# Will mangrove forests survive sea level rise caused by anthropogenic climate change?

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## Abstract

Mangroves, forests that grow in coastal zones, provide many benefits to humans and the environment. They are some of the oldest forests in the world, having persisted through environmental changes over millennia. A key factor of their survivability is peat accretion, a process in which mangrove soil accumulates in layers in response to rising sea levels. As ocean levels rise, water currents transport sediment to mangrove forests, which accumulates in the soil along with decomposing organic matter to form peat. Newly formed layers of peat increase soil elevations, and mangrove forests continue to grow at these higher elevations. Most records of peat accretion are within the context of historical sea level rise caused by natural climate change. Only in the past few centuries have sea levels risen at unnatural rates, caused by human impacts on climate change. This paper aims to understand how contemporary changes in sea level will affect the process of peat accretion in mangrove forests. Specifically, whether mangrove forests will survive anthropogenic sea level rise is addressed by comparing current peat accretion rates found in the literature to projected future sea level rise rates. Mangrove forests' short-term survival is variable, but accretion will inevitably fall behind sea level rise in the future if climate change is not addressed, after which mangrove forests will be forced inland. By addressing these and similar problems faced by mangrove forests, we will gain a better understanding of actions to take to protect mangrove forests from unprecedented sea level rise.

## Introduction

Mangrove forests are part-terrestrial, part-aquatic forests located primarily in tropical and subtropical zones. These wetland habitats serve crucial roles for both the environment and humanity. For example, a diversity of terrestrial and aquatic species use mangrove forests for habitation, food, and spawning (Marx et al., 2020), and the subsequent high biocomplexity allows researchers to study ecosystem dynamics (Feller et al., 2010). Furthermore, mangrove forests directly benefit humans by providing natural resources, nutrients for agriculture, and supporting commercial fishery populations (Novinzantara et al., 2022). Indirect benefits include filtration of outgoing runoff and insulation of inland areas from storms, tides, and floods (Marx et al., 2020). Novizantara et al. (2022) estimated the total economic value of mangrove forests in Bengkalis Regency, Indonesia alone to be over 5.8 million USD per year. Additionally, mangrove forests are highly efficient carbon sinks, sequestering a global average of 10.7 mol carbon $m^{-2}$ $yr^{-1}$ of $CO_2$ from the atmosphere (Feller et al., 2010). The carbon stored in their soil is over four times greater than that of boreal, tropical, and terrestrial forests (Alongi, 2012). Mangrove forests constitute 3% of all carbon sequestered by tropical forests and 14% of carbon sequestered by global oceans (Alongi, 2012).

For a majority of Earth's history, changes in sea level have had natural causes such as the fluctuation between ice ages and warming periods over millions of years. However, in recent centuries, sea levels have risen at unprecedented rates because of contemporary climate change (Sanders et al., 2008). Climate change has been accelerated by human activity, such as burning fossil fuels and industrial production, which releases large quantities of greenhouse gasses. There is a positive relationship between the concentration of greenhouse gasses in the atmosphere and global temperatures because of the gasses' insulating properties (Stern and Kaufmann, 2014). Consequences of anthropogenic global warming include thermal expansion of ocean water and global ice melt rates, both of which are the greatest contributors to sea level rise (Kopp et al., 2014). Numerous coastal ecosystems around the world, including mangrove forests, can be drastically affected by accelerating sea level rise.

Peat accretion is a natural response of mangrove forests to sea level rise, in which soil elevations are raised through gradual accumulation of mangrove soil. Studies have been performed to better understand this process and how it will be affected by contemporary changes in sea level rise rates. Their findings show that anthropogenic sea level rise will negatively affect mangrove forests by impacting their peat accretion process (Krauss et al., 2010; Marx et al., 2020; Sanders et al., 2008).

## The role of peat accretion in mangrove forest survival

Peat accretion has allowed mangroves to survive since the early Cretaceous period (~145.5 million years ago) despite drastic changes in sea level (Parkinson et al., 1994). Peat accretes when its two essential components, organic plant matter and inorganic mineral sediment, accumulate in mangrove soil over time. Sediment eroded from other land masses is transported to mangrove forests by water currents, floods, and tidal exchange (Cahoon et al., 2020; Krauss et al., 2010). Mangrove trees' submerged roots disrupt the currents, increasing the chances of sediment settling to the bottom of mangrove forests during periods of flowing water (Cahoon et al., 2020). Sediment is also trapped on the surfaces of submerged plant bodies and mats composed of algae, cyanobacteria, and microorganisms (McKee, 2011). The particles then settle during periods of slack water (Smoak and Patchineelam, 1999). Organic material is contributed by mangrove vegetation, which constantly produces leaf litter, roots, rhizomes, etc. which accumulate in the soil and decompose. Over time, accumulated organic and inorganic matter forms layers in the soil, causing peat accretion (see Fig. 1). Mangrove root systems retain accreted peat, provide soil structure, and increase resistance to erosion (Cahoon et al., 2003). Because a majority of peat is organic (McKee et al., 2000), it is especially important that the rate of organic matter contribution is greater than the rate of decomposition for peat accretion to occur (McKee, 2011).

Although sediment comprises a smaller proportion of peat than organic matter (Cahoon et al., 2003), it is often most important in determining how well mangrove forests survive sea level rise. Mangrove forests that receive contributions of eroded sediment from nearby land bodies have higher rates of peat accretion than isolated locations such as carbonate reefs or mangrove islands, whose accretion almost entirely relies on organic production (Parkinson et al., 1994; Marx et al., 2020). Peat accretion is enhanced when there is a greater volume of water transporting sediment to mangrove forests (Callaway et al., 1997). This can result from storms — accretion rates are significantly higher during monsoon season due to stronger and more frequent flooding (Saad et al., 1999) — or sea level rise. However, the amount of sediment deposited is not directly proportional to the increase in volume of water. Sea levels eventually rise faster than soil levels, creating an increasing deficit between mangrove forest elevation and water elevation.

When peat accretion is unable to keep pace with sea level rise, mangrove forests are forced to grow inland to higher elevations (Krauss et al., 2010). Trees submerged too far below water drown, while surviving trees at higher elevations continue to grow and propagate. Thus, forests gradually “move” to higher elevations. However, mangrove migration will eventually be obstructed by human infrastructure (Woodroffe et al., 2016). This prevents mangrove forests from reaching higher elevations, and as sea levels continue to rise, the trapped forests perish and convert into swamps and bays (Scholl et al., 1964).

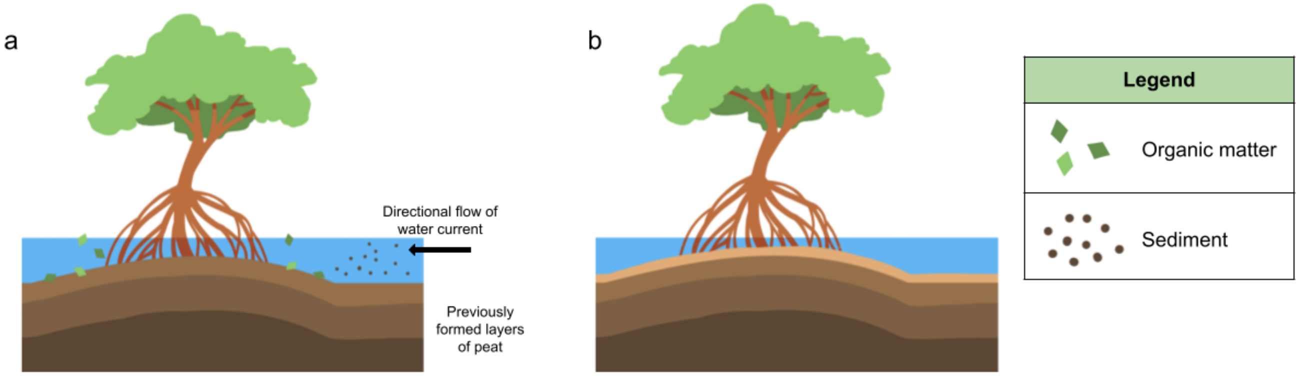

**Fig. 1 Peat accretion in mangrove forests.** (a) Sediment is transported to mangrove forests through water currents. At the same time, organic matter (e.g. leaves) accumulates on the forest floor. (b) Over time, a new layer of peat is formed from the combination of sediment and decomposing organic matter, increasing soil elevation and raising mangrove trees above the new water level.

## Future prospects of mangrove forests

Peat accretion allows mangrove forest to survive sea level rise to an extent; there is a point at which sea level rise is too rapid for peat accretion to keep pace. From a study conducted in Ilha Grande, Sanders et al. (2008) concluded that peat accretion must be approximately equal to or greater than sea level rise rates for mangrove forests to survive. Other researchers have estimated specific thresholds: Saintilan et al. (2020) state that mangrove forests were ~90% unlikely to sustain accretion at sea level rise rates of >6.1 mm $yr^{-1}$, and the probability increased to ~95% at sea level rise rates of >7.6 mm $yr^{-1}$. An upper estimate of 12 mm $yr^{-1}$ is established by findings that mangrove forests moved landward in response to sea level rise rates of >12 mm $yr^{-1}$ in the period prior to the Holocene (Saintilan et al., 2020).

To gain a better understanding of whether mangrove forests will survive anthropogenic sea level rise, peat accretion rates and projected future sea level rise rates were gathered from relevant literature. 53 peat accretion rates across multiple studies were compared to projected sea level rise rates in 2100 under low- and high-emission scenarios. Low-emission sea level rise rates were estimated by dividing the projected sea level rise of 4.3 m by 2100 (relative to 1986-2005) (IPCC, 2019) by 100 years. High-emission sea level rise rates were directly obtained from the IPCC 2019 report. By 2100, global sea levels will rise at an estimated rate of 4.3 mm $yr^{-1}$ under low-emission scenarios and 15 mm $yr^{-1}$ under high-emission scenarios, surpassing the upper estimates of the sea level rise rate threshold (IPCC, 2019).

Table 1 displays peat accretion rates in mangrove forests obtained from various studies. Of the 53 accretion rates, 31 exceed the estimated low-emission sea level rise rates for 2100, while only 2 exceed projected high-emission rates, indicating that the realized emission scenario will have a significant influence on the amount of mangrove forests at risk of being unable to outpace sea level rise. Compared to sea level rise thresholds from Saintailan et al. (2020), 21 of the 53 accretion rates exceed the 6.1 mm $yr^{-1}$ estimate and 12 exceed the 7.6 mm $yr^{-1}$ estimate. This indicates that mangrove forests' ability to survive future sea level rise is not absolute; tolerance of sea level rise will be influenced by differences in forests' characteristics. Krauss et al. (2010) studied accretion rates in fringe, riverine, and basin mangroves, which grow along the coastline, flowing waters, and inland bodies of stillwater respectively (Ewel et al., 1998). Fringe and riverine mangroves are frequently flooded by the ebb and flow of tides, whereas basin mangroves retain the same water for extended periods of time (Ewel et al., 1998). The study found that fringe accretion rates were the lowest of the three at almost all sites, while riverine rates were the highest at almost all sites. The study also reveals that peat accretion rates alone are not indicative of overall soil elevation; fringe forest sites often had net losses of soil elevation, despite positive accretion rates, because of changes belowground. Other characteristics such as plant productivity rates, soil structure, and tidal range influence how different mangrove forests are affected by sea level rise (Feller et al., 2010; Callaway et al., 1997).

| Location | Accretion rate (mm $yr^{-1}$) | Forest type | Reference |
|---|---|---|---|
| Yela River (Kosrae) | 11.6 ± 1.3 | Fringe | Krauss et al., 2010 |
| | 12.9 ± 2.1 | Riverine | |
| | 12.0 ± 1.2 | Interior | |
| Utwe River (Kosrae) | 11.9 ± 1.7 | Fringe | |
| | 18.7 ± 2.2 | Riverine | |
| | 12.9 ± 4.3 | Interior | |
| Enipoas River (Pohnpei) | 6.6 ± 3.1 | Fringe | |
| | 6.3 ± 0.9 | Riverine | |
| | 2.9 ± 1.4 | Interior | |

| | | | |
|---|---|---|---|
| Sapwalap River (Pohnpei) | 4.1 ± 1.5 | Fringe | |
| | 14.1 ± 1.7 | Riverine | |
| | 8.2 ± 1.2 | Interior | |
| Pukusruk (Kosrae) | 20.8 ± 2.4 | Backswamp | |
| Tweed Estuary (Australia) | 7.8 ± 1.2 | Basin; substrate subenvironment | Marx et al., 2020 |
| | 4.7 | Basin; pool subenvironment | |
| | 4.0 | Basin; pool subenvironment | |
| | 5.0 | Basin; central basin ridge subenvironment | |
| Twin Cays (Belize) | 1.64 ± 0.69 | Fringe | McKee et al., 2011 |
| | 2.03 ± 1.25 | Scrub | |
| | 0.72 ± 0.34 | Dwarf | |
| | 0.7 ± 0.3 | Interior | McKee et al., 2007 |
| | 2.0 ± 1.3 | Transition | |
| | 1.6 ± 0.7 | Fringe | |
| Rookery Bay National Estuarine Research Reserve; Naples Bay (Florida) | 2.00 ± 0.35 | Basin | McKee et al., 2011 |
| | 7.55 ± 0.94 | Basin | |
| | 5.74 ± 0.78 | Fringe | |
| | 5.97 ± 0.45 | Restored | |
| Tongatupu | 0.77 | - | Ellison and Stoddard, 1991 |
| Grand Cayman | 0.89 | - | |
| Fiji | 1.17 | - | |
| | 0.76 | - | |
| | 1.31 | - | |
| Caroline Islands | 1.37 | - | |

| | | | |
|---|---|---|---|
| | 1.37 | - | |
| | 0.3 | - | |
| Samoa | 0.99-1.05 | - | |
| | 1.88 | - | |
| Rookery Bay (Florida) | 7.2 | Fringe | Cahoon and Lynch, 1997 |
| | 6.0 | Basin | |
| | 5.35 | Island | |
| Ukerebagh Island (Australia) | 2.21 ± 0.30 | Interior | Rogers et al., 2006 |
| Kooragang Island (Australia) | 4.72 ± 0.05 | Transition | |
| Homebush Bay (Australia) | 4.58 ± 0.28 | Fringe | |
| Minnamurra River (Australia) | 6.64 ± 0.52 | Riverine | |
| Cararma Inlet (Australia) | 3.03 ± 0.41 | - | |
| Currambene Creek (Australia) | 0.65 ± 0.34 | - | |
| French Island (Australia) | 9.49 ± 2.69 | - | |
| Kooweerup (Australia) | 7.20 ± 0.85 | - | |
| Quail Island (Australia) | 6.77 ± 0.79 | - | |
| Rhyll (Australia) | 5.10 ± 0.72 | - | |
| Shark River, pre-Hurricane Wilma (Florida) | 6.6 | Riverine | Whelan et al., 2005 |
| Shark River, post-Hurricane Wilma (Florida) | 11.5 | Riverine | Whelan et al., 2009 |

**Table 1 Peat accretion rates in various mangrove forests.** Displayed in the table are the location, accretion rate, and type of each mangrove forest studied. Certain forest types were not specified.

Another factor that must be considered when evaluating the future of mangrove forests is projections of future sea level rise, which fall within a wide range because they depend on emission scenarios, global temperature increase, and calculation methodologies (IPCC, 2019). The sea level rise rates used thus far only represent extremities of emissions released by humans. They are also not indicative of regional sea level rise rates, which differ from the global average depending on factors such as geographic location and elevation. For example, regional sea level rise near the equator is greater than global rates, while areas near the poles experience regional rates closer to global rates (Kopp et al., 2014). The actual sea level rise experienced by mangrove forests will vary across different regions, influencing the survivability of forests depending on geographic location.

Outside stressors, both anthropogenic and natural, can hinder peat accretion and increase mangrove forest susceptibility to sea level rise. Activities such as mining, dredging, and groundwater and hydrocarbon extraction disturb soil integrity, causing land to sink or cave in (Woodroffe et al., 2016). Mass tree mortality events remove the source of organic material and soil structure in mangrove forests. A common cause of mass tree mortality is high-intensity storms, which uproot, defoliate, or physically damage mangrove trees (Jimenez et al., 1985). For example, following Hurricane Mitch, medium- and high-impact mangrove forest sites in the Bay Islands suffered elevation losses of around -9.35 mm $yr^{-1}$ (Cahoon et al., 2003). The negative changes in elevation are indicative of peat collapse caused by mass tree mortality. Climate change will heighten the intensity of extreme tropical storms, worsening their impact on mangrove forests (Bender et al., 2010). Other natural causes of mass tree mortality include disease outbreaks, frost periods, and droughts (Jimenez et al., 1985). Humans clearcut mangrove forests to obtain natural resources, make space for urban development, or establish aquaculture and mariculture sites, directly causing mass tree mortality (Alongi, 2012; Alongi et al., 2005). Human activity indirectly harms mangroves through pollution, eutrophication, and chemical waste (McKee, 2011; Woodroffe et al., 2016). Outside stressors, both natural and anthropogenic, can influence peat accretion rates, adding further variability to predicting the survivability of mangrove forests to future sea level rise.

## Conclusion

Whether mangrove forests will survive anthropogenic sea level rise is variable. Mangrove forests vary in response to sea level rise due to their differing characteristics. Additionally, projected sea level rise rates are within a broad range dependent on emission scenarios. However, inferences can be made to predict the future of mangrove forests. Sea level rise past a critical threshold negatively impacts mangrove forests, but the severity of these impacts are dependent on the realized emission scenario, which are controllable by humans. In general, sea level rise rates are less likely to surpass the estimated threshold for peat accretion to keep pace under low-emission scenarios compared to under high-emission scenarios.

If the causes of anthropogenic sea level rise are not addressed immediately and with appropriate policies, sea level rise under even the lowest emission scenario will inevitably outpace peat accretion, forcing mangroves to move landward. Human infrastructure will eventually obstruct further movement, causing forests to perish under rapidly rising sea levels. The findings of this review can be used to understand what actions should be taken to assist a crucial ecosystem in adapting to ever-changing environmental conditions.

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