, coupling these approaches can help predict when and where Pacific species may reach high-latitude estuaries in Greenland or northern Canada. In more isolated or understudied areas, climate analogues that use present-day conditions elsewhere to anticipate future ecological states (Fitzpatrick and Dunn 2019) could be a valuable tool that allows managers to anticipate and

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communicate future trends in meadow structure. Combining these data with other physical and biological data can further strengthen dynamic modeling, applications, and digital twins.

Integrating these tools into management systems can improve both local action and regional coordination. Numerical ocean models and ecological forecasts can be used not only to guide restoration siting and species selection, but also to prioritize areas for conservation or regulation. Replacing static maps with dynamic and predictive models built from layered and functionally relevant datasets can improve permitting and long-term zoning decisions. Mapping also shapes public communication and policy framing. For instance, distinguishing climate-driven range expansions from invasive spread can affect a species' legal status, influence restoration eligibility, and alter stakeholder responses. Further, resolving regulatory barriers to moving genetic and species material across jurisdictions will enable adoption of frameworks like assisted gene flow/migration to enhance restoration outcomes. Ultimately, linking environmental monitoring, oceanographic forecasting, and seagrass ecology allows predictions and scenario analyses that enhance management actions. Building on existing tools (e.g., Marzan, InVest, Ecopath) by including seagrass ecological knowledge can create an integrated modeling approach that empowers managers to anticipate and plan for change instead of being forced to react to change. As climate-driven reorganization accelerates, predictive and spatially explicit frameworks will be essential to designing a coastal seascape that sustains ecosystems, supports livelihoods, and contributes to long-term climate resilience. Achieving this kind of forward-looking, spatially explicit management will require governance systems that are flexible, well-resourced, and aligned with ecological realities.

Governance, policy, and economies must catch up with seagrass ecology

Translating seagrass restoration potential into real climate mitigation requires governance actions that integrate seagrasses into both national climate adaptation plans and local socio-economic systems. Effective policies can unlock restoration opportunities, enable accurate carbon accounting, and provide roadmaps for large-scale investment in seagrass restoration. Some countries are already advancing this agenda: Seychelles has committed to 100% protection and monitoring by 2030 under the Paris Agreement (Government of Seychelles 2021); Belize plans to enhance seagrass carbon sequestration through land-use management and restoration (Belize National Climate Change Office 2021); and the European Union is incorporating coastal blue carbon into its greenhouse gas reporting frameworks (Picourt et al. 2021). Although these actions hold promise, ***most seagrass governance remains fragmented or insufficient.*** In the United States, federal commitments to resources like biodiversity and blue carbon are vague, but at the state level, Virginia has established the world's first certified seagrass carbon credit market (Code of Virginia 2020). In Australia, national strategies recognize blue carbon's importance but defer implementation to the states, resulting in uneven progress (NSW Department of Planning and Environment 2022). Although blue carbon provides a strong, relatively recent incentive for increased seagrass stewardship, seagrass governance must extend past blue carbon value and into co-benefits such as fisheries habitat, nitrogen sequestration, and avoided erosion, that is, nature-based credits (Kerns et al. 2025). Without coordinated policy frameworks, investment incentives, broadened perspective on the value of seagrass resources, and long-term commitments, the next generation of seagrass climate solutions may remain out of reach. Encouragingly, many of these enabling conditions exist in agriculture, aquaculture, and forestry. With the right support, governance systems can replicate and adapt proven models to accelerate scalable cultivation of resilient seagrass meadows.

As climate and ecological pressures mount, governance systems have an opportunity to build the industries and infrastructure for scalable seagrass restoration. Emerging sectors such as seagrass mariculture, sod and seed production, automated planting technologies, and genetic screening services can scale restoration while creating jobs and diversifying coastal economies. As available land for terrestrial offsets shrinks (IPCC 2023) and seagrass restorations have potentially large return on investment (Orth et al. 2020), ***policy and investment frameworks could unlock hundreds of thousands of additional hectares for restoration and natural capital finance.*** Early investment incentives like blue carbon and nature credits, restoration subsidies, habitat offset banking, or public–private partnerships can de-risk these markets and expand participation. Long-term commitments to restoration targets, permitting reforms, and coastal zoning can help governments designate priority areas for seagrass planting. Supply chains can be accelerated through investment in seagrass nurseries, mariculture hubs, and centralized propagule banks, modeled after shellfish hatcheries or native plant nurseries. With the right incentives and coordination, seagrass blue carbon could anchor the next generation of coastal climate solutions that advance ecological resilience while catalyzing economic opportunity.

Conclusion

Seagrass ecosystems are poised to expand their ecological and economic influence under climate change. As persistent species decline and climate-tolerant opportunists rise, meadows are already reshaping themselves, from their composition to food webs to ecosystem services. Megaherbivores are migrating, blue carbon dynamics are shifting, and seagrass-dependent fisheries are being redefined in real time. Currently observed ecological transformations are likely not temporary but rather are previews of the coastal futures for which we must now plan. Because stressors are strengthening, social and financial capital are increasing, polar habitats are opening, and restoration technologies are improving, the scope of seagrass stewardship must expand. Traditional tools like nearshore protection and run-off control remain essential, but they are no longer enough (Brown et al. 2013, Buelow et al. 2023). Future success depends on scaling strategies that are adaptive, anticipatory, and built for novel conditions, such as actively cultivating climate-resilient meadows, monitoring for early warning signs of environmental change, mapping where new habitats are likely to form, and using ocean models to generate predictions of where and when conservation and restoration are most likely to yield positive results. But it also means closing key knowledge gaps: understanding the transition to formerly non-dominant species and how they may function under similar stress, predicting outcomes of climate-driven substitution, and investing in genetic tools and assisted migration. Without these advances, seagrass management risks falling behind ecological reality.

Seagrasses face the same threats as other coastal ecosystems and offer rare potential for scalable, science-based recovery backed by a strong foundation of scientific and management successes. With their

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global reach, management responsiveness, and measurable benefits to fisheries, coastal protection, and carbon storage, seagrasses are positioned to play a major role in a new era of climate-aligned coastal management. Seagrass futures will depend not on what has been done in the past, but on how quickly and ambitiously we act now.

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Supplemental materials

Supplemental data are available at *BIOSCI* online.

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