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FOCUS ARTICLE

Mangrove forests under climate change in a 2°C world

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Abstract

The world's nations are committed to keeping global temperature rises to less than 2°C to avoid the worst impacts of climate change. Such a target is crucial for mangrove forests, because they are located primarily in tropical and subtropical regions that are expected to see large changes in climatic conditions; their intertidal location and sensitivity to changes in environmental conditions means that mangroves are expected to be on the front line of climate change impacts. We conceptualize what a 2°C world might look like for mangroves, and in particular the potential negative and positive responses of the mangrove ecosystem to anticipated changes in future atmospheric CO₂ concentrations, temperature, sea level, cyclone activity, storminess and changes in the frequency, and magnitude of climatic oscillations. We also assess the spatial distribution of such stressors, their relative contributions to mangrove ecosystem dynamics, and discuss the challenges in attributing mangrove ecosystem dynamics to climate change versus other global change stressors. Such knowledge can help future-proof conservation and restoration activities, improve the Intergovernmental Panel on Climate Change's confidence level ascribed to climate change impacts on mangrove forests, and highlight the key temperature thresholds beyond which the future of the world's mangroves is less certain.

This article is categorized under:

- Climate, Ecology, and Conservation > Modeling Species and Community Interactions
- Climate, Ecology, and Conservation > Observed Ecological Changes

KEYWORDS

cyclone, global warming, Paris Agreement, range expansion, sea-level rise

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1 | INTRODUCTION

There is a short window to rapidly decarbonize the global economy and undertake other climate change mitigation efforts, before the world experiences the rapid and irreversible impacts of climate change. In 2018, the Intergovernmental Panel on Climate Change (IPCC) special report on Global Warming of 1.5°C (IPCC, 2018) introduced the anticipated impacts of climate change on natural and human systems under warming scenarios of 1.5 and 2°C above pre-industrial levels. Breaching the 2°C temperature target has been associated with a range of potential climate change impacts, including continental-scale changes in precipitation and temperature extremes and rapid ice melt and sea-level rise (DeConto et al., 2021; IPCC, 2018). The impacts of a 2°C warming are likely to be disproportionate for coastal and marine ecosystems (Frieler et al., 2013).

Coastal mangrove forests are at particular risk of climate change impacts beyond 2°C warming. First, their predominantly tropical and sub-tropical distribution overlaps with areas of the planet that are expected to face some of the worst impacts of climate change. Second, their intertidal location exposes them to a number of processes exacerbated by climate change, including sea-level rise, tropical storm activity, and temporary sea-level fluctuations due to climatic oscillations (Ward et al., 2016). Third, mangrove vegetation already exists in a dynamic intertidal environment, and in many instances species are already operating at or near their physiological limits (Adame et al., 2021), so are susceptible to relatively small changes in environmental conditions. But despite the potential sensitivity of mangroves to climate change, IPCC (2018) could only attribute moderate risk of climate change impacts at 1.5 and 2°C with medium confidence, and low certainty as to when this ecosystem is likely to transition to higher levels of risk. However, IPCC (2018) also acknowledged that recent climatic events leading to the large-scale dieback of mangroves along arid coastlines such as in Northern Australia suggest that the influence of climate change on mangroves has been underestimated.

We aim to provide more confidence to estimates of climate change impact on mangroves by synthesizing the evidence of the response of mangroves to climate change stressors. We frame this evidence within the 2°C warming threshold used by IPCC (2018, 2022). The scientific underpinning of a 2°C limit has been critiqued, but we use it as a heuristic because it is a useful framing to anchor discussions about what a warming world may look like in the future, and this threshold has stimulated substantial discussion about climate change mitigation. Although climate change is expected to impact many facets of the mangrove ecosystem, we use ecosystem areal extent and mangrove vegetation biomass as two indicators of climate change impact, because both indicators are well mapped at the global scale, allowing us to consider spatial patterns of climate change. Biomass is also linked to carbon uptake, which has a high risk and high confidence of being impacted at 2°C (IPCC, 2018). However, we acknowledge that a focus on biomass and ecosystem extent may underplay impacts on other important components and dynamics of the mangrove ecosystem, such as species diversity, fauna, biogeochemical processes, and social–ecological interactions.

2 | WHAT WOULD A 2°C WORLD LOOK LIKE FOR MANGROVES?

2.1 | Impacts of climate change stressors on mangroves

Climate change impacts of relevance to mangroves vary in origin and process and include CO₂ enrichment, temperature increases, sea-level rise, precipitation increases and decreases, changes in cyclone intensity, frequency, and distribution, changes in hydrodynamic energy, and climatic oscillations (such as the El Niño Southern Oscillation [ENSO]). Climate change can have both positive and negative impacts on components of the mangrove ecosystem (Table 1; Sidebar 1), and different climate change impacts may interact. The magnitude and direction of impact at the species-level may be influenced by species-specific responses to environmental changes, while at the habitat patch scale is likely to be controlled by large-scale environmental settings.

2.1.1 | CO₂ enrichment

A 2°C world is likely to have an atmospheric CO₂ concentration of 568–590 ppm, similar to Representative Concentration Pathway (RCP) 6 by the 2080s (IPCC, 2018). Higher CO₂ levels will enhance mangrove growth and productivity due to increased photosynthetic and water use efficiency (McKee et al., 2012). At CO₂ concentrations of 700 ppm, *Rhizophora mangle* seedlings showed significant increases in biomass, stem length, maturation rates, total leaf area,

TABLE 1 Potential positive and negative impacts of climate change on mangrove forest biomass and extent

Climate change stressor	Expected climate change impacts		Confidence in impact on mangroves according to IPCC (2022)	Key references
	Vegetation biomass	Areal extent		
CO ₂ enrichment	Increased growth and productivity	Increased competition with salt marsh plants	—	McKee et al. (2012)
Temperature increases	Increased growth and productivity Reduced growth in arid areas	Increased extent at latitudinal range limits, replacing salt marsh Reduced extent in arid areas	Medium to high confidence	Saintilan et al. (2014), Adame et al. (2021), Chapman et al. (2021)
Sea-level rise	Reduced growth in lower intertidal zone Potentially increased growth in upper intertidal zone	Reduced extent Landward migration in locations with no barriers	Robust evidence, high agreement; likely, medium confidence; likely at high risk; high confidence	Lovelock et al. (2015), Sasmito et al. (2016), Schuerch et al. (2018)
Precipitation increase	Increased plant growth in response to freshwater input, salinity reduction, and nutrients	Decrease in area due to scouring, sediment deposition and smothering during floods	—	Jennerjahn et al. (2017), Simard et al. (2019), Adams and Rajkaran (2021)
Precipitation decrease	Reduced growth and productivity	Decrease in area in arid regions	Medium confidence	Duke et al. (2017), Lovelock et al. (2017), Asbridge et al. (2019), Adame et al. (2021)
Increase in cyclone activity	Reduced aboveground biomass and tree height	Decrease in area where cyclones lead to large-scale mortality	High confidence	Asbridge et al. (2018), Simard et al. (2019), Krauss and Osland (2020)
Increase in hydrodynamic energy	Single plant mortality, reduced recruitment	Decrease in area due to erosion	—	Walcker et al. (2015), Sippo et al. (2018), Adams and Rajkaran (2021)
Changes in climatic oscillations	Reduced growth due to physiological stress Decreased productivity from mechanical damage, winds, and inundation Increased productivity from nutrient input from floodwaters in arid estuaries	Decrease in area due to dieback	Very high evidence, medium evidence	Duke et al. (2017), Lovelock et al. (2017), Asbridge et al. (2019)

and photosynthetic rates (Farnsworth et al., 1996). The magnitude of response can be variable among species and according to interactive effects with other drivers. For example, Reef et al. (2015) showed that the salinity optima for *Avicennia germinans* shifted at a CO₂ concentration of 800 ppm and that mangroves growing in conditions above their salinity optima had reduced growth and biomass/carbon assimilation, even at higher atmospheric CO₂ concentrations. Similarly, at 800 ppm the growth of *Avicennia marina* and *Rhizophora stylosa* responded positively even when exposed to increasing tidal flooding to simulate sea-level rise. However, gains were minimal under prolonged flooding conditions (Alongi, 2021; Jacotot et al., 2018).

The influence of CO₂ enrichment may be more pronounced in particular locations, such as the latitudinal range limits of mangroves, where they come into inter-specific competition with plants of other ecosystems such as salt marshes. At a CO₂ concentration of 600 ppm (broadly equivalent to that expected in a 2°C world), mangrove seedlings created more biomass when in competition for light with salt marsh species (Manea et al., 2020), which may enhance the encroachment of mangroves into salt marshes in the future (Section 2.1.2).

SIDEBAR 1 Climate change can have a positive influence on mangrove forests too

The public perception of climate change impacts is overwhelmingly negative, and the scientific consensus suggests that this is particularly the case for the fate of mangrove forests over the next century (IPCC, 2018, 2022). Although the net impact of climate change on mangroves will be strongly negative, it is important to communicate that the exact impacts can be nuanced, depending on the climate change stressor and the location and biophysical setting within which the mangrove forest sits. For example, recent projections of wetlands (including mangroves) suggest that global wetland loss may be lower than previously estimated, because up to 37% of the world's wetlands have the potential to migrate laterally as new landward areas become exposed to the tide (Schuerch et al., 2018). Similarly, if there are no dispersal barriers, then increases in mean air temperature and/or decreases in the frequency and intensity of extreme cold events at the latitudinal range limit of mangroves will lead to their poleward expansion (Cavanaugh et al., 2014; Gabler et al., 2017). However, such expansion will be to the possible detriment of existing ecosystems such as salt marshes. All these positive influences need to be incorporated into our understanding of mangroves under climate change, if we are to increase the confidence and robustness of future projections.

2.1.2 | Temperature increases

A 2°C warming will influence mangroves at two different scales. At the plant scale, mangrove productivity and biomass will increase until an upper temperature threshold is reached. Warmer temperatures will alter phenological patterns (e.g., timing of flowering and fruiting) and species composition (Ward et al., 2016). The influence of temperature on factors such as mangrove biomass is likely to be greatest at latitudinal range limits, as mangroves are limited by frosts at higher latitudes along some coastlines (Chapman et al., 2021). In arid areas, an increase in temperature will increase the water vapor deficit and decrease the growth and survival of mangrove plants (Adame et al., 2021). Hypersaline conditions with high evaporation rates also lead to mangrove degradation, causing changes in species dominance and biodiversity (Alongi, 2021).

At the ecosystem scale, rising temperatures are associated with the poleward expansion of mangroves at their subtropical and warm temperate latitudinal limits. Temperature-driven range shifts have been described for different regions around the world, including North America, East Asia, Southern Australia, Southeast Africa, and the east coast of South America (Fazlioglu et al., 2020; Osland et al., 2017; Saintilan et al., 2014). Poleward expansion can be driven by an increase in minimum surface air temperature or a reduction in frequency and severity of freeze events in some locations such as the eastern United States (Cavanaugh et al., 2014). Along some coasts, expansion will further depend on propagule dispersal and the availability of suitable habitats for colonization in estuaries (Raw et al., 2019). Most range expansion studies have focused on mapping historical poleward shifts (Cavanaugh et al., 2019; Fazlioglu et al., 2020; Rodriguez et al., 2016), with only a few studies projecting range expansion into the future under different temperature scenarios. Many of these projections have been conducted for the Gulf of Mexico, where Gabler et al. (2017) projected substantial poleward shifts of mangroves and increases in tree height and biomass with a 2 and 4°C increase in minimum surface air temperature. A future 2°C warming was identified as a threshold by Osland et al. (2013) after which large areas of saltmarsh in five southern US states could become vulnerable to mangrove encroachment.

2.1.3 | Sea-level rise

A 2°C world may experience rates of sea-level rise between 0.36 and 0.87 m by 2100 (IPCC, 2018). Antarctic ice loss alone is expected to contribute 9 cm to global sea levels by 2100 under a 2°C warming, though this increases dramatically to as much as 33 cm by 2100 under a 3°C scenario, equivalent to 0.5 cm per year between 2060 and 2100 (DeConto et al., 2021). Such high rates of sea-level rise will arguably be one of the main climate change factors determining the survival of mangroves over the long term (Saintilan et al., 2020), considering their distribution is constrained to the narrow intertidal zone. Mangrove plants are vulnerable to inundation stress and lateral erosion caused by rising sea levels.

SIDEBAR 2 The concept of accommodation space

A key factor in projecting the fate of mangrove forests under sea-level rise is to understand the processes that control how this intertidal ecosystem can adjust to a changing physical environment. Accommodation space is defined as the space available for vertical and lateral adjustments by wetlands as sea levels change, involving the accumulation of both organic and mineral sediments (Woodroffe et al., 2016). Originally a geological concept, it has since been applied to coastal wetlands and has been extended to three dimensions to incorporate lateral space. The latter is clearly described by Rogers (2021), who discusses the concept as a unifying framework to draw together knowledge of geology, geography and ecology to conceptualize how wetlands will respond to sea-level rise. Rogers (2021) describes how several continually changing boundary conditions (e.g., relative sea-level rise, hydrodynamic energy) control the total amount of accommodation space, and this space can be filled or “realized” through a range of processes. For example, the pace at which available accommodation space becomes filled in minerogenic systems is primarily a function of sediment supply.

Mangroves can potentially keep pace with and adapt to moderate rates of sea-level rise through a number of physical and biological mechanisms, the rates of which are ultimately related to the magnitude of accommodation space. Accommodation space is defined as the lateral and vertical space in which mineral and organic sediments and organic material from vegetation in situ can accumulate and be colonized by vegetation (Rogers, 2021; Sidebar 2).

Vertical accommodation space is created by a range of minerogenic and biogenic processes, including the trapping of sediment from fluvial or surrounding coastal sources, belowground root production, leaf litter additions, microbial and algal mat production, and wrack deposition (Krauss et al., 2014). Biogenic mangrove systems (e.g., karstic systems) depend primarily on below-ground peat production to maintain and increase surface elevation (Cahoon et al., 2021), which is affected by a range of other climate change processes (Section 2.1.2). However, the majority of the world's mangroves are minerogenic, and in addition to biogenic processes, current and future mangrove surface elevation dynamics in these mangrove systems are also strongly influenced by the broader coastal sediment budget (Lovelock et al., 2015). The sediment budget determines the availability of sediment that is able to be deposited and trapped by mangroves (Adame et al., 2010). Sea-level rise increases accommodation space, providing opportunities for enhanced sediment accretion, as well as mangrove expansion to higher elevations landward (Lovelock et al., 2021; Nguyen et al., 2022), and seaward progradation if sediment supply is adequate (Woodroffe et al., 2016).

Meta-analyses of surface elevation change measurements suggest that current surface elevation change and surface accretion rates are unlikely to keep pace with the RCP8.5 sea-level rise scenario (Sasmito et al., 2016). Palaeoecological studies from across the world show that mangroves forests in the past have been able to keep pace with sea-level rise when the latter is limited to rates of <0.7 cm per year (Saintilan et al., 2020). Thus, an additional 0.5 cm increase in annual sea-level rise (on top of projected rates) caused by the collapse of the West Antarctic Ice Sheet in the latter half of the century beyond a 2°C warming scenario (DeConto et al., 2021) is of huge concern to the survival of many mangrove forests around the world.

Lateral accommodation space in mangroves may also allow some adaptation under rising sea levels, as supratidal areas landward of current mangrove extent become increasingly intertidal and suitable for mangrove colonization. This is expected to lead to gains in biomass and blue carbon (Lovelock & Reef, 2020). However, landward coastal developments and topographical barriers will prevent the transgression of mangroves in many areas, leading to potentially extensive losses in areal extent (Schuerch et al., 2018). This is already the case for many mangrove-fringed shorelines, with up to $1.0\text{--}3.4 \times 10^6$ km² of the world's seascape modified by coastal infrastructure (Bugnot et al., 2020). Such “coastal hardening” is expected to continue to increase substantially in the future, further limiting the proportion of coastlines suitable for landward migration of mangroves.

2.1.4 | Changes in precipitation

A 2°C warming is expected to lead to heavier precipitation in several regions and precipitation deficits in some regions, with the risk of both extremes higher at 2°C compared to 1.5°C (IPCC, 2018). Substantial variation is expected even

within regions; under 2°C warming South American mangroves may experience a 150 mm per year precipitation increase above preindustrial levels (central coast of Brazil) delivered in more extreme pulses, or a 150 mm per year decrease (Caribbean coast of Colombia, Venezuela) (Torres et al., 2022).

Precipitation can be a key control on mangrove ecosystem productivity, diversity, and distribution (Ribeiro et al., 2019). High rainfall increases moisture, decreases salinity stress, and promotes mangrove growth. Mangroves are more productive, taller, and more diverse in regions with high rainfall compared to those with lower rainfall (Jennerjahn et al., 2017). Globally, mangrove canopy height is closely linked to rainfall as well as temperature and potentially cyclone frequency (Simard et al., 2019). Sedimentation increases with rainfall promote mangrove growth, productivity, and expansion. Increased freshwater inflow to estuaries maintains open estuary mouth conditions, tidal connectivity, and ideal conditions for mangrove growth (Adams & Rajkaran, 2021). However, extreme precipitation events can also scour estuary banks and lead to extended inundation, thereby removing mangroves in intertidal habitats. Such habitats may be able to re-establish, but this can take decades. For example, mangroves that were removed by flooding in the Mnyameni and Mzimvubu estuaries only re-established after 11 years (Adams & Rajkaran, 2021). Floods can also deposit sediments that cause the smothering and die-back of mangroves. Increased siltation, turbidity and salinity changes associated with floods will influence the growth and distribution of mangroves.

Climate change scenarios indicate that a substantial proportion of global mangrove area will experience scarcity in freshwater runoff and a drier climate (Dai, 2013; Sippo et al., 2018). A decrease in rainfall reduces mangrove photosynthesis, productivity, growth and reproduction. In low rainfall areas, hypersalinity is a major threat and mangroves can be replaced by salt pans and hypersaline flats. A decrease in precipitation threatens the survival of mangroves in arid and semi-arid areas. These mangrove forests occur in tide-dominated geomorphic settings with freshwater flows restricted to groundwater or during sporadic tropical storms, which makes them vulnerable to changes in hydrology and reduced freshwater inputs (Adame et al., 2021). Because these mangroves occur at their limit of salinity tolerance, small changes can cause extensive degradation (Lovelock et al., 2009). Extensive mangrove mortality and loss of areal extent has been reported as a result of drought in combination with other climate change stressors (Asbridge et al., 2019; Duke et al., 2017; Lovelock et al., 2017).

2.1.5 | Changes in cyclone activity

Peak wind speed and cyclone-driven precipitation is expected to be markedly higher at 2°C compared to 1.5°C as cyclones become more intense. This is a concern for mangroves because approximately half of the world's mangrove forests are located in cyclone-prone areas, where they are damaged by broken branches and defoliated canopies, leading to large and long-term losses in aboveground biomass and plant height (Krauss & Osland, 2020). The impacts of wind on mangroves is species-specific, for example, *Rhizophora* spp. are unable to regrow after storm damage through epicormic sprouting, unlike *Avicennia* spp. (Villamayor et al., 2016), creating species-specific post-recovery pathways (Aung et al., 2013).

Larger-scale and more long-term disturbance regimes can also influence the degree of damage experienced by mangroves during a cyclone event and hint at their future susceptibility, though the processes involved may vary with scale. At the landscape scale, mangrove loss and shoreline erosion is related to the cumulative effect of historical cyclone disturbance, with previously eroding mangrove shorelines experiencing the highest damage in subsequent cyclone events (Bhargava & Friess, 2022). Global comparisons suggest that mangrove canopy damage is greater when closer to the cyclone path, though higher cyclone frequency is correlated with a lower degree of mangrove damage (Peereman et al., 2022).

Strong winds, flooding rain, high-energy waves, and storm surges associated with cyclones can also lead to substantial losses in mangrove areal extent, and mangrove dieback caused by inundation through unusually high water levels have also been recorded (Adams & Rajkaran, 2021). Mass mangrove mortality can be followed by peat collapse (Cahoon et al., 2003), loss of elevation, and in some instances conversion of the mangrove area to a mudflat or open water (Krauss & Osland, 2020). Asbridge et al. (2018) found that *R. stylosa* was slow to recover following cyclone damage as the trees did not resprout, and a change in sediment elevation caused persistent inundation that prevented propule establishment.

However, cyclones can bring positive benefits to mangroves in some circumstances. Pulses of offshore eroded sediments can be deposited within the mangrove ecosystem in layers up to 4.5 cm thick, providing a sediment subsidy that can increase surface elevations and assist mangroves in adapting to longer term sea-level rise (Castañeda-Moya

et al., 2010). Nutrient pulses associated with these sediments can also benefit mangroves in nutrient-limited settings. For example, carbonate mangrove systems that overlap many cyclone-prone areas are often phosphorous-limited. Studies have shown enhanced mangrove stem growth after cyclone activities, associated with increased nutrient availability (Lovelock et al., 2011).

2.1.6 | Changes in hydrodynamic energy

Wave energy on coasts is expected to change across the world's coastlines with increased warming, with increases in wave height expected in mangrove areas in the tropical West Pacific Ocean and the Indian Ocean (Morim et al., 2019). This causes erosion and mortality of mangroves (Sippo et al., 2018), and can limit further plant recruitment. Higher water levels due to waves can lead to flooding and mangrove dieback. Periods of increased wave energy during positive cycles of the North Atlantic Oscillation winter index caused erosion and loss of mangrove areal extent (Walcker et al., 2015). Waves can also deposit sediments on seaward margins, causing mangrove smothering and mortality. Deposited sediments can also close the mouths of estuaries and lagoons to the sea, leading to inundation and dieback of mangroves (Adams & Rajkaran, 2021).

2.1.7 | Variability in climatic oscillations

Climate change is altering the frequency and intensity of climatic cycles such as the El Niño Southern Oscillation (Cai et al., 2021), and warming above 1.6°C carries high risk of such oscillations and other events leading to major shifts in the climate system (IPCC, 2018). For example, the frequency of heating events such as El Niño are expected to double even at 1.5°C warming, while the frequency of balancing events such as La Niña will remain the same (IPCC, 2018). There is very strong evidence that marine heatwaves (with assumed links to changes in climatic oscillations) are having impacts on mangroves (IPCC, 2022), and variation in the frequency and intensity of El Niño events is driving mangrove mortality (Sippo et al., 2018). Changes in climatic oscillations are likely to exacerbate many other climate change stressors, such as precipitation. We have already seen large-scale impacts of climatic oscillations on mangroves, even at current levels of intensity. In Northern Australia, the 2016 extreme El Niño event led to extensive dieback of mangroves in the Gulf of Carpentaria and dieback in isolated stands in Western Australia through a combination of extreme drought and a temporary drop in sea level (Duke et al., 2017; Lovelock et al., 2017). At Kakadu in Northern Australia, lateral increases in mangrove extent occurred in response to sea-level rise but there was subsequent mangrove dieback due to a decrease in water level associated with negative phases of the ENSO (Asbridge et al., 2019). The scale and severity of this event increased the prominence of mangroves in the climate change debate and is mentioned several times in subsequent climate change reports (IPCC, 2018, 2022). Given that the intensity and the frequency of ENSO events are projected to increase (Cai et al., 2021), this large-scale mortality could be a key signature of climate change. However, attribution remains unclear given the uncertainty in the processes linking variation in ENSO with climate change.

2.2 | Relative contributions of climate change impacts

The overall impact of climate change on mangroves requires nuanced interpretation, because it is clear that different climate change impacts will be both negative and positive (Figure 1). A single climate change impact can also have both positive and negative impacts; for example, cyclones can substantially reduce mangrove biomass in disturbed areas, but can also promote biomass growth by canopy gap creation and providing nutrient subsidies (Krauss & Osland, 2020). Similarly, precipitation increases can have negative impacts on mangroves through localized flooding, but may increase vegetation biomass more broadly (Eslami-Andargoli et al., 2009).

The overall magnitude of impact (Figure 1) is in part determined by the spatial distribution of different climate change impacts (see also Section 2.3). We anticipate that sea-level rise will have an outsized impact on mangroves, because this impact will be widespread across much of the global range of mangroves (Schuerch et al., 2018). In contrast, increases in precipitation and temperature will likely have a smaller magnitude of impact on mangroves globally, because their effect will be spatially localized, and particularly limited to latitudinal range limits in the subtropics and warm temperate locations (temperature) or arid environments (precipitation).

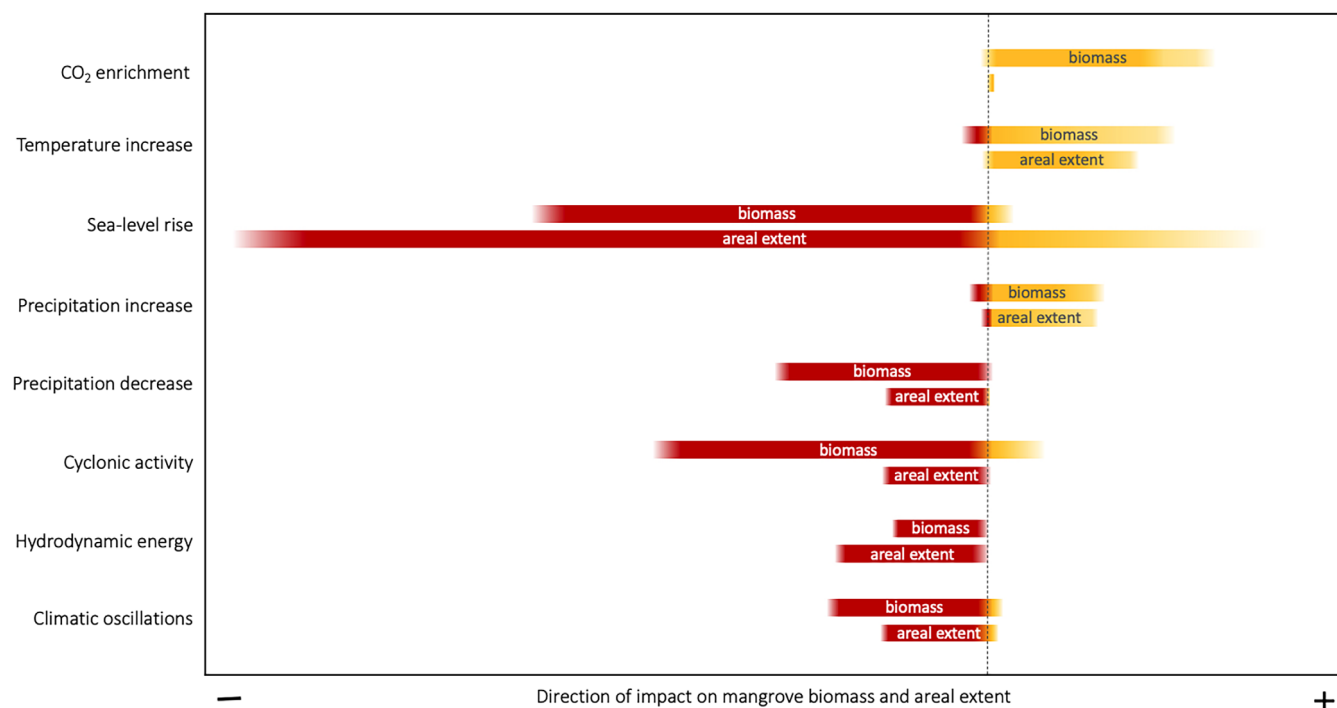


FIGURE 1 Contributions of different climate change impacts to increases and decreases in mangrove biomass and areal extent under 2.0°C warming. The magnitude of positive and negative impacts ascribed to each stressor is indicative only, and based on expert judgment

The magnitude of impacts may also be influenced by the interacting effects of different climate change impacts. For example, sea-level rise and changing hydrodynamics may show additive or synergistic interactions, where increases in sea level may also increase penetration of storm waves into mangroves, causing the loss of seaward fringing mangrove stands (Lovelock et al., 2021). Similarly, intense drought and resulting high salinity reduces mangrove cover and biomass, which may be partially offset by landward migration in response to increasing sea levels (Mafi-Gholami et al., 2020). Feedback between mangroves and their soils may add further complexity. For example, mangrove mortality results in loss of soil elevation as roots decompose and soil pores collapse, which exacerbates the impacts of sea-level rise (Cahoon et al., 2003). However, some climate change impacts may have antagonistic or ameliorating effects. For example mangrove soil organic carbon decay increases under warming conditions, but is moderated by increased inundation due to sea-level rise (Arnaud et al., 2020). The presence of strong interactions among influencing factors on ecological systems is common (Parmesan et al., 2013). In mangroves only a few of these interactions have been elaborated, and there is limited evidence available from monitoring.

2.3 | Spatial distribution of climate change stressors

The distribution of individual climate change stressors is spatially variable across the global extent of mangroves, with concomitant variation in mangrove response (Ward et al., 2016; Figure 2). The strongest evidence for the spatial distribution of a climate change impact is for sea-level rise; IPCC's AR6 showed robust evidence and high agreement for sea-level rise to influence mangroves more in North and Central America, Asia and Australia, compared to South America (IPCC, 2022).

Some mangrove areas are expected to experience extensive climate change impacts; mangroves in Southeast Asia are likely to be impacted by increases in sea-level rise, precipitation, cyclone activity, and hydrodynamic energy, in addition to being a global hotspot for existing human pressures (Goldberg et al., 2020). Of particular concern in these areas are interactions between climate change impacts. Other mangrove areas such as the north eastern coast of South America, East Africa, East Asia, and Southeast Australia, are expected to face a smaller number of climate change impacts in the future.

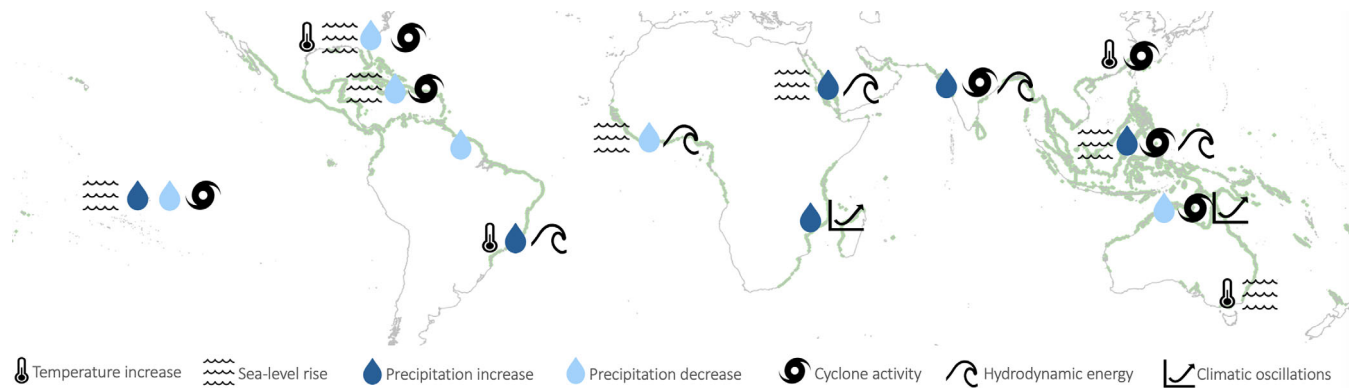


FIGURE 2 Indicative global distribution of major climate change impacts on mangrove forests, based on existing global reviews or datasets. Temperature increases based on areas of potential latitudinal expansion. Sea-level rise based on Schuerch et al. (2018). Precipitation changes based on Ward et al. (2016) and Giorgi et al. (2019). Cyclone activity based on Ward et al. (2016) and Knutson et al. (2020). Increase wave climate based on Morim et al. (2019). Climatic oscillations based on author judgment. Current global mangrove distribution (green) based on 2016 data from Global Mangrove Watch

The net spatial distribution of negative and positive climate change impacts on mangroves is the sum of variation in climate change processes compared to variations in the ability of mangroves to respond to climate change. The latter can be influenced by a range of physical, ecological, and human factors. Such variation is exemplified by the response of mangroves to sea-level rise. Future sea-level rise is expected to be spatially variable across the world, and relative sea-level rise will also vary due to variations in natural and anthropogenic subsidence. How mangroves respond to variable rates of sea-level rise is dependent on spatially variable factors such as geomorphic setting (Sasmito et al., 2016), allochthonous sediment supply (Lovelock et al., 2015), and human development that determines the potential for mangroves to migrate landwards to higher elevations (Schuerch et al., 2018). These patterns explain why some mangroves will be expected to suffer substantial losses related to sea-level rise, while other mangroves could remain stable to the end of the century or see gains in area. Such spatial variation is seen at landscape scales (Mazor et al., 2021; Nguyen et al., 2022), regional scales (Lovelock et al., 2015), and the global scale (Schuerch et al., 2018).

3 | CHALLENGES IN ATTRIBUTING IMPACTS ON MANGROVES TO CLIMATE CHANGE

Attributing climate change to observed changes in physical, ecological, and human systems is challenging (Parmesan et al., 2013), but it is crucial to do so if we are to understand the responses of different systems and develop resilient strategies for their adaptation.

Attribution is challenging because uncertainties in the impacts of climate change factors on mangrove ecology can confound attribution. There are differences in species responses and spatial and temporal variability in responses to climate change factors that are moderated by natural (e.g., geomorphological setting) and human influences (e.g., clearing and conversion) (Schuerch et al., 2018). However, our knowledge of climate change impacts on mangrove ecology and functioning is improving. Both experimental and correlative studies have increased, including evidence of asymmetric responses (e.g., abrupt mangrove mortality but slow recovery; Asbridge et al., 2018) and key thresholds beyond which ecosystem collapse is expected (Saintilan et al., 2020). At this time, long-term monitoring studies that enhance the potential for establishing strong causal links between ecological change and climate change are limited.

Attribution is further challenging because of difficulties in disentangling climate change impacts from ongoing direct and indirect anthropogenic stressors on the mangrove ecosystem, and understanding any synergistic interactions between anthropogenic and climate change processes. The direct influence of human activities on mangrove extent and condition has been enormous, particularly in the late 20th century, and continuing at a reduced rate in the early 21st century (Bryan-Brown et al., 2020; Goldberg et al., 2020). Human influence was assumed to overwhelm any impacts of climate change, resulting in a “medium” assessment of climate change impacts on mangroves (IPCC, 2018). However, a recent global assessment of drivers of mangrove loss found that while loss due to conversion to human land uses for

commodities (e.g., aquaculture, rice agriculture) were the strongest drivers of change in previous decades, more recently in some regions extreme climate events are the largest cause of mangrove loss (Goldberg et al., 2020).

However, human activities and climate change drivers interact, and human activities have likely enhanced the impacts of and sensitivity to climate change (Cinco-Castro & Herrera-Silveira, 2020). Construction of aquaculture ponds, agriculture, and associated infrastructure causes coastal squeeze (reducing habitat for landward migration with sea-level rise), which will have detrimental effect on mangrove cover under sea-level rise (Schuerch et al., 2018). Coastal squeeze may also exacerbate the effects of extreme storms and drought on hydrologically isolated (from tidal flows and groundwater inputs), smaller patches of mangroves.

Human modifications of the coastal zone may also indirectly interact with climate change to impact mangroves. The most recent IPCC report has stated with very high confidence that human impacts have increased the vulnerability of mangroves to climate change (IPCC, 2022). For example, nutrient enrichment due to pollution could enhance the probability of mangrove mortality during droughts (Lovelock et al., 2009) and to canopy damage from intense storms (Feller et al., 2015). Similarly, reductions in coastal sediment supply due to damming in terrestrial catchments can remove one of the keys responses of minerogenic mangroves to sea-level rise through sediment accretion (Lovelock et al., 2015). However, as yet (while sea-level rise rates are relatively low) empirical evidence for mangrove loss to sea-level rise is relatively weak because long-term monitoring is limited. Trends must be detected against a background of annual and interannual variation in human activities and atmospheric and oceanic conditions. Investment in long-term monitoring, improvements in models that link coastal processes to global climate models (e.g., coastal waves), and empirical studies of interactions among different climate stressors and human activities, will increase certainty of projections of the impacts of climate change on mangroves.

4 | PREPARING MANGROVE FORESTS FOR A 2°C WORLD

As climate change progresses, we face increased urgency to prepare mangroves for new and uncertain conditions, where rainfall is less predictable, sea levels are higher, and extreme weather events are more intense. Preparing mangroves for the future will include increasing protection of intact mangrove areas, improving management, and developing climate-smart restoration programs.

Protection is the first step to increasing mangrove resilience to climate change. First, the resilience of existing and proposed protected areas could be assessed (Ellison, 2015). Prioritization of new protected areas can consider the future impacts of climate change, for example, by selecting protected areas most resilient to climate change impacts. For instance, in the Sundarbans in India and Bangladesh, islands that are unlikely to be submerged by sea-level rise have been considered as key for the protection of mangroves and the Bengal tigers that inhabit them (Hansen et al., 2010). Similarly, models of the response of mangroves to sea-level rise have been used to project the most suitable and long-term placing of potential protected areas in Australia (Mazor et al., 2021) and Singapore (Nguyen et al., 2022). Protected areas should include risk-spreading strategies by selecting various types of geomorphology and species (Runting et al., 2018). Connected mangroves are likely to have higher resilience than fragmented ones (Bryan-Brown et al., 2020), and therefore the conservation of contiguous extents of mangroves using a seascape approach, and managing the seascape to enhance connectivity are important for adapting to climate change.

Protected areas must also be future-proofed by ensuring adequate landward space for protected ecosystems to migrate inland (Mazor et al., 2021), since migration will be a key mechanism to reduce the proportion of wetlands threatened by sea-level rise (Schuerch et al., 2018). Marine-protected areas must begin to incorporate terrestrial components in anticipation of mangroves moving into them in the future. Rolling covenants and land titles can help facilitate the movement of coastal protected areas and allow for alternative land uses until mangroves begin to migrate landwards (Bell-James et al., 2021).

Adaptive management needs to follow protection, focusing on reducing non-climate stressors to mangroves, such as water pollution and hydrological modifications, to reduce potential synergistic interactions (Hansen et al., 2010) where one stressor disproportionately increases risk from another, beyond the impact expected from an additive effect alone. An essential component of adaptive management is the establishment of baseline data that can be monitored to assess the effects of climate change, allowing appropriate, evidence-based actions to take place.

Restoration is currently attracting huge interest across the tropics, and several countries have set ambitious mangrove restoration targets. Restoration will continue to be a key strategy to repair mangroves lost to anthropogenic and climate change impacts in the future. Suitable locations should be selected so that physical conditions (such as adequate

hydroperiod, freshwater inputs, and sediment supply if required) alongside social and governance conditions fit the requirements for mangroves to establish (Friess et al., 2022). But restoration projects also need to be future-proofed. Restoration projects can be designed with a range of climate change impacts in mind. For example, mangroves grow within species-specific elevation envelopes (Ellison et al., 2022); engineering restoration projects so that prepared site elevations match the upper limits of these envelopes will buy time for the newly established mangroves to survive. Restoration projects can also be planned with suitable landward areas that are prepared so that mangroves can migrate with rising sea levels. In cyclone-prone areas, species can be selected that are more likely to tolerate or re-sprout after a tropical storm, such as *Laguncularia racemosa* or *Avicennia* spp. (Adame et al., 2021; Krauss & Osland, 2020; Villamayor et al., 2016). The optimal timing of mangrove restoration projects (e.g., immediate or delayed restoration) could also be influenced by climate change impacts, and needs to be considered in project planning (Agaton & Collera, 2022). Such actions will increase the long-term survival and cost effectiveness of mangrove restoration projects and will create new mangroves that are more resilient to anticipated climate change impacts.

5 | CONCLUSION

The current mixed progress in global climate change mitigation means that a projected 1.5 or 2°C world may still become a reality. Without continued strengthened commitments, it is expected that mangrove forests will be heavily influenced by a range of climate change stressors. There is already evidence of climate change impacts on mangroves, and extensive research on what mangrove forests might look like in the future as the climate continues to change. Although much of this work has not been explicitly framed within the 1.5 and 2°C scenarios, there is a clear understanding that the potential impacts of climate change on mangroves will be both positive and negative. The direction and magnitude of impact will be dependent on the stressor, the potential interactions between stressors, and the geographical location of the mangrove alongside site-specific biophysical factors. There is also enough knowledge of climate change processes and their spatial scale to know that sea-level rise is likely to have an outsized effect on mangrove forests compared to other climate change stressors. Overall, the scientific understanding gained from studies conducted around the world suggests that we can have increased confidence in the impacts that climate change will have on mangrove forests over the course of this century.

However, substantive challenges remain in untangling the impacts of climate change from the anthropogenic stressors that many mangroves face across their range. Climate change can have indirect impacts on mangrove forests, or impacts that are exacerbated by human actions, such as river damming that limits terrigenous sediment delivery to the coastal zone and reduces the ability of mangroves to realize their accommodation space. Untangling human influences from climate change impacts will remain a challenge, but is important to do if we are to ascribe a greater confidence to climate change impacts, and if we are to better manage mangroves within a much more dynamic and changing biophysical environment. However, the evidence suggests that such changes can be anticipated and planned for. Innovative coastal management can make space for mangroves to migrate landward, while releasing mangroves from other anthropogenic pressures that are reducing ecosystem resilience. Such information is crucial for managing mangroves in a changing world, and for better representing the fate of mangroves in international climate change assessments.

AUTHOR CONTRIBUTIONS

Daniel Friess: Conceptualization (lead); project administration (lead); visualization (lead); writing – original draft (equal); writing – review and editing (lead). **Maria Fernanda Adame:** Conceptualization (supporting); visualization (supporting); writing – original draft (equal); writing – review and editing (supporting). **Janine Adams:** Conceptualization (supporting); visualization (supporting); writing – original draft (equal); writing – review and editing (supporting). **Catherine Lovelock:** Conceptualization (supporting); visualization (supporting); writing – original draft (equal); writing – review and editing (supporting).

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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FURTHER READING

- Alongi, D. M. (2015). The impact of climate change on mangrove forests. *Current Climate Change Reports*, 1, 30–39.
- Friess, D. A., Krauss, K. W., Horstman, E. M., Balke, T., Bouma, T. J., Galli, D., & Webb, E. L. (2012). Are all intertidal wetlands naturally created equal? Bottlenecks, thresholds and knowledge gaps to mangrove and saltmarsh ecosystems. *Biological Reviews*, 87, 346–366.
- Friess, D. A., Rogers, K., Lovelock, C. E., Krauss, K. W., Hamilton, S. E., Lee, S. Y., Lucas, R., Primavera, J., Rajkaran, A., & Shi, S. (2019). The state of the world's mangrove forests: Past, present and future. *Annual Review of Environment and Resources*, 44, 89–115.
- Rogers, K., Kelleway, J. J., Saintilan, N., Megonigal, J. P., Adams, J. B., Holmquist, J. R., Lu, M., Schile-Beers, L., Zawadski, A., Mazumder, D., & Woodroffe, C. D. (2019). Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. *Nature*, 567, 91–95.
- Rogers, K., Saintilan, N., & Copeland, C. (2012). Modelling wetland surface elevation dynamics and its application to forecasting the effects of sea-level rise on estuarine wetlands. *Ecological Modelling*, 244, 148–157.
- Rogers, K., Saintilan, N., & Heijnis, H. (2005). Mangrove encroachment of salt marsh in Western Port Bay, Victoria: The role of sedimentation, subsidence, and sea level rise. *Estuaries*, 28, 551–559.
- Saintilan, N. S., Asbridge, E., Lucas, R., Rogers, K., Wen, L., Powell, M., Colloff, M. J., Rodriguez, J. F., Saco, P. M., Sandi, S., Pham, T. D., & Lymburner, L. (In press). Australian wetlands under climate change: Collapse or proliferation? *Marine and Freshwater Research*. <https://doi.org/10.1071/MF21233>
- Sippo, J. Z., Santos, I. R., Sanders, C. J., Gadd, P., Hua, Q., Lovelock, C. E., Santini, N. S., Johnston, S. G., Harada, Y., Reithmeir, G., & Maher, D. T. (2020). Reconstructing extreme climatic and geochemical conditions during the largest natural mangrove dieback on record. *Biogeosciences*, 17, 4707–4726.
- Soares, M. L. (2009). A conceptual model for the responses of mangrove forests to sea level rise. *Journal of Coastal Research*, SI56, 267–271.
- Lovelock, C. E., Krauss, K. W., Osland, M. J., Reef, R., & Ball, M. C. (2016). The physiology of mangrove trees with changing climate. In *Tropical tree physiology. Adaptations and responses in a changing environment*. Springer International Publishing.
- Macamo, C. C., Massuanganhe, E., Nicolau, D. K., Bandeira, S. O., & Adams, J. B. (2016). Mangrove's response to cyclone Eline (2000): What is happening 14 years later. *Aquatic Botany*, 134, 10–17.

REFERENCES

- Adame, M. F., Neil, D., Wright, S. F., & Lovelock, C. E. (2010). Sedimentation within and among mangrove forests along a gradient of geomorphological settings. *Estuarine, Coastal and Shelf Science*, 86, 21–30.
- Adame, M. F., Reef, R., Santini, N. S., Najera, E., Turschwell, M. O., Hayes, M. A., Masque, P., & Lovelock, C. E. (2021). Mangroves in arid regions: Ecology, threats, and opportunities. *Estuarine, Coastal and Shelf Science*, 248, 106796.
- Adams, J. B., & Rajkaran, A. (2021). Changes in mangroves at their southernmost African distribution limit. *Estuarine, Coastal and Shelf Science*, 248, 107158.
- Agaton, C. B., & Collera, A. A. (2022). Now or later? Optimal timing of mangrove rehabilitation under climate change uncertainty. *Forest Ecology and Management*, 503, 119739.
- Alongi, D. M. (2021). Responses of mangrove ecosystems to climate change in the Anthropocene. In *Mangroves: Ecology, biodiversity and management* (pp. 201–224). Springer.
- Arnaud, M., Baird, A. J., Morris, P. J., Dang, T. H., & Nguyen, T. T. (2020). Sensitivity of mangrove soil organic matter decay to warming and sea level change. *Global Change Biology*, 26, 1899–1907.

- Asbridge, E. F., Bartolo, R., Finlayson, C. M., Lucas, R. M., Rogers, K., & Woodroffe, C. D. (2019). Assessing the distribution and drivers of mangrove dieback in Kakadu National Park, northern Australia. *Estuarine, Coastal and Shelf Science*, 228, 106353.
- Asbridge, E. F., Lucas, R. M., Rogers, K., & Accad, A. (2018). The extent of mangrove change and potential for recovery following severe Tropical Cyclone Yasi, Hinchinbrook Island, Queensland, Australia. *Ecology and Evolution*, 8, 10416–10434.
- Aung, T. T., Mochida, Y., & Than, M. M. (2013). Prediction of recovery pathways of cyclone-disturbed mangroves in the mega delta of Myanmar. *Forest Ecology and Management*, 293, 103–113.
- Bell-James, J., Fitzsimons, J. A., Gillies, C. L., Shumway, N., & Lovelock, C. E. (2021). Rolling covenants to protect coastal ecosystems in the face of sea-level rise. *Conservation Science and Practice*, 4, e593.
- Bhargava, R., & Friess, D. A. (2022). Previous shoreline dynamics determine future susceptibility to cyclone impact in the Sundarban mangrove forest. *Frontiers in Marine Science*, 9, 814577.
- Bryan-Brown, D. N., Connolly, R. M., Richards, D. R., Adame, F., Friess, D. A., & Brown, C. J. (2020). Global trends in mangrove forest fragmentation. *Scientific Reports*, 10, 7117.
- Bugnot, A. B., Mayer-Pinto, M., Airolidi, L., Heery, E. C., Johnston, E. L., Critchley, L. P., Strain, E. M., Morris, R. L., Loke, L. H., Bishop, M. J., Sheehan, E. V., Coleman, R. A., & Dafforn, K. A. (2020). Current and projected global extent of marine built structures. *Nature Sustainability*, 4, 33–41.
- Cahoon, D. R., Hensel, P., Rybczyk, J., McKee, K. L., Proffitt, C. E., & Perez, B. C. (2003). Mass tree mortality leads to mangrove peat collapse at Bay Islands, Honduras after Hurricane Mitch. *Journal of Ecology*, 91, 1093–1105.
- Cahoon, D. R., McKee, K. L., & Morris, J. T. (2021). How plants influence resilience of salt marsh and mangrove wetlands to sea-level rise. *Estuaries and Coasts*, 44, 883–898.
- Cai, W., Santoso, A., Collins, M., Dewitte, B., Karamperidou, C., Kug, J. S., Lengaigne, M., McPhaden, M. J., Stuecker, M. F., Taschetto, A. S., & Timmermann, A. (2021). Changing El Niño–Southern Oscillation in a warming climate. *Nature Reviews Earth & Environment*, 2, 628–644.
- Castañeda-Moya, E., Twilley, R. R., Rivera-Monroy, V. H., Zhang, K., Davis, S. E., & Ross, M. (2010). Sediment and nutrient deposition associated with Hurricane Wilma in mangroves of the Florida Coastal Everglades. *Estuaries and Coasts*, 33, 45–58.
- Cavanaugh, K. C., Dangremond, E. M., Doughty, C. L., Williams, A. P., Parker, J. D., Hayes, M. A., Rodriguez, W., & Feller, I. C. (2019). Climate-driven regime shifts in a mangrove-salt marsh ecotone over the past 250 years. *Proceedings of the National Academy of Sciences*, 116, 21602–21608.
- Cavanaugh, K. C., Kellner, J. R., Forde, A. J., Gruner, D. S., Parker, J. D., Rodriguez, W., & Feller, I. C. (2014). Poleward expansion of mangroves is a threshold response to decreased frequency of extreme cold events. *Proceedings of the National Academy of Sciences*, 111, 723–727.
- Chapman, S. K., Feller, I. C., Canas, G., Hayes, M. A., Dix, N., Hester, M., Morris, J., & Langley, J. A. (2021). Mangrove growth response to experimental warming is greatest near the range limit in Northeast Florida. *Ecology*, 102, e03320.
- Cinco-Castro, S., & Herrera-Silveira, J. (2020). Vulnerability of mangrove ecosystems to climate change effects: The case of the Yucatan Peninsula. *Ocean and Coastal Management*, 192, 105196.
- Dai, A. (2013). Increasing drought under global warming in observations and models. *Nature Climate Change*, 3, 52–58.
- DeConto, R. M., Pollard, D., Alley, R. B., Velicogna, I., Gasson, E., Gomez, N., Sadai, S., Condron, A., Gilford, D. M., Ashe, E. L., Kopp, R. E., Li, D., & Dutton, A. (2021). The Paris Climate Agreement and future sea-level rise. *Nature*, 593, 83–89.
- Duke, N. C., Kovacs, J. M., Griffiths, A. D., Preece, L., Hill, D. J., Van Oosterzee, P., Mackenzie, J., Morning, H. S., & Burrows, D. (2017). Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: A severe ecosystem response, coincidental with an unusually extreme weather event. *Marine and Freshwater Research*, 68, 1816–1829.
- Ellison, J. C. (2015). Vulnerability assessment of mangroves to climate change and sea-level rise impacts. *Wetlands Ecology and Management*, 23, 115–137.
- Ellison, J. C., Buffington, K. J., Thorne, K. M., Gesch, D., Irwin, J., & Danielson, J. (2022). Elevations of mangrove forests of Pohnpei, Micronesia. *Estuarine, Coastal and Shelf Science*, 268, 107780.
- Eslami-Andargoli, L., Dale, P., Sipe, N., & Chaseling, J. (2009). Mangrove expansion and rainfall patterns in Moreton Bay, Southeast Queensland, Australia. *Estuarine, Coastal and Shelf Science*, 85, 292–298.
- Farnsworth, E. J., Ellison, A. M., & Gong, W. K. (1996). Elevated CO₂ alters anatomy, physiology, growth, and reproduction of red mangrove (*Rhizophora mangle* L.). *Oecologia*, 108, 599–609.
- Fazlioglu, F., Wan, J. S., & Chen, L. (2020). Latitudinal shifts in mangrove species worldwide: Evidence from historical occurrence records. *Hydrobiologia*, 847, 4111–4123.
- Feller, I. C., Dangremond, E. M., Devlin, D. J., Lovelock, C. E., Proffitt, C. E., & Rodriguez, W. (2015). Nutrient enrichment intensifies hurricane impact in scrub mangrove ecosystems in the Indian River Lagoon, Florida, USA. *Ecology*, 96, 2960–2972.
- Frieler, K., Meinshausen, M., Golly, A., Mengel, M., Lebek, K., Donner, S., & Hoegh-Guldberg, O. (2013). Limiting global warming to 2°C is unlikely to save most coral reefs. *Nature Climate Change*, 3, 165–170.
- Friess, D. A., Gatt, Y. M., Ahmad, R., Brown, B. M., Sidik, F., & Wodehouse, D. (2022). Achieving ambitious mangrove restoration targets will need a transdisciplinary and evidence-informed approach. *One Earth*, 5, 456–460.
- Gabler, C. A., Osland, M. J., Grace, J. B., Stagg, C. L., Day, R. H., Hartley, S. B., Enwright, N. M., From, A. S., McCoy, M. L., & McLeod, J. L. (2017). Macroclimatic change expected to transform coastal wetland ecosystems this century. *Nature Climate Change*, 7, 142–147.

- Giorgi, F., Raffaele, F., & Coppola, E. (2019). The response of precipitation characteristics to global warming from climate projections. *Earth System Dynamics*, *10*, 73–89.
- Goldberg, L., Lagomasino, D., Thomas, B., & Fatoyinbo, T. (2020). Global declines in human-driven mangrove loss. *Global Change Biology*, *26*, 5844–5855.
- Hansen, L., Hoffman, J., Drews, C., & Miellbrecht, E. (2010). Designing climate-smart conservation: Guidance and case studies. *Conservation Biology*, *24*, 63–69.
- IPCC. (2018). *Special report: Global warming of 1.5°C*. Intergovernmental Panel on Climate Change.
- IPCC. (2022). *Climate change 2022: Impacts, adaptation and vulnerability*. Intergovernmental Panel on Climate Change.
- Jacotot, A., Marchand, C., Gensous, S., & Allenbach, M. (2018). Effects of elevated atmospheric CO₂ and increased tidal flooding on leaf gas-exchange parameters of two common mangrove species: *Avicennia marina* and *Rhizophora stylosa*. *Photosynthesis Research*, *138*, 249–260.
- Jennerjahn, T. C., Gilman, E., Krauss, K. W., Lacerda, L. D., Nordhaus, I., & Wolanski, E. (2017). Mangrove ecosystems under climate change. In *Mangrove ecosystems: A global biogeographic perspective* (pp. 211–244). Springer.
- Knutson, T., Camargo, S. J., Chan, J. C., Emanuel, K., Ho, C. H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., & Wu, L. (2020). Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, *101*, E303–E322.
- Krauss, K. W., McKee, K. L., Lovelock, C. E., Cahoon, D. R., Saintilan, N., Reef, R., & Chen, L. (2014). How mangrove forests adjust to rising sea level. *New Phytologist*, *202*, 19–34.
- Krauss, K. W., & Osland, M. J. (2020). Tropical cyclones and the organization of mangrove forests: A review. *Annals of Botany*, *125*, 213–234.
- Lovelock, C. E., Ball, M. C., Martin, K. C., & Feller, I. C. (2009). Nutrient enrichment increases mortality of mangroves. *PLoS One*, *4*, e5600.
- Lovelock, C. E., Cahoon, D. R., Friess, D. A., Guntenspergen, G. R., Krauss, K. W., Reef, R., Rogers, K., Saunders, M. L., Sidik, F., Swales, A., & Saintilan, N. (2015). The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature*, *526*, 559–563.
- Lovelock, C. E., Feller, I. C., Adame, M. F., Reef, R., Penrose, H. M., Wei, L., & Ball, M. C. (2011). Intense storms and the delivery of materials that relieve nutrient limitations in mangroves of an arid zone estuary. *Functional Plant Biology*, *38*, 514–522.
- Lovelock, C. E., Feller, I. C., Reef, R., Hickey, S., & Ball, M. C. (2017). Mangrove dieback during fluctuating sea levels. *Scientific Reports*, *7*(1), 1–8.
- Lovelock, C. E., & Reef, R. (2020). Variable impacts of climate change on blue carbon. *One Earth*, *3*, 195–211.
- Lovelock, C. E., Reef, R., & Masqué, P. (2021). Vulnerability of an arid zone coastal wetland landscape to sea level rise and intense storms. *Limnology and Oceanography*, *66*, 3976–3989.
- Mafi-Gholami, D., Zenner, E. K., & Jaafari, A. (2020). Mangrove regional feedback to sea level rise and drought intensity at the end of the 21st century. *Ecological Indicators*, *110*, 105972.
- Manea, A., Geedicke, I., & Leishman, M. R. (2020). Elevated carbon dioxide and reduced salinity enhance mangrove seedling establishment in an artificial saltmarsh community. *Oecologia*, *192*, 273–280.
- Mazor, T., Runtung, R. K., Saunders, M. I., Huang, D., Friess, D. A., Nguyen, N. T., Lowe, R. J., Gilmour, J. P., Todd, P. A., & Lovelock, C. E. (2021). Future-proofing conservation priorities for sea level rise in coastal urban ecosystems. *Biological Conservation*, *260*, 109190.
- McKee, K., Rogers, K., & Saintilan, N. (2012). Response of salt marsh and mangrove wetlands to changes in atmospheric CO₂, climate, and sea level. In *Global change and the function and distribution of wetlands* (pp. 63–96). Springer.
- Morim, J., Hemer, M., Wang, X. L., Cartwright, N., Trenham, C., Semedo, A., Young, I., Bricheno, L., Camus, P., Casas-Prat, M., Erikson, L., Mentaschi, L., Mori, N., Shimura, T., Timmermans, B., Aarnes, O., Breivik, Ø., Behrens, A., Dobrynin, M., ... Andutta, F. (2019). Robustness and uncertainties in global multivariate wind-wave climate projections. *Nature Climate Change*, *9*, 711–718.
- Nguyen, N. T. H., Friess, D. A., Todd, P. A., Mazor, T., Lovelock, C. E., Lowe, R., Gilmour, J., Chou, L. M., Bhatia, N., Jaafar, Z., Tun, K., Yaakub, S. M., & Huang, D. (2022). Maximising resilience to sea-level rise in urban coastal ecosystems through systematic conservation planning. *Landscape and Urban Planning*, *221*, 104374.
- Osland, M. J., Day, R. H., Hall, C. T., Brumfield, M. D., Dugas, J. L., & Jones, W. R. (2017). Mangrove expansion and contraction at a poleward range limit: Climate extremes and land-ocean temperature gradients. *Ecology*, *98*, 125–137.
- Osland, M. J., Enwright, N., Day, R. H., & Doyle, T. W. (2013). Winter climate change and coastal wetland foundation species: Salt marshes vs. mangrove forests in the southeastern United States. *Global Change Biology*, *19*, 1482–1494.
- Parnesan, C., Burrows, M. T., Duarte, C. M., Poloczanska, E. S., Richardson, A. J., Schoeman, D. S., & Singer, M. C. (2013). Beyond climate change attribution in conservation and ecological research. *Ecology Letters*, *16*, 58–71.
- Peereman, J., Hogan, J. A., & Lin, T.-C. (2022). Disturbance frequency, intensity and forest structure modulate cyclone-induced changes in mangrove forest canopy cover. *Global Ecology and Biogeography*, *31*, 37–50.
- Raw, J. L., Godbold, J. A., Van Niekerk, L., & Adams, J. B. (2019). Drivers of mangrove distribution at the high-energy, wave-dominated, southern African range limit. *Estuarine, Coastal and Shelf Science*, *226*, 106296.
- Reef, R., Winter, K., Morales, J., Adame, M. F., Reef, D. L., & Lovelock, C. E. (2015). The effect of atmospheric carbon dioxide concentrations on the performance of the mangrove *Avicennia germinans* over a range of salinities. *Physiologia Plantarum*, *154*, 358–368.
- Ribeiro, R. d. A., Rovai, A. S., Twilley, R. R., & Castañeda-Moya, E. (2019). Spatial variability of mangrove primary productivity in the neotropics. *Ecosphere*, *10*, e02841.
- Rodriguez, W., Feller, I. C., & Cavanaugh, K. C. (2016). Spatio-temporal changes of a mangrove-saltmarsh ecotone in the northeastern coast of Florida, USA. *Global Ecology and Conservation*, *7*, 245–261.

- Rogers, K. (2021). Accommodation space as a framework for assessing the response of mangroves to relative sea-level rise. *Singapore Journal of Tropical Geography*, *42*, 163–183.
- Runting, R. K., Beyer, H. L., Dujardin, Y., Lovelock, C. E., Bryan, B. A., & Rhodes, J. R. (2018). Reducing risk in reserve selection using Modern Portfolio Theory: Coastal planning under sea-level rise. *Journal of Applied Ecology*, *55*, 2193–2203.
- Saintilan, N., Khan, N. S., Ashe, E., Kelleway, J. J., Rogers, K., Woodroffe, C. D., & Horton, B. P. (2020). Thresholds of mangrove survival under rapid sea level rise. *Science*, *368*, 1118–1121.
- Saintilan, N., Wilson, N. C., Rogers, K., Rajkaran, A., & Krauss, K. W. (2014). Mangrove expansion and salt marsh decline at mangrove poleward limits. *Global Change Biology*, *20*, 147–157.
- Sasmito, S. D., Murdiyarso, D., Friess, D. A., & Kurnianto, S. (2016). Can mangroves keep pace with contemporary sea level rise? A global data review. *Wetlands Ecology and Management*, *24*, 263–278.
- Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M. L., Wolff, C., Lincke, D., McOwen, C. J., Pickering, M. D., Reef, R., Vafeidis, A. T., & Hinkel, J. (2018). Future response of global coastal wetlands to sea-level rise. *Nature*, *561*, 231–234.
- Simard, M., Fatoyinbo, L., Smetanka, C., Rivera-Monroy, V. H., Castañeda-Moya, E., Thomas, N., & Van der Stocken, T. (2019). Mangrove canopy height globally related to precipitation, temperature and cyclone frequency. *Nature Geoscience*, *12*, 40–45.
- Sippo, J. Z., Lovelock, C. E., Santos, I. R., Sanders, C. J., & Maher, D. T. (2018). Mangrove mortality in a changing climate: An overview. *Estuarine, Coastal and Shelf Science*, *215*, 241–249.
- Torres, R. R., Benassi, R. B., Martins, F. B., & Lapola, D. M. (2022). Projected impacts of 1.5 and 2°C global warming on temperature and precipitation patterns in South America. *International Journal of Climatology*, *42*, 1597–1611.
- Villamayor, B. M., Rollon, R. N., Samson, M. S., Albano, G. M., & Primavera, J. H. (2016). Impact of Haiyan on Philippine mangroves: Implications to the fate of the widespread monospecific *Rhizophora* plantations against strong typhoons. *Ocean & Coastal Management*, *132*, 1–14.
- Walcker, R., Anthony, E. J., Cassou, C., Aller, R. C., Gardel, A., Proisy, C., Martinez, J. M., & Fromard, F. (2015). Fluctuations in the extent of mangroves driven by multi-decadal changes in North Atlantic waves. *Journal of Biogeography*, *42*, 2209–2219.
- Ward, R. D., Friess, D. A., Day, R. H., & Mackenzie, R. A. (2016). Impacts of climate change on mangrove ecosystems: A region by region overview. *Ecosystem Health and Sustainability*, *2*, e01211.
- Woodroffe, C. D., Rogers, K., McKee, K. L., Lovelock, C. E., Mendelsohn, I. A., & Saintilan, N. (2016). Mangrove sedimentation and response to relative sea-level rise. *Annual Review of Marine Science*, *8*, 243–266.

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