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Review Article

To what extent is coastal wetland biodiversity endangered by climate change? How can we boost the resilience of coastal ecosystems?

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Abstract

Global projections indicate that between 20% and 90% of current coastal wetland areas may be lost due to sea-level rise (SLR), depending on the severity of the scenario. Warming, acidification and other global change stressors such as eutrophication also show negative impacts on coastal wetlands. Such a scenario poses a dramatic threat to biodiversity, particularly in deltas and estuaries, which are vital for the conservation of coastal species and ecosystem functions. This paper summarizes the main impacts of climate change on coastal wetland biodiversity, with focus on vegetation, birds and fish. Management options to cope with climate change impacts are also summarized. Many coastal wetlands are already undergoing degradation or disappearing due to the combined impacts of climate change and other global drivers, including SLR, subsidence, sediment deficits, coastal erosion, and salt stress. Coastal squeeze, the restriction of natural habitat migration due to human infrastructure and natural constraints, also threatens these ecosystems. Enhancing the resilience of coastal wetlands involves improving hydrological connectivity, increasing sediment inputs, boosting wetland plant productivity, and allowing space for natural coastal processes. However, these efforts are highly dependent on active conservation, management and restoration policies. The future of coastal wetland biodiversity will vary significantly based on the climate scenarios that unfold, and the policies implemented.

Highlights

• Coastal wetland biodiversity has severely declined due to habitat loss and other aspects of global change. Remaining wetlands are endangered by climate change impacts such as sea level rise.
• Salt marshes are the most endangered coastal wetlands in Europe, along with their associated flora and fauna. The Mediterranean coast may lose up to 90% of those habitats by the end of the 21st century due to sea level rise.
• Boosting coastal wetland resilience is critical to avoid biodiversity loss. To do this requires increasing the pace and scale of coastal wetland restoration, and enhancing the ecogeomorphic dynamics through the increase of hydrological connectivity and the supply of sediments to the coasts.

Key words: Adaptation, biodiversity, coastal ecosystems, global warming, sea level rise

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Introduction

Coastal wetland biodiversity, present status and historical losses

More than a billion people live within 10 km of the sea, and over one-third of humans live within 100 km, illustrating humanity's reliance on coastal infrastructure and ecosystems (Cosby et al. 2024). As a result, 40% of coastal areas are developed globally, making their coastal wetlands particularly vulnerable to degradation. Using the WET Index (Dixon et al. 2016), it has been calculated that marine and coastal wetlands have declined by about 35% between 1970 and 2015 (Ramsar Convention on Wetlands 2018). Until recently, climate change played a minor role in coastal wetland loss compared to other factors, including wetland reclamation, pollution, and altered hydrology and sediment balance (Yang et al. 2005; Day et al. 2011; Kondolf et al. 2014; Schuerch et al. 2018). Climate change effects are expected to increase, however, especially as sea-level rise (SLR) and warming accelerate.

Wetland types

Coastal wetlands constitute a transition between terrestrial and marine ecosystems (Basset et al. 2013; Hopkinson et al. 2019) and are found in sheltered areas with low-energy marine processes or where the fluvial sediment supply is large (Masselink and Gehrels 2014). Macroclimatic conditions globally govern the presence of habitat types within these wetlands (Osland et al. 2016): seagrass meadows, intertidal flats, salt marshes, mangrove forests, and freshwater tidal wetlands. The distribution and abundance of plant species and communities within these ecosystems vary based on factors such as temperature at broad scales, and locally – where transitions may be sharp – by flooding regime, salinity, and substrate. Here, we focus on the main coastal wetland habitats present in Europe, with emphasis on salt marshes and tidal flats (Fig. 1), but also reference other habitats and regions to give broader insight on climate change's impacts. We address the main biodiversity components for which extensive literature on climate change and other global change impacts exist, especially vegetation, birds and fish.

Salt marshes primarily occur in temperate regions but also occur in tropical, especially arid or monsoonal areas landward of the mangrove belt (Chapman 1977). They primarily occur in the intertidal zone but can extend inland over large saline areas, commonly found in deltas. Estimates of their area vary up to 400,000 km^2 (Duarte et al. 2013) and 550,000 km^2 (Ramsar Convention on Wetlands 2018), but more recent assessments suggest the extent is less (53,000 km^2; Worthington et al. 2024). Vegetation varies from herbaceous (*Scirpus*, *Cyperus*, *Distichlis*, *Juncus*, *Phragmites*, *Sporobolus*, *Triglochin*, etc.), to low scrub (*Salicornia*, *Halimione*, *Atriplex*, *Suaeda*, etc.), to shrubs (*Tamarix*, *Baccharis*, *Melaleuca*, *Casuarina*, etc.). Salt marshes have experienced significant area losses estimated at 1–2%/year over the past 50 years (Duarte et al. 2013). Global data indicate that at least 42% of salt marshes have been lost or degraded (Temmink et al. 2022).

Freshwater tidal wetlands occur in the upper reaches of estuaries and in river deltas, between non-tidal freshwater wetlands and tidal oligohaline wetlands (Odum et al. 1984; Barendregt and Swarth 2013; Day et al. 2024). There is no



Figure 1. Mediterranean *Salicornia*-type salt marsh (Ebro Delta, Spain).

comprehensive global inventory of tidal freshwater wetlands as they are often grouped with other wetland types (Baldwin et al. 2009; Hopkinson et al. 2019; Day et al. 2024). In Europe, primary locations are in the estuaries of large rivers along the coasts of the Atlantic, the English Channel, and the North Sea, including regions in Germany, the Netherlands, Belgium, and France (Struyf et al. 2009).

Seagrass meadows occur in permanently flooded estuaries and coastal lagoons, and the lower intertidal zone. Their global area is estimated to be between 177,000 and 600,000 km^2 (Duarte et al. 2013). These ecosystems host a few perennial angiosperms (*Posidonia*, *Cymodocea*, *Halophila*, *Zostera*, *Ruppia*, etc.) along with a diversity of macroalgae and marine fauna.

Tidal flats are intertidal areas of sand, rock, or mud without macroscopic vegetation, and are estimated to cover between approximately 128,000 km^2 (Murray et al. 2019) and 458,000 km^2 (Ramsar Convention on Wetlands 2018).

Wetland biodiversity

The vegetation in coastal wetlands is highly varied, from submerged and emergent macrophytes to shrub formations and forests, with highly specific compositions that differ among types of wetlands and across geographic regions. Beyond structural and compositional diversity, the vegetation performs critical ecosystem services, including organic matter production, sediment trapping

and stabilization, reduction of wave and current energy, and the provision of food resources and habitats for wildlife (e.g., Barbier 2019; Hopkinson et al. 2019; Clarke et al. 2021).

Besides supporting diverse plant assemblages, these highly productive ecosystems are crucial for many animals, including numerous bird and fish species, fewer herptile and mammal species, and many invertebrates (Barbier et al. 2011; Mitsch and Gosselink 2015; Elphick et al. 2022). Fish biodiversity within these ecosystems not only maintains ecological interactions but also supports local fisheries, which are a significant source of food and income for coastal communities worldwide (Colvin et al. 2019; Owusu-Achiaw and Osei-Owusu 2023; Bozzeda et al. 2024).

Bird use of coastal wetlands varies seasonally and depends on the tidal cycle, with birds moving between habitats as water levels rise and fall (Elphick et al. 2022). Mudflats frequently support the greatest bird densities, especially during the nonbreeding season, when huge flocks of waders gather to feed on invertebrates. At high tide, these birds move to higher-elevation habitats that remain unflooded, often roosting in dense packs until the tide falls. Waders also feed in these other coastal habitats, with some species especially likely to be found on beaches or in saltmarsh pools. Waterfowl also occur at high densities in coastal wetlands during the nonbreeding period, with dabbling ducks often foraging in flooded salt marshes, while diving ducks use deeper water. Some geese feed on saltmarsh vegetation when the marsh platform is unflooded, while others forage on seaweed or seagrass beds. Various other waterbirds also feed on mudflats and salt marshes, though generally not in such high densities as waders and waterfowl.

Some species of wader and waterfowl nest in tidal wetlands, but most migrate to grassland, boreal, or tundra habitats to breed. Salt marshes do not provide nesting habitat for many species, but some of those that do nest in this habitat are rarely found elsewhere, particularly in North America where endemism in saltmarsh vertebrates is most common (Greenberg et al. 2006a). Some gulls and terns nest and roost in salt marshes, and raptors are often drawn to coastal wetlands to prey on the large flocks of waders and ducks.

Present impacts of climate change on coastal wetland biodiversity

Climate change already presents a significant threat to coastal wetland biodiversity (Kibria and Yousuf Haroon 2017; Kang et al. 2024), altering the distribution and abundance of many species. Functional diversity – the range of ecological roles that species perform – is particularly vulnerable to the effects of climate change. High functional diversity and redundancy – whereby multiple species can play the same role – bolsters the resilience of wetlands, thus helping to sustain ecosystem stability and productivity even as environmental conditions shift (Pelletier et al. 2020). This diversity is essential for supporting the intricate relationships within wetlands and for providing critical ecosystem services, such as fisheries and water purification.

Coastal wetlands are vulnerable to various climate change impacts, including rising temperatures and sea level, as well as changes in the frequency and/or intensity of extreme events such as heatwaves, droughts, storms, and heavy rainfall (Day et al. 2008; Brito et al. 2012; Newton et al. 2014). Low-elevation

habitats including barrier islands, beaches, coastal lagoons, deltas, mudflats and salt marshes are particularly threatened. These pressures affect coastal wetland biodiversity by exacerbating erosion and flooding, changing sediment distribution, and increasing salinity and heat stress, among other effects. Other human activities often aggravate the impact of climate change, especially through activities such as water abstraction, water diversion, and dams on rivers, which can cause saltwater intrusion into coastal aquifers, soil salinization, altered flooding regimes, and reduced sediment supply (e.g. Park et al. 2005; Mastrocicco and Colombani 2021).

The aspects of climate change for which a lot of information about coastal wetlands is available are SLR and increasing air and water temperatures (McKee et al. 2012; Osland et al. 2022). Pressures such as altered hydrology (Zhang et al. 2019), changes in salinity (Herbert et al. 2015) and water quality (Lloret et al. 2008), and changes in sedimentary dynamics (Day et al. 2008) are less well studied, although clearly important. Soil and water hypersalinity, for example, may promote the dieback of nontidal marsh plants in areas expected to experience seasonal declines in precipitation (Touchette et al. 2019).

Vegetation

Monitoring data from over 390 sites suggest that climate change negatively affects all wetland plant communities (Birnbaum et al. 2021). Increased salinity and flooding are major ongoing impacts of SLR and warming on salt marshes. The change in water level can benefit salt marshes connected to the sea but harm isolated marshes that have lower rainfall and higher evapotranspiration. In a disconnected wetland (Nueva Lagoon in southern Spain), salinity increased from 4.5 $g \cdot l^{-1}$ in 2003 to 7.5 $g \cdot l^{-1}$ in 2008, corresponding to approximately 20% of species potentially affected (Amores et al. 2013). In an experiment, Gedan and Bertness (2009) found that warming reduced Shannon diversity in salt marsh vegetation by 44–74%, favouring *Spartina patens* growth over forb panne species.

SLR is also already exerting a significant effect on plant communities and the survival of wetland vegetation facing SLR is strongly correlated with the availability of suspended matter for vertical accretion and the capacity of plant species to migrate inland (Craft et al. 2009; Lovelock et al. 2015). In transitional waters, species richness is usually low at higher salinities and species are highly sensitive to salinity changes, although productivity is high (Whitfield et al. 2012; Olli et al. 2019). There are specific adaptations to these environmental conditions, however, with rare and endemic species tolerant to specific ranges of flooding and salinity (e.g., *Limonium* spp. and *Salicornia* spp. in salt marshes). Warmer conditions tend to favour C4 over C3 plant species, however, salinity stress and alternating flooded and dry conditions make it difficult to predict how plants growing in salt marshes will respond (Erickson et al. 2007; Sendall et al. 2024).

Rising sea levels compromise the resilience of salt marshes since an excess of flooding can decrease plant productivity. Plants, however, also play a major role in maintaining marshes above sea level due to their capacity to enhance marsh accretion (Cahoon et al. 2021; Ibáñez and Caiola 2021). Plants with fibrous roots, for example, accrete sediment more efficiently than those with tap roots, and perennial plants are more efficient than annuals (Pang et al. 2023).

Some rare and endemic species tolerant of specific flooding and salinity regimes (e.g., *Limonium* spp.) are threatened by coastal erosion and changes in hydro-saline conditions (Baumberger et al. 2012; Al Hassan et al. 2017).

Increased coastal erosion, and SLR are also the main identified causes of tidal flat degradation and loss. Between the 1980s and 2016, one-sixth of the habitat was lost from areas with sufficient information for analysis (Murray et al. 2019). Less is known about the effects of climate change on tidal flat vegetation, although net gains of tidal marshes (+ 200 km^2) have been recorded (Murray et al. 2022) resulting from the rapid expansion of introduced *Spartina alterniflora* partly on tidal flats across China's intertidal zone. Encroachment of seagrass onto tidal flats may also be expected because of SLR.

Tidal freshwater wetlands rely on the dynamic balance between river flows and tidal forces. Climate change affects this balance though SLR and altered river discharge, particularly reductions in flow (Barendregt and Swarth 2013). These changes result in greater seawater intrusion and increased salinity within river channels. Reduced rainfall in the watershed diminishes freshwater inputs, further contributing to elevated salinity (Neubauer and Craft 2009; Woods et al. 2020). Grieger et al. (2020) synthesized the impacts of climate change on tidal freshwater wetlands. Increased salinity affects the species composition and structural organization of plant communities, particularly forests. Although tree survival may still be possible, salinization has led to selective tree mortality, reduced recruitment, and the replacement of understory flora by herbaceous and shrub species typical of salt marshes (Williams et al. 2003; Langston et al. 2017; McCarthy et al. 2022).

Effects on coastal wetland vegetation are further complicated by the interaction of increased CO_2 concentrations in the air with climatic changes, such as higher temperatures. This combination may result in higher plant productivity, but other changes can cause enhanced coastal erosion, altered flooding height and frequency, increased water and soil salinity, etc. (Anthony et al. 2009, McKee et al. 2012; Cazenave and Le Cozannet 2013; Newton et al. 2014). In some coastal wetlands, new macroclimatic conditions may result in the replacement of plant species, thus affecting ecosystem services and resilience (Osland et al. 2016).

Large losses of seagrass meadows have been registered due to a number of human impacts (Waycott et al. 2009; Duarte et al. 2013; Dunic et al. 2021), including increased nutrient inputs, direct destruction, alteration of sedimentary dynamics, and invasive species (Schramm and Nienhuis 1996; Orth et al. 2006; Boudouresque et al. 2009; Le Fur et al. 2018; Stipcich et al. 2022). Reduced light resulting from increased water depth is also an issue, and is relatively greater in shallow lagoons than in the open sea, but remains limited compared to the impact of eutrophication (Le Moal et al. 2019).

Higher temperature reduces oxygen availability, enhances nutrient fluxes from the sediment into the water column, and favours phytoplankton, aggravating the frequency of anoxic crises due to eutrophication (Lloret et al. 2008; Lacoste et al. 2023). These events constitute a major disturbance leading to important mortality of benthic life, including seagrasses (*Zostera nolteii*, *Z. marina*, *Ruppia maritima*), and fish (Kemp et al. 1992; Souchu et al. 1998; Plus et al. 2003; Moore and Jarvis 2008; Derolez et al. 2020). Algal blooms are further enhanced by nitrogen regeneration resulting from the impacts of high temperature and low oxygen solubility on benthic nutrient recycling in coastal lagoons (Magri et al. 2020).

In the open sea, seagrass losses have been recorded following marine heatwaves (Mayot et al. 2005; Marbà and Duarte 2010; Strydom et al. 2020; Marbà et al. 2022). However, in *P. oceanica*, mass flowering has been shown to be induced by warming (Ruiz et al. 2018; Tomas et al. 2024) and rare pseudovivipary has been observed in the Western Mediterranean after an unprecedented warming event (Tomas et al. 2024). This strategy combining sexual and asexual reproduction can contribute significantly to both meadow maintenance and adaptation to warming (Ballesteros et al. 2005; Sinclair et al. 2016; Tomas et al. 2024).

Finally, there is evidence that rapid SLR is causing the loss of seagrasses in some parts of the world (Capistrant-Fossa and Dunton 2024). Some seagrass species such as the Mediterranean *P. oceanica* have a high capacity to trap sediments and store organic carbon in the soil (Serrano et al. 2016).

Fauna

Although many coastal bird species are likely affected by SLR, few have been studied in detail. Nonetheless, nesting declines in species as varied as flamingos (Kumar 1986), terns (Scarton 2010), and sparrows (Field et al. 2017) have been directly linked to sea level changes. Reduced feeding habitat also coincides with declining populations, although it is not always clear that declines should be attributed to SLR (Norris et al. 2004).

Sometimes, habitat loss may not be as important as the demographic consequences of increased flooding. Most birds that breed in coastal areas build nests near the ground, and nest flooding is common (Greenberg et al. 2006b). van de Pol et al. (2010) showed that this risk has increased for six saltmarsh species in the Wadden Sea, with increases more than doubling for Eurasian oystercatchers *Haematopus ostralegus*, sufficient to cause population declines. Similar effects likely apply to many coastal wetland birds (e.g., Franklin and Noske 2000, Bayard and Elphick 2011). Drought has also been shown as a climate change driver affecting bird populations; for instance, drought events have been shown to favour the dispersal of the glossy ibis *Plegadis falcinellus* to Europe (Santoro et al. 2013) (Fig. 2).

The ways in which climate change influences fish biodiversity are multi-layered and interconnected. Temperature variations can directly affect fish physiology, while changes in habitat structure and water chemistry can disrupt species interactions and alter ecosystem dynamics. Among the most frequently mentioned impacts are rising temperatures and decreasing oxygen levels. SLR and ocean acidification also pose substantial threats to fish biodiversity. For example, increased absorption of CO_2 leads to water acidification, which can impair fish sensory functions and behaviour, further complicating their survival (Silva et al. 2018). Developing successful conservation and management strategies requires a deeper comprehension of these processes.

The impacts of climate change on coastal wetland fish biodiversity, especially rising water temperatures, altered salinity, and increased frequency of hypoxic events, are already evident in many regions. Profound changes in these parameters are likely disrupting the metabolic rates and reproductive cycles of fish, causing changes in growth patterns, timing of spawning, and larval development (Pörtner and Farrell 2008; Somero 2010). Long-term fisheries data have frequently illustrated the impact of climate change on fish stocks dependent on the nursery habitat provided by coastal wetlands. For instance, in the



Figure 2. Glossy ibis in Camargue wetlands (Rhone Delta, France).

German Wadden Sea, where coastal wetlands are very important in supporting coastal fisheries, the growth and abundance of a non-migratory eelpout *Zoarces viviparus* declined when summer temperatures and dissolved oxygen exceeded the upper and lower thresholds, respectively, with larger individuals the first to be harmed (Pörtner and Knust 2007).

SLR can cause substantial shifts in coastal habitats, altering environmental factors that influence community structure and the population dynamics of certain fish species (Shenker 2009). For instance, as salinity changes, nursery habitats like mangroves and marshes may be lost, reducing safe zones for juvenile fish that rely on these protected areas for food and shelter (Abdullah-Al-Mamun et al. 2017). Rising salinity can place additional stress on freshwater and estuarine species, decreasing populations and changing community composition.

Future scenarios and potential impacts under accelerated climate change

Sea-level rise

Predictions from the latest Intergovernmental Panel on Climate Change reports (Masson-Delmotte et al. 2021; Ali et al. 2022) indicate that global SLR will average between 40–46 cm and 79–81 cm by 2100, and between 56–62 cm and 122–127 cm by 2150, depending on the greenhouse gas emissions scenario (Representative Concentration Pathway 2.6 and 8.5, respectively). The impact of SLR on coastal wetlands will also depend on topography, potential for habitats to migrate inland, catchment management, etc. (Schuerch et al. 2018). Passive inundation models, however, suggest that 20–90% (for low and high SLR scenarios, respectively) of the current coastal wetland area will be lost (Spencer et al. 2016; Temmink et al. 2022).

Other research suggests that a 60% increase in area is possible if high-end estimates of the area available for marsh expansion are correct and current sediment supply persists, but that losses could reach 30% by 2100 with no additional space for marsh migration (Schuerch et al. 2018). Another recent study found that marsh sediment accretion matches SLR, but subsidence also increases with SLR, constraining elevation gain for marsh survival to less than 10 mm per year (Saintilan et al. 2022). The effects of SLR also vary from place to place and depend on the magnitude of relative SLR after accounting for subsidence, coastal morphology, and human interventions, among other factors. These impacts can be particularly severe where the tidal range is small and accommodation space is limited, such as the Mediterranean, where depending on climate mitigation scenarios, widespread coastal marsh loss is projected, ranging from 8% to 92% of current extents (Schuerch et al. 2025).

Coastal wetlands could potentially migrate inland, but human infrastructure often prevents this shift causing the coastal squeeze (Torio and Chmura 2013). As SLR rates accelerate, sediment accumulation may be insufficient to maintain the hydrosedimentary balance, leading to the disappearance of certain wetlands and beaches. This underscores the importance of maintaining and restoring flows of water and sediment from rivers to the sea, which have been significantly reduced in most basins due to the construction of dams (Rovira and Ibáñez 2007). Protecting the coast from SLR can itself alter coastal wetlands; SLR and river flooding can increase flooding in areas affected by subsidence and surrounded by dikes, especially during extreme events that cause dikes to break (Pont et al. 2017).

Temperature increase

In confined coastal systems (marshes, lagoons, and bays), a greater impact of warming can be expected due to shallow depths and small volume. Data on temperature trends are scarce for these ecosystems but modelling studies show a higher water temperature increase than in the open sea (Shalby et al. 2021). For a set of 10 Mediterranean lagoons, hydrological modelling results suggest that on average the water temperature increase will be 15% greater than that of the open sea (Ferrarin et al. 2014). The general trend is for water temperature in lagoons to match air temperature trends with short time lags. Ocean warming rate in coastal areas has been reported as 0.17 ± 0.11 °C/decade (Liao et al. 2015) while higher warming rates have been recorded in enclosed seas (0.36 ± 0.06 °C SE /decade in Cyprus, Mediterranean Sea) and 0.26 ± 0.06 °C SE /decade in the Gulf of Aqaba (Red Sea) (Nguyen et al. 2020). However, the increased intensity and duration of marine heat waves might have more severe impacts on biodiversity than the average seawater temperature (Smale et al. 2019; Fragkopoulou et al. 2023).

Expected impacts of warming on coastal wetland ecosystems include increased respiration relative to photosynthesis, reducing net primary production; composition shifts towards species adapted to higher temperatures; mortality of species, especially fish and bivalves, susceptible to extreme temperatures and increased hypoxia; shifts in the metabolism of organisms, the distribution of ecological niches, trophic interactions and the structure of food webs, species distributions, and biogeochemical cycles; and changes in the hydrology and salinity of wetlands, lagoons and bays (Eisenreich 2005).

Species that cannot move elsewhere or compete will face increased risk of extinction. Changes in community composition can alter biogeochemical cycles and energy transfer (Viaroli et al. 2001). Furthermore, alteration of biogeochemical processes can affect water quality and the adaptability of species. Increased metabolic rates may also affect the mineralization rates of organic matter while increasing nutrient availability and enhancing oxygen deficits in many coastal lagoons. Greater availability of nutrients can favour the proliferation of macroalgae, causing dystrophic crises and harmful microalgae blooms during colder periods (Lloret et al. 2008). The warming of coastal waters and the increasing frequency of extreme temperatures (marine heat waves) can be an important stressor for aquatic species, which occur more frequently in temperate, subtropical, and tropical coastal wetlands.

Other potential impacts

Other expected impacts of climate change on coastal wetland biodiversity may result from changes in precipitation and increase in CO_2 concentration and acidification. Precipitation effects include changes in water balance, the transport of dissolved nutrients to coastal ecosystems, and sediment transport from the river basin to the coast. Altered rainfall and river flow can increase flooding risk in coastal areas or enhance the effects of drought. Extreme events can alter the balance of salinity and nutrients in coastal lagoons and affect the survival of marine algae (Short and Neckles 1999). Prolonged drought can reduce water and nutrient supplies (Stefanova et al. 2015), decreasing phytoplankton production with negative effects on secondary production.

Increasing CO_2 levels also could enhance photosynthesis and plant production in coastal wetlands. Ratliff et al. (2015) suggests that doubling the CO_2 concentration will increase both above- and belowground biomass, producing higher rates of vertical accretion and greater deposition of suspended inorganic sediments. Other studies indicate that C3 plants will benefit more from higher CO_2 levels and could displace C4 species (FitzGerald and Hughes 2019). However, increased acidification in estuarine and coastal waters due to increased CO_2 levels might reduce the N removal function of these ecosystems, exacerbate eutrophication, and accelerate global climate change (Wu et al. 2022). Interestingly, seagrass beds may be more resilient to ocean acidification than other ecosystems, though the effects depend on species. For instance, prolonged ocean acidification exposure enhanced *P. oceanica* seedling resilience to marine heat waves. Current CO_2 concentrations and elevated temperatures induced stress in *P. oceanica* seedlings, impacting photosynthesis and respiration, but ocean acidification could mitigate the impact of warming in the future, enhancing *P. oceanica*'s resilience to climate change (Pazzaglia et al. 2025).

Consequences for vegetation

The primary expected impacts of climate change on coastal wetland vegetation result from changes in air and water temperature, flooding, and salinity regimes resulting from SLR and changes in the water budget via precipitation and evapotranspiration regime. Salinization of wetlands is already happening and will increase globally (van Dijk et al. 2015), leading to profound impacts on

vegetation structure, species richness, and seedbanks (Anderson et al. 2022; Zhao et al. 2022; Tootoonchi et al. 2023).

Saltmarsh plants are very sensitive to flooding and salinity regimes and are predicted to experience longer periods of inundation and increased summer salinities under SLR (Cayan et al. 2008). Saltmarsh vegetation will therefore be especially affected through inundation and salinity changes, which vary with elevation, and by temperature increases that affect species with different photosynthetic pathways. Areas with large tidal ranges are less vulnerable to sea level change due to greater sediment transport and higher plant production, resulting in enhanced accretion (Spencer et al. 2016; Simas et al. 2001; FitzGerald and Hughes 2019). This relationship cannot be generalized to all systems, though. Even low rates of SLR make microtidal marshes vulnerable (Lovelock et al. 2015; Spencer et al. 2016) due to the limited vertical growth range for vegetation (Day et al. 1995) and increased flooding and draining (FitzGerald and Hughes 2019). Higher-elevation intertidal species (e.g., *Limonium* spp., *Bassia* spp.) are less tolerant of increased flooding, especially their juvenile stages, than are lower-elevation intertidal species; salinity tolerance also is species dependent (Baumberger et al. 2012; Tabot and Adams 2013; Al Hassan et al. 2017). The impact of climate change at higher elevations also will be more related to rainfall and evapotranspiration. In subtropical areas, salt marshes will be partly displaced by mangrove expansion (Saintilan et al. 2014).

Topographic slope is the primary natural factor governing the conversion of upland to marsh vegetation (Hussein 2009), but invasive species (Smith 2013) and the level of human development and infrastructure (FitzGerald and Hughes 2019) also matter. Greater production of belowground and aboveground biomass will be caused by increased CO_2 concentration and temperatures. The positive effect of elevated temperature on plant production will likely be higher at higher latitudes, while temperatures at lower latitudes might already be optimal or even too high, potentially decreasing biomass production with warming (Lin et al. 2010). Increased biomass production can enhance organic accretion and sediment trapping, helping marshes maintain elevation with SLR. Prediction is often difficult, however, because different changes have opposing effects (Erickson et al. 2007; Sendall et al. 2024). For example, increased CO_2 levels disproportionately benefit C3 plants, while warmer conditions tend to favour C4 plants (Cherry et al. 2009; Sendall et al. 2024).

The upstream migration of salinity along rivers is expected to drive tidal freshwater wetlands upstream, within the limits of tidal influence (Neubauer and Craft 2009), but has not yet been observed (Grieger et al. 2020). During an intermediate phase, forests persist but fail to regenerate and eventually disappear (Langston et al. 2017; Kirwan and Gedan 2019). Along the Gulf of Mexico coastline, the rate of forest loss has significantly accelerated since 2010 and is likely to continue or intensify, with rising water levels sufficient to explain this decline (McCarthy et al. 2022). Salinization compounds this hydrological stress and influences the species composition of the communities that replace freshwater systems (Woods et al. 2020).

For marine macrophytes, ocean warming is considered the most severe threat from climate change (Duarte et al. 2018). Impacts vary among species and *Zostera marina* at lower latitude (Moore and Jarvis 2008) and *P. oceanica* appear as particularly at risk. For example, *P. oceanica*, a Mediterranean

endemic, might lose 75% to 90% of its suitable habitat by 2050 and is at risk of functional extinction by 2100 (Jordà et al. 2012), while *Cymodocea nodosa*, a Mediterraneo-Atlantic species, is expected to lose only 47% of its range, with losses compensated for in the Atlantic (Chefaoui et al. 2018). However, interactions with other factors could reduce the effects of ocean warming. Similarly to the case of salt marshes, CO_2 enrichment, and the resulting ocean acidification could stimulate seagrass photosynthesis sufficiently to offset the negative effects of temperature increases (Zimmerman 2021). Improved water quality may reduce the effects of thermal stress on eelgrass populations near their southern limits and decrease the risks of anoxic crises (Le Fur et al. 2018; Zimmerman 2021). Sexual reproduction may provide the potential to increase genetic and phenotypic diversity and promote adaptation to increased temperature (Duarte et al. 2018). Heat waves can enhance sexual reproduction of *Posidonia oceanica* (Ruiz et al. 2018; Marín-Guirao et al. 2019) and the potential for adaptation by that species. Other expected impacts of climate change on seagrass meadows are the introduction of exotic and opportunistic species outcompeting local species and the acceleration of the herbivore or the detritivore pathway (Pergent et al. 2014; Beca-Carretero et al. 2020).

The adaptation potential of seagrass species might have initially been underestimated for *P. oceanica*, for which large differences between plant origins in thermal tolerance have been identified (Marín-Guirao et al. 2015) and which maintained populations in the Mediterranean Sea from the Pleistocene while experiencing considerable environmental changes (Aurelle et al. 2022; Procaccini et al. 2023). The diversity of seagrass responses to environmental changes is likely related to genotypes and the related phenotypic plasticity of individuals, but also dependent on external factors (Pazzaglia et al. 2021; Nguyen et al. 2023). Heat waves can enhance sexual reproduction of *P. oceanica* (Ruiz et al. 2018; Marín-Guirao et al. 2019; Procaccini et al. 2023) and thus the potential to increase genetic and phenotypic diversity and promote adaption to increased temperature. Contrasting results have been obtained on the response of *P. oceanica* populations to marine heat waves and more research is needed in order to understand the impacts of heat waves on this species (review in Stipcich et al. 2022).

Consequences for birds and fish

Climate change has potential to affect coastal birds in many ways (Sutherland 2004). SLR and increased storm surge will inundate coastal habitats, causing long-term effects such as habitat change and short-term effects like nest flooding. Increased air and water temperatures could alter prey availability. Changing precipitation could alter salinity or change upstream conditions in the rivers that feed estuaries. Reduced ice cover could influence the geomorphology of existing sites and make new sites available. Shifting wind directions and strength might affect migration patterns. Human responses to climate change that are designed to make coastlines more resilient for people – such as shoreline hardening, barrages, and other controls of tidal flow – could also have far-reaching consequences for many species (Elphick 2025).

The loss of habitat to SLR is perhaps the biggest concern, especially where topography and human infrastructure limit the movement of habitats inland. Even when movement is possible, the rates may lag behind the inundation of

habitat at the seaward edge, resulting in a net loss (Field et al. 2016). The gradual process of habitat change may also have benefits. For example, decreases in high-elevation marsh may be accompanied by increases in lower-elevation marsh and mudflats, at least in the short term. Increased disturbance caused by more frequent storms also can benefit some species, such as when storm over-wash moves sand in ways that create unvegetated habitat suitable for beach-nesting birds (Walker et al. 2019) or raises elevation.

Predicting climate change effects on coastal birds is similarly challenging due to uncertainty regarding the severity of changes to coastal systems, and detailed analyses have only been conducted for a few species. Eurasian oystercatchers in the Netherlands appear unlikely to simply nest at higher elevations, and shifts in nest site selection based on environmental indicators of breeding success are unlikely to match the increased flooding risk (Bailey et al. 2017, 2019). Similarly, reproduction and survival rates in saltmarsh sparrow *Ammospiza caudacuta*, appear insufficient to maintain viable populations (Field et al. 2017; Field et al. 2018; Roberts et al. 2019). These studies suggest that coastal marshes are becoming ecological sinks.

The lack of data linking flooding to reproduction or survival means that projected effects of SLR are usually based on simple extrapolations of habitat change. When breeding success declines before habitat changes though, due to more frequent nest flooding, these extrapolations will underestimate the consequences of SLR (van de Pol et al. 2024). If habitat losses induce negative density-dependence, then extinction risk also may increase even without greater flooding risk (Aiello-Lammens et al. 2011). Many past estimates of habitat change also assume simple increases in sea level without fully accounting for the capacity of habitats to gain elevation by accretion or to move inland. Interpretation of many projections is therefore complicated, but studies increasingly suggest considerable risk to saltmarsh bird populations (Klingbeil et al. 2021).

Similar predictions apply to the loss of intertidal foraging habitat (Galbraith et al. 2002), high tide roosting sites for waders (Mann et al. 2017), reduced access to eelgrass beds for geese (Shaughnessy et al. 2012), and loss of freshwater wetlands used by rare species to saltwater intrusion (Gilbert et al. 2010; van Rees and Reed 2018). Ensuring the long-term persistence of populations will require focused protection of areas where habitat persistence is most likely, while improving capacity to identify and manage areas most likely to benefit from conservation action.

Projecting the future effects of climate change other than SLR has received even less attention. Models suggest that hurricanes or other disturbances are likely to alter long-term population trajectories only if they have extreme impacts on survival or reproduction (Field et al. 2019), suggesting that coastal bird populations may be more resilient to seemingly catastrophic "pulse" events than to more gradual "press" changes, such as SLR. This balance could change if there were substantial increases in the magnitude of extreme events or their frequency, but serious impacts are likely limited to situations where populations are small or localized. Effects of other changes – rising and extreme temperatures, altered precipitation rates, shifting wind patterns, etc. – are largely unknown. Understanding the synergistic interactions between climate change and other threats is likely to become increasingly important as many aspects of climate change have high potential to exacerbate ongoing threats (Elphick 2025).

The projected effects of climate change on coastal wetland fish biodiversity present an alarming forecast. Future climate scenarios indicate that many fish species will shift their ranges in search of more suitable habitats (Champion et al. 2018). For example, temperate species may migrate to higher latitudes or into deeper waters to avoid rising temperatures, while tropical species may expand their ranges. Such distribution shifts could alter community composition and species interactions, potentially destabilizing existing food webs and disrupting ecological relationships. Species with specific habitat needs, or that cannot disperse or adapt fast enough, face an increased risk of population decline and extinction.

The use of climate models and ecological forecasts plays a crucial role in identifying the species and ecosystems most at risk from climate change. Some models project significant habitat loss for species dependent on mangroves and seagrasses (Waycott et al. 2009; Brown et al. 2019; James et al. 2020). Similarly, estuarine species are expected to face rising salinity and more frequent hypoxia, both of which threaten survival and reproduction (MacKenzie et al. 2007; Komoroske et al. 2014; Hallett et al. 2018; Davis et al. 2019).

The long-term effects on fish biodiversity and coastal communities could be extensive and deeply transformative. Declining populations may reduce fisheries yields, threatening food security and local economies. The loss of biodiversity also affects critical ecosystem services like nutrient cycling, water purification, and climate regulation through carbon storage, weakening the overall health and resilience of coastal ecosystems. The cultural and recreational significance of rich, diverse coastal environments may also be compromised.

Management options and policy recommendations to enhance coastal wetland resilience

The adaptation of coastal wetlands to climate change occurs both naturally and through management (Table 1). These measures must align with natural processes to avoid maladaptation.

Table 1. Some examples of adaptation mechanisms of coastal wetlands as a function of the impacts of climate change (modified from Camacho et al. 2024).

Pressures and impacts	Ecosystem's adaptation	Human-driven adaptation
Sea-level rise and marine storms		
Higher water level and flooding frequency	Higher sedimentation and vertical accretion	Controlled driver diversions, sediment by-pass in dams
Higher coastal erosion	Inland migration of coastal wetlands	Sand nourishment, dune restoration, etc.
Higher water and soil salinity	Natural habitat shift	Freshwater supply
Rising sea temperature		
Higher hydro-saline stress	Natural habitat shift	Freshwater supply
Thermal stress and more hypoxia	Thermal adaptation, change in species	Increased water turnover
More exotic species from warmer areas	Structural and functional change of the ecosystem	Early detection and adaptative management
Acidification		
Difficulties for calcification of marine life	Replacement by species resistant to lower pH	Introduction of varieties more resistant to lower pH

Natural resilience mechanisms

Positive feedback between increased flooding because of SLR and sedimentation (Schuerch et al. 2018), potentially allows coastal wetlands to maintain elevation relative to sea level, provided there is sufficient sediment available (Day et al. 1995). High rates of SLR (> 1 cm/year) or reduced sediment, however, can lead to the collapse of coastal wetlands (Saintilan et al. 2022). Marsh vegetation helps to capture sediment and generate organic matter, which enhances soil formation as sea levels rise, provided flooding does not exceed thresholds that decrease plant production (Morris et al. 2002). Where soil accretion does not keep pace with SLR or where landward migration is impeded, salt marshes may convert to open water or mudflat.

Globally, warming causes a poleward shift of the boundary between salt marshes in temperate climates and mangroves in tropical climates (Saintilan et al. 2014). Local adaptation through acclimatization includes mechanisms such as reducing foliar respiration in response to increased temperature, though efficiency varies by species (Sturchio et al. 2022). Increased CO_2 generally boosts primary production, but this response is context-specific, influenced by local abiotic conditions such as nitrogen load, salinity, and a species' photosynthetic pathway (Caplan et al. 2015).

Management for resilience

Natural adaptation mechanisms are often insufficient or disrupted by human activities, necessitating management to facilitate resilience. Mediterranean coastal wetlands, for example, could lose 17–94% of their area by 2100 depending on the SLR scenario without proactive management measures (Schuerch et al. 2025). Thus, implementing coastal management that supports passive inland migration of marshes, or actively restores wetlands and river-to-coast connectivity to enhance sediment delivery may be necessary to mitigate losses.

If upland migration is impossible, maintaining wetlands in place requires substantial increases in sediment supply and/or biogenic accretion (Törnqvist et al. 2021). Strategies include releasing sediment trapped in catchment infrastructures (e.g., dam and impoundment removals) and promoting high plant biomass production to increase both mineral and organic sedimentation (Crosby et al. 2016). This approach can be modulated by selectively protecting extensive areas of salt marsh while allowing others to retreat, leveraging natural resilience through lateral marsh loss (Mariotti and Carr 2014).

Integrated management, large-scale restoration, and comprehensive territorial planning are essential to minimize the loss of coastal wetlands due to climate change. Large-scale coastal wetland restoration, including restoring sediment flow from rivers and creating space for coastal systems to migrate, is crucial. The barriers to restoration are often financial and governance-related rather than technical (Sánchez-Arcilla et al. 2022). Policy recommendations should stress the need for the interconnectedness of land, water, and marine environments. This includes funding for research and monitoring, incentives for sustainable practices, and frameworks for community involvement in decision-making.

Management for habitats and species

Management to limit the effects of climate change are primarily linked to protecting and maintaining habitats in light of SLR. Although many methods have been proposed and an increasing number are being trialled, relatively little information is available on their effects. In salt marshes, solutions involve either adding sediment to raise elevations or altering hydrology to improve drainage. Sediment additions often involve direct applications over large areas (van Zomeren and Piercy 2019; Raposa et al. 2022), but smaller-scale projects have used raised sediment mounds to create small, low islands of unflooded habitat at high tide. Creating low islands or rafts in other coastal habitats could also compensate for the loss of habitat vulnerable to inundation (Burgess and Hirons 1992; Overton et al. 2015; Williams et al. 2020).

Modifying hydrology to reduce extreme high tides or to facilitate drainage and prevent water pooling after high tides, could benefit some species but comes with risks. When roads and other human infrastructure cross coastal wetlands, they often restrict tidal flow, which can alter salinity, sediment movement, and flooding patterns in upstream areas, often in detrimental ways (Correll et al. 2017). Installing tide gates where water flows through these restrictions can set an upper limit on tide heights and eliminate extreme tides during critical periods, such as the bird breeding season. Another hydrological solution is to install channels to drain water off the marsh. These ditches can reduce surface elevation, however, exacerbating the effects of SLR, and current management increasingly aims to refill them (Burdick et al. 2020). Shallower and narrower channels ("runnels") show potential to mitigate short-term effects of SLR by reducing water pooling and enhancing vegetation growth, potentially buying time for longer-term solutions (Perry et al. 2022).

Engineering shorelines to mimic natural systems is increasingly seen as an alternative to hardening the coast with physical structures to reduce erosion and limit flooding (Bilkovic et al. 2016; O'Donnell 2017; de la Vega-Leinert et al. 2026). These "living shorelines" take many forms and have been little studied for their biological impacts (though see Leu et al. 2023) but offer potential to create new habitats while protecting existing ones.

Restoration can also focus on rehabilitating degraded habitats, such as replanting vegetation in marshes or seagrass beds. These actions help maintain nursery areas, improve water quality, and provide refuges for fish. Establishing marine protected areas can create refuges that allow ecosystems to recover and may also provide spillover benefits to adjacent areas.

Ultimately, species persistence in areas facing SLR may require the assisted migration of habitats inland. A review of studies attempting to restore or create salt marsh by increasing tidal exchange in other coastal habitats suggests success in increasing habitat extent, although plant communities often differ from reference sites (Taylor et al. 2021). Some evidence suggests communities converge toward the target state, but differences can persist for at least 2–3 decades. The impact of these differences may depend more on vegetation structure than composition, but this is likely to depend on the functions that management is designed to target.

In conclusion, addressing the challenges posed by climate change to coastal wetland biodiversity requires a comprehensive approach that integrates scien-

tific knowledge, effective management, and robust policy frameworks. By taking proactive measures, we can enhance the resilience of coastal ecosystems and ensure the sustainability of their valuable biodiversity and ecosystem services.

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Data availability

All of the data that support the findings of this study are available in the main text.

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