



Mangrove forests as a nature-based solution for coastal flood protection: Biophysical and ecological considerations

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Abstract

Nature-based coastal protection is increasingly recognised as a potentially sustainable and cost-effective solution to reduce coastal flood risk. It uses coastal ecosystems such as mangrove forests to create resilient designs for coastal flood protection. However, to use mangroves effectively as a nature-based measure for flood risk reduction, we must understand the biophysical processes that govern risk reduction capacity through mangrove ecosystem size and structure. In this perspective, we evaluate the current state of knowledge on local physical drivers and ecological processes that determine mangrove functioning as part of a nature-based flood defence. We show that the forest properties that comprise coastal flood protection are well-known, but models cannot yet pinpoint how spatial heterogeneity of the forest structure affects the capacity for wave or surge attenuation. Overall, there is relatively good understanding of the ecological processes that drive forest structure and size, but there is a lack of knowledge on how daily bed-level dynamics link to long-term biogeomorphic forest dynamics, and on the role of combined stressors influencing forest retreat. Integrating simulation models of forest structure under changing physical (e.g. due to sea-level change) and ecological drivers with hydrodynamic attenuation models will allow for better projections of long-term natural coastal protection.

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1. Introduction

Coastal flood risk is increasing globally, as sea-level rise is further accelerating, and coastal storms are predicted to increase in both frequency and intensity in this century (IPCC, 2022). Growing populations and increasing urban development along the coast raise the demand for flood protection measures (Kulp and Strauss, 2019). Coastal areas are generally protected by traditional structures such as breakwaters, levees, and seawalls, but increasing flood risk poses unprecedented challenges. Accelerating sea-level rise requires expensive strengthening and heightening of these structures (Hinkel et al., 2014), while unlikely but potential structural failure may have devastating consequences (Zhu et al., 2020). Nature-based coastal protections – where coastal ecosystems such as mangroves are used to create more resilient flood defence designs – are increasingly recognised as a solution to reducing these challenges (Borsje et al., 2011; Temmerman et al., 2013). Mangroves can attenuate waves, which can reduce the risk of overtopping and direct wave impact on levees and seawalls, allowing for lower structures and consequently lower construction costs (van Zelst et al., 2021). However, implementing nature-based coastal protections remains complex (Bouma et al., 2014). Globally, mangroves have prevailed over millions of years and numerous catastrophic climate events (Alongi, 2015). However, nature-based flood defence requires that mangrove presence is known not at global but at local scale. Coastal protection structures are typically designed with a lifespan of 50–100 years, requiring in-depth knowledge of long-term functioning (CIRIA et al., 2013). Estimating this for coastal mangrove ecosystems is currently challenging as they are not uniform but fluctuate in space (e.g. species distributions within the forest and presence of creeks) and time (e.g. forest expansion and retreat; Koch et al., 2009) across various timescales (e.g. daily bed-level dynamics versus long-term changes in elevation). These spatiotemporal fluctuations in forest structure and size are caused by natural and anthropogenic drivers (e.g. Alongi, 2008; Sherman et al., 2000), and recent work has highlighted the importance of untangling the physical drivers and ecological processes that affect mangrove resilience and structure (Gijsman et al., 2021).

In this perspective, we evaluate the current state of knowledge on the processes that determine the long-term resilience and functioning of mangroves as part of a nature-based flood defence. We write the perspective from an eco-engineering design point of view and use knowledge from relevant domains (Fig. 1). Hence, we assume that there are local socio-political motivation and means to implement a nature-based flood defence. We first identify which aspects of mangrove forest structure are most important for a nature-based flood defence, and at what spatial scale. Then, we evaluate how local physical drivers affect these aspects of forest structure. We examine the physical drivers that govern forest expansion through seedling establishment. Next, we assess how physical drivers, which are affected by global change, govern forest retreat. Finally, we look at how establishment, growth, and mortality of trees lead to changes in forest vegetation density and height.

2. Forest properties for optimal coastal protection capacity

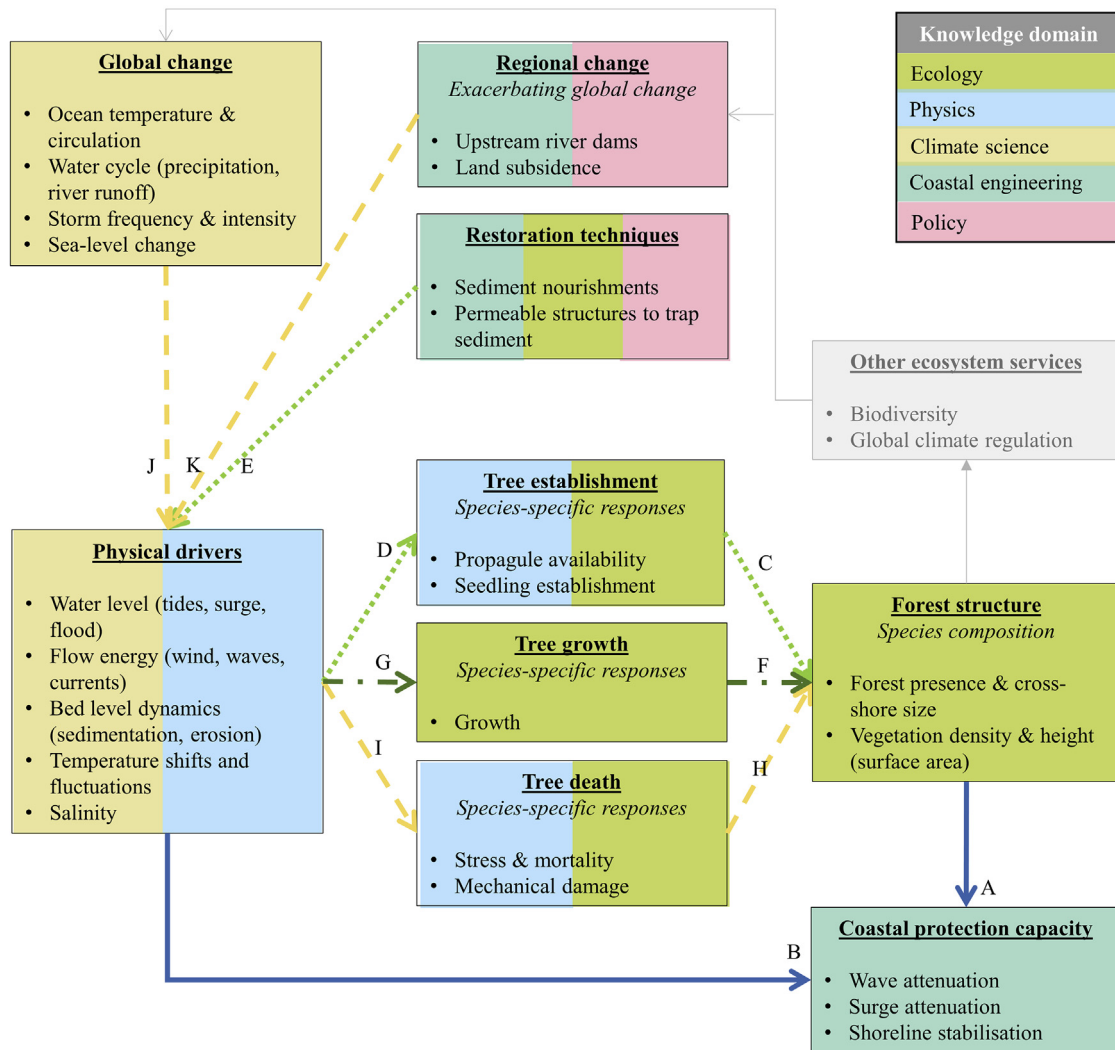
Mangrove forests can reduce energy of wind and swell waves (McIvor et al., 2015; Sánchez-Núñez et al., 2019) and attenuate storm surges (McIvor et al., 2012; Menéndez et al., 2020; Fig. 2). Although mangroves do not block water, they may reduce the extent of flooding in the absence of levees or seawalls by reducing the direct wave impact and surge water levels (Horstman et al., 2014; Maza et al., 2021; Van Coppenolle et al., 2018). Furthermore, mangroves can stabilise shorelines and enhance sediment deposition (for details, see Section 1 of Appendix A). In this section, we mainly focus on wave and surge attenuation.

2.1. Forest width, density, and height are important for wave attenuation

The mangrove forest properties that are relevant for wave attenuation are relatively well understood and include forest width, vegetation density, and vegetation height (Fig. 3). Together with the incoming hydraulic conditions (such as wave height, wave period, and combined current-wave flow), these properties determine the effectiveness of wave attenuation (Horstman et al., 2018; Hu et al., 2014; Maza et al., 2019; Paul et al., 2012). A wider (cross-shore) forest provides more wave attenuation, where the greatest rate of wave height attenuation is found in the first few metres of the forest and decreases along the forest (Dalrymple et al., 1984; Lee et al., 2021; Quang Bao, 2011). A denser and taller forest also provides more wave attenuation. Specifically, the vegetation density and height together make up the frontal surface area of ‘structures’ that are met by waves, which determine the amount of energy transferred from waves to trees (Fig. 3; Horstman et al., 2014; Mazda et al., 1997, 2006). Here, we define density as the entire vegetation density made up by tree structures (i.e. branches, trunks, and aboveground roots), which increases as trees mature, stem diameters thicken, and trees grow taller and develop more side branches and leaves (as opposed to stem density, which decreases as the forest matures and self-thinning takes place; Azman et al., 2021; Jimenez et al., 1985). Moreover, vegetation height should be considered relative to the water level. In any coastal ecosystems, emerged canopies that match or exceed the water level dissipate more wave energy than submerged short canopies (Maza et al., 2015; Ysebaert et al., 2011). Additionally, root layers, trunk layers, and canopies differ in geometry, resulting in different wave energy attenuation rates depending on the water level (Horstman et al., 2014; Maza et al., 2021; Mazda et al., 1997).

2.2. Modelling wave attenuation

Over the decades, numerical models have improved to capture the interaction between vegetation and flow to predict wave attenuation. The first analytical model expressed the vegetation-induced drag force using the Morison equation (Morison et al., 1950) and represented forests as arrays of



Arrows	Processes	Section
→ A, B	Mangrove forest structure determines flood defence capacity of a forest (A), depending on the water level and flow energy generated (B).	2
→ C, D, E	Forest size increases when seedlings establish (C), which depends on species-specific tolerances to local physical drivers (D) that can be improved with restoration techniques (E).	3
→ H, I, J, K	Forest size and presence may reduce when trees get damaged and die (H). Trees die if stress from physical drivers (I) exceeds the tolerance limit, or damage e.g. from storm wind and waves (I). Global change , and regional change that exacerbates global change can worsen physical drivers (J, K).	4
→ C, F, H, D, G, I	Vegetation height and density are driven by establishment, growth, and death of trees (C, F, H), which in turn are affected by physical drivers (D, G, I).	5

Fig. 1. Processes (boxes) and interactions (arrows) discussed in this perspective for assessing the coastal protection capacity of coastal mangroves, showing the relevant knowledge domain (box colour) and the section in which each arrow is discussed. Other ecosystem services are grey as they are mentioned but not explicitly discussed in this perspective (see Appendix A).

vertical cylinders (Dalrymple et al., 1984). It has paved the way for modelling advanced physics, such as wave breaking, wave randomness, and wave–current interaction (Hu et al.,

2014, 2022; Losada et al., 2016). Further advancements have obtained generic drag coefficient equations for various flow and wave conditions and different vegetation types, without

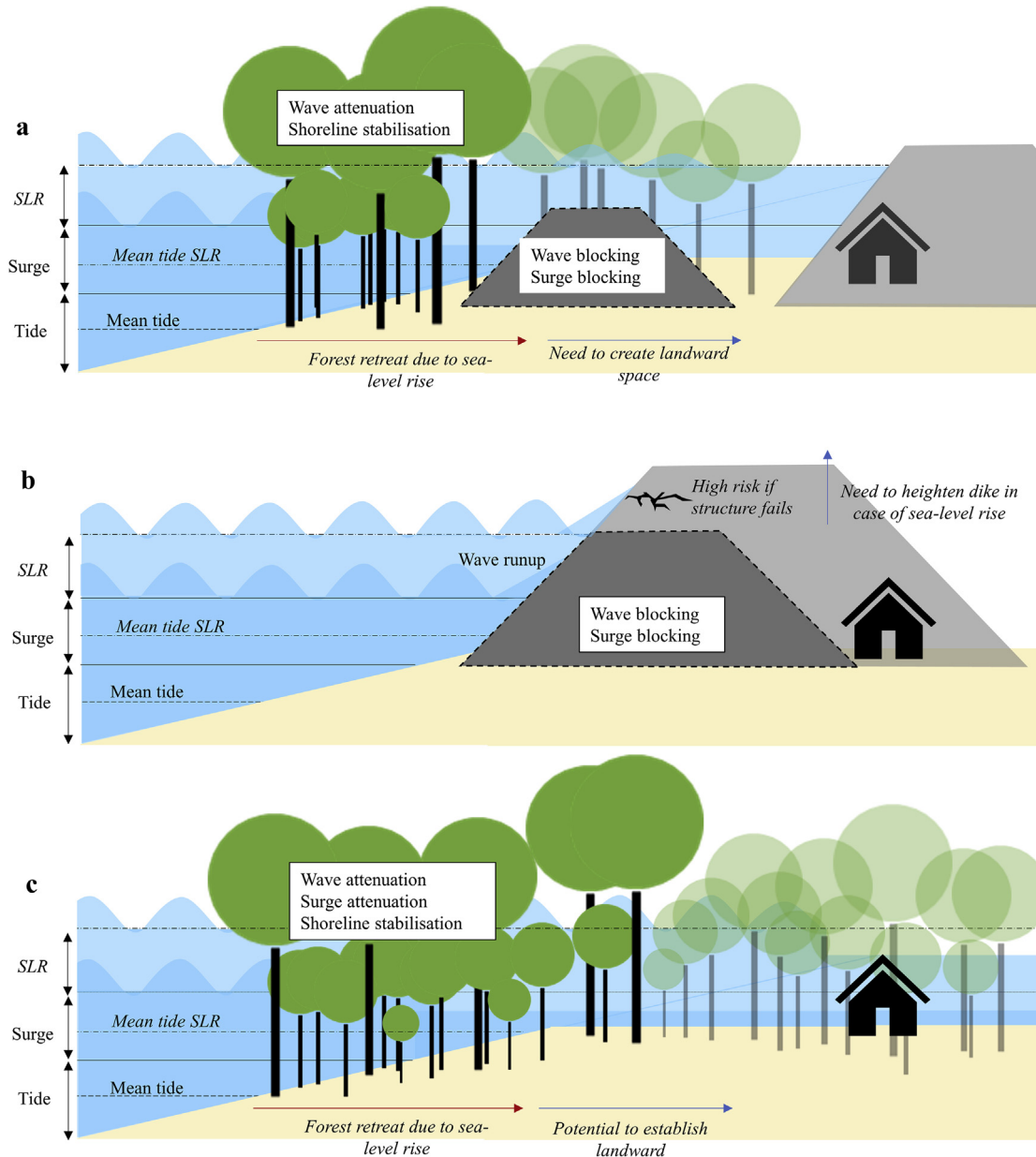


Fig. 2. Simplified overview of coastal protection functions by mangroves and engineering structures and potential consequences of sea-level rise (SLR) (not to scale): (a) mangrove forest and dike, (b) traditional engineering structure, and (c) only mangrove forest. In case of sea-level rise (lightest blue), mangroves may require space for landward migration (transparent forest), and engineering structures may need to be heightened (light grey).

requiring experimental or field data to correctly estimate drag coefficients (Chen et al., 2018; Hu et al., 2021b; Liu et al., 2015; van Veelen et al., 2021; Yao et al., 2018). Additionally, experimental studies have accounted for the complex structure of mangrove forests by considering more complex forest configurations with horizontal roots or extremely dense vegetation, and even scaled mangrove mimics (e.g. Maza et al., 2017). This has led to the development of a predictive approach using empirical relations between wave height attenuation and forest submerged solid volume fraction (Maza et al., 2019). As the tree architecture of most mangrove species

is known (Tomlinson, 2016), this approach can reliably account for the complex structure of mangrove forests – given that field validation is possible. However, there is still high uncertainty in the effect of flexible vegetation on wave attenuation. Currently, model approaches assume that vegetation is rigid under flow action (e.g. Maza et al., 2021), but at high velocities, stems, branches, and leaves can break or bend to realign in the water stream (van Wesenbeeck et al., 2022; Vollsinger et al., 2005). Realignment leads to reduction of frontal surface area, which differs between mangrove species that vary in flexibility and strength of branches and leaves (van

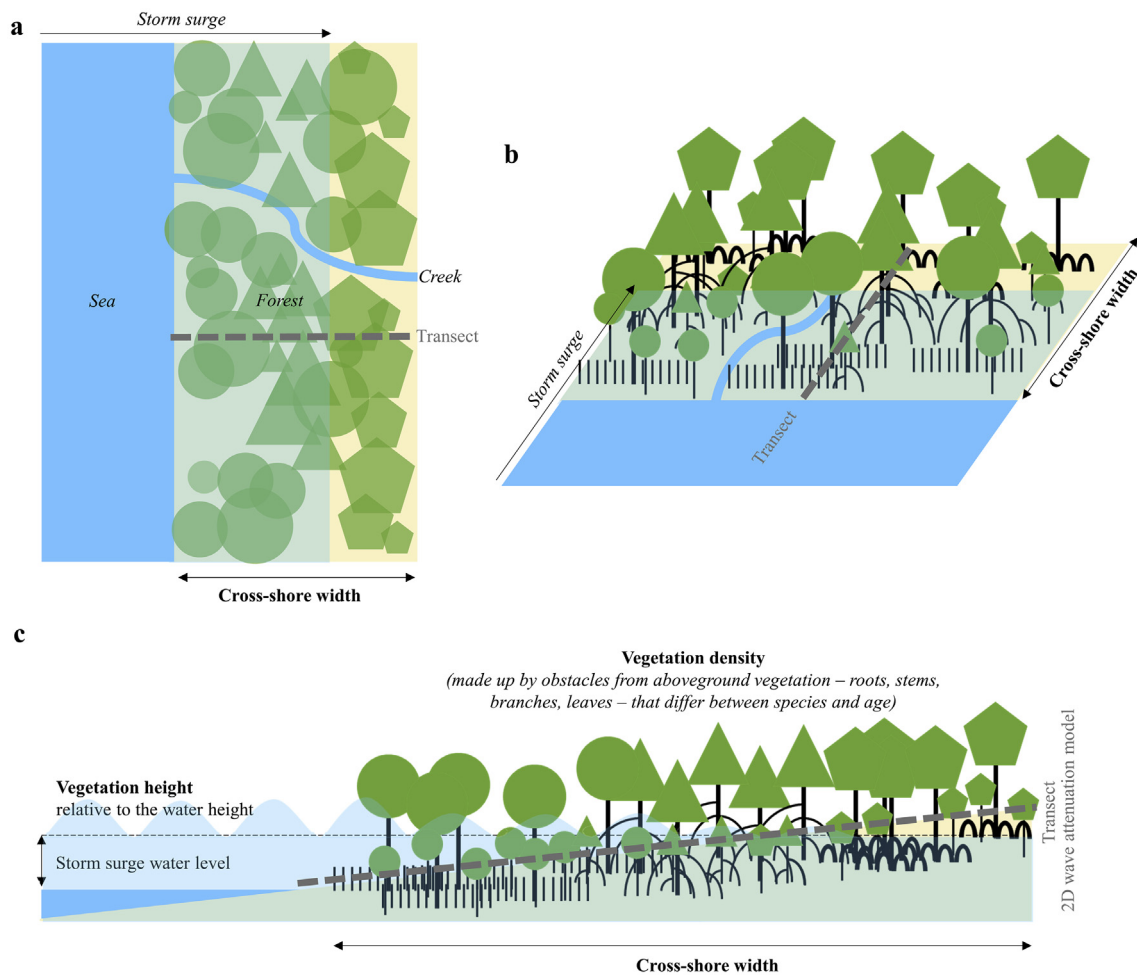


Fig. 3. Simplified overview of relevant mangrove properties for wave attenuation with top-down view (a), three-dimensional (3D)-frontal view (b), and cross-shore side view (c).

Hespén et al., 2021). Despite this, realigned vegetation still contributes to wave attenuation, yet to what extent is complex to quantify (Kalløe et al., 2022).

2.3. Estimating mangrove surge attenuation requires capturing surrounding landscape

Mangrove forests can reduce surge water levels during tropical storms. This ability depends on the forest structure, storm properties (intensity, duration, forward speed, and track), and the surrounding landscape (McIvor et al., 2012). The relevant forest properties are similar to those for wave attenuation, and wider, denser, and taller forests are more effective (Montgomery et al., 2018; Sheng et al., 2012; Zhang et al., 2012). However, resolving the contribution of mangroves to surge attenuation is complicated and requires detailed spatially explicit modelling, as surge effects are strongly dependent on the interaction with the surrounding topography, landscape, and storm properties (Liu et al., 2013, 2015). For example, creeks inside the forest may actually work as a conveyor and increase storm surges (reviewed in McIvor et al., 2015). In the past decade, surge attenuation modelling

with mangroves has started to emerge, with models that include the effect of vegetation by an enhanced bottom friction (Dasgupta et al., 2019; Liu et al., 2013; Xu et al., 2010). Further model developments, together with a collection of observations of surge attenuation during extreme events, could help to resolve the current uncertainty around the role of mangrove forest properties in surge attenuation.

3. Forest expansion requires space and successful seedling establishment

3.1. Propagule availability and seedling establishment

Forest expansion of cross-shore width is driven by successful seedling establishment (Fig. 4). Maximum cross-shore width is limited. At the landward side, factors such as presence of dikes or alternative land use can be limiting (van Bijsterveldt et al., 2022; Section 2 of Appendix A). At the seaward side, space is mainly limited by physical drivers that control seedling establishment. Here, the area must be reached by propagules that disperse from existing mangrove stands. Propagule availability depends on (1) the number of

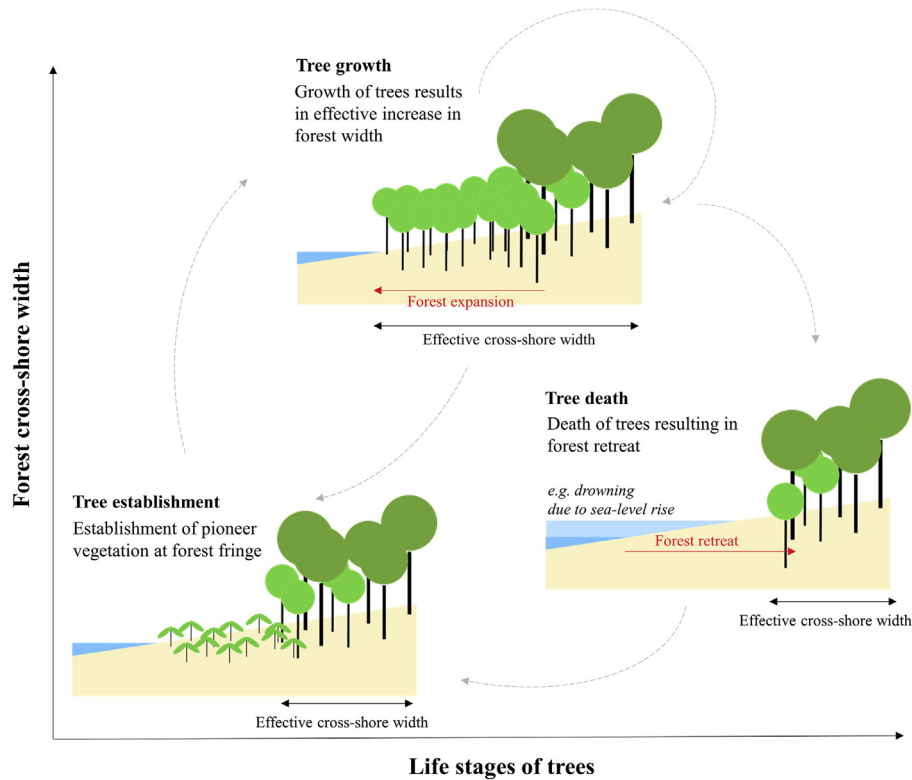


Fig. 4. Simplified overview of seaward forest expansion and retreat (cross-shore width) as a function of tree development (life stage). Establishment does not affect the effective forest width, as seedlings cannot yet provide coastal protection but are the essential basis for forest expansion (Section 3). Forest retreat takes place when trees at the forest edge die (Section 4). Life stage progression (establishment, growth, and mortality) is species-specific and depends on environmental and physical drivers. Arrows suggest possible directions in which forest changes can take place.

reproducing trees in a forest and (2) tree fecundity (i.e. the number of propagules produced per tree; Clarke, 1995). Fecundity increases with tree age, temperature, and species that produce smaller propagules, and varies greatly among individual trees (Alleman and Hester, 2011; Clarke, 1992; Duke, 1990). Fecundity also tends to be higher in years after tropical storms, unless there was large canopy damage (Alleman and Hester, 2011; Proffitt et al., 2006). While reproductive trees ensure propagule production, propagules need to disperse beyond the forest edge to expand forest size. Mangrove propagules disperse via water, a process mediated by propagule traits, tidal currents, wind, and waves (see Van der Stocken et al., 2019 for a review). Landscape features such as vegetation may impact dispersal through the effects of vegetation-induced drag force on hydrodynamics (Maza et al., 2017) or by interacting with the propagules directly. For example, saltmarsh vegetation can enable stranding and facilitate mangrove recruitment beyond the established tree line, particularly during spring or storm tides (Peterson and Bell, 2015). When a propagule has reached the seaward forest fringe, successful establishment will require a ‘window of opportunity’, where disturbance from hydrodynamic forces is absent (Balke et al., 2011). During this window of opportunity, a seedling can grow roots to anchor and overcome buoyancy during high tide, and avoid dislodgement from wave drag and sediment erosion. Seedlings must also

grow long enough shoots to avoid suffocation from sediment burial (Balke et al., 2013). The ability to grow roots and shoots fast enough varies across species and environmental settings, as germination and growth rates depend on species-specific tolerances to environmental drivers, such as salinity, temperature, waterlogging, sediment type, and light availability (Krauss et al., 2008; Sloey et al., 2022; van Hespén et al., 2022).

3.2. Modelling forest expansion

Mechanistic models can use the window of opportunity framework to predict seedling establishment and estimate seaward forest expansion. Such a model has been developed for mangroves (Balke et al., 2015), and compares tidal data and sediment erosion depth to seedling root length to predict population survival rates of establishing mangrove seedlings. This approach has been further developed for saltmarshes, allowing for spatial and temporal variability (Hu et al., 2015) and different intertidal environments (Hu et al., 2021a). Further developing these saltmarsh models for mangroves requires experimental data on (1) mangrove species and environment-specific seedling root growth rates and uprooting tolerance and (2) daily bed-level dynamics. The former can be obtained from studies on establishment under sediment dynamics (Balke et al., 2011, 2013; van Hespén et al., 2022) and

other seedling establishment studies (reviewed in Krauss et al., 2008). Up until recently, daily bed-level data have been more challenging to obtain due to the labour-intensiveness of measuring at daily temporal resolutions. However, new tools are emerging. Surface elevation dynamic (SED) sensors provide a cheap and reliable way to collect long-term measurements of daily bed-level dynamics at many locations simultaneously (Hu et al., 2020; Willemsen et al., 2018). This makes it possible to gain understanding of the role of daily bed-level dynamics in long-term mangrove development and seedling establishment at the forest fringe.

4. Forest retreat under global change

Mangrove forest retreat at the seaward fringe takes place when local physical drivers hamper seedling establishment and cause tree mortality (Fig. 4), leading to loss of effective biomass for coastal flood protection (Fig. A.1). If too many trees are lost during forest retreat, forest width can even reach beyond a point of no return (tipping point; Scheffer et al., 2001). In the coming century, massive mangrove tree mortality events are expected to be exacerbated by global change, where general shifts in mean temperature or rainfall patterns may even affect the survival of mangroves at the geographic edge of their tolerances (Ward et al., 2016). Overall, extreme weather events such as storms, heatwaves, droughts, and oscillating sea levels are expected to lead to massive mortality (Sippo et al., 2018), with sea-level rise expected to have the biggest impact globally (Friess et al., 2022).

4.1. Keeping up with relative sea-level rise

The mechanisms that drive forest retreat under relative sea-level rise are quite well understood. Relative sea-level rise is the outcome of large-scale sea-level changes and vertical land movement, such as regional land subsidence from geological movements and anthropogenic activities like groundwater extraction (Woodroffe et al., 2016). Relative sea-level rise can result in an altered tidal regime, which can lead to stress and drowning of mangrove trees and impede seedling establishment if inundation becomes too frequent or too long (He et al., 2007; Sippo et al., 2018). Moreover, the risk of drowning is higher for mangroves in microtidal settings, where any relative sea-level rise represents a much bigger proportion of the tidal range than in a macrotidal setting (Lovelock et al., 2015).

As mangrove vegetation can promote sediment accretion (Section 1 of Appendix A), minerogenic mangroves can keep pace with (relative) sea-level rise if the forest surface elevation is able to rise faster than the sea level (Schuerch et al., 2018; Woodroffe et al., 2016). The ability of mangrove forests to keep pace may vary with factors such as tidal range and vegetation density. For example, mangrove forests with a small tidal range may accrete less sediment, as sediment deposition remains limited in such tidal systems (Xie et al., 2022). Furthermore, the increased water depths in front of the mangrove forest may deepen the foreshore, and larger waves

may hamper seedling establishment (van Bijsterveldt et al., 2020). If a mangrove forest is not able to overcome relative sea-level rise, alternative measures are needed to maintain enough forest biomass for nature-based flood defence, such as restoration techniques to improve conditions for seedling establishment at the seaward fringe or developing suitable space at the landward forest fringe (Section 2 of Appendix A).

4.2. Extreme weather events and mangrove forest resilience

The general mechanisms of extreme weather impact on mangrove forests are quite well known. Extreme weather events such as El Niño Southern Oscillations (ENSO) can lead to heatwaves, drought, and temporary drops in sea level (Sippo et al., 2018). Heatwaves may lead to desiccation as evaporation increases with high temperatures, leading to water loss (Rennenberg et al., 2006). Droughts, as a result of low rainfall and groundwater inputs combined with high temperature, can lead to development of hypersaline soils and cause hydraulic failure and desiccation in mangrove trees (Ward et al., 2016). Temporary drops in sea level may result in forest diebacks comprising canopy loss due to desiccation and reduced recruitment (Lovelock et al., 2017). Furthermore, coastal storms can impose stress from reduced oxygen supply to roots, caused by prolonged flooding or burial of roots by large volumes of sediment (Jimenez et al., 1985). They can also generate strong wind gusts, high waves, and enhanced tidal currents that lead to mechanical damage (Fig. A.1; Krauss and Osland, 2020; Tanaka, 2008).

Although there is relatively good understanding of the mechanisms that drive forest mortality, there are few tools to estimate the long-term resilience of a specific forest under repeated or combined extreme weather events (but see Asbridge et al., 2015). However, such tools are necessary, as tree mortality and hence forest retreat can vary widely, depending on environmental settings (e.g. Krauss and Osland, 2020). Previous storm history or pre-existing conditions such as long-term shoreline erosion trends can affect the impact of future storms (Bhargava and Friess, 2022; Taillie et al., 2020), while combined stressors can lead to widespread mangrove dieback, and subsequent storms can limit the re-establishment of mangrove seedlings (Asbridge et al., 2019; Duke et al., 2020). Furthermore, the risk of mechanical damage and mortality will vary across species, depending on their stress tolerance and mechanical properties such as strength and flexibility (Aung et al., 2013; van Hespén et al., 2021). The direct impact of coastal storms could be estimated by using storm damage models developed for terrestrial forests, which predict wind damage during storms using average canopy height, frontal surface area, and local wind speed (Gardiner et al., 2008). Furthermore, field experiments, such as testing the impact of storm waves with wave-generating field flumes (de Smit et al., 2020), could be used to test mangrove resilience to repeated storms, and could even be combined with drought or heatwave experiments to test resilience of mangrove trees to multiple stressors.

4.3. Modelling forest retreat under global change

The risks of extreme weather events and sea-level rise will vary regionally (Ward et al., 2016). Hence, understanding forest retreat requires translating the consequences of global change to local scale. This can be done by downscaling global climate models, an application that is currently still limited but certainly possible. Global climate models (such as the Coupled Model Intercomparison Project Phase 6 (CMIP6); Eyring et al., 2016) project future atmospheric and ocean conditions (e.g. wind, temperature, salinity, and sea surface height) at large spatial scales (25–100 km) using various emission scenarios to account for the uncertainty in future human choices (e.g. Representative Concentration Pathway or Shared Socioeconomic Pathways scenarios). As they have coarse resolutions and lack representation of ocean dynamics in shallow coastal areas (Jevrejeva et al., 2019), they are downscaled to produce regional climate projections that use global predictions as boundary conditions (e.g. Gutowski Jr. et al., 2016). Those regional climate projections can then force (i.e. provide boundary conditions) high-resolution models for specific coastlines, and project, for example, how global sea-level rise will affect local water levels (e.g. De Dominicis et al., 2020). Such high-resolution models may then be combined with the local forest structure and species-specific stress tolerances to obtain predictions of forest retreat at local

scales (for example, forest-specific responses to sea-level rise or storms; Gardiner et al., 2008; Xie et al., 2022, 2020).

5. Forest structure depends on species composition and biophysical interactions

5.1. Effect of shifts in species composition on wave attenuation capacity

Vegetation density and height are determined by establishment, growth, damage, and mortality of mangrove trees (Fig. 5). Therefore, variation in density and height stems from species-specific environmental tolerances that drive these processes. For example, the height that a tree can reach, and how long it takes to reach this, depend on the environment it grows in and the species it belongs to. Globally, mangrove canopy height is related to precipitation, temperature, and potentially cyclone frequency (Simard et al., 2019). Locally, salinity, nutrients, hydrology, and light availability can impact growth (Krauss et al., 2007; Lovelock et al., 2006; Peters et al., 2014). Between mangrove species, there are differences in the maximum heights that species can reach, ranging between 3 m and 40 m (Quadros and Zimmer, 2017). In addition to tree height, tree architecture can also vary widely between environmental settings and mangrove species (Clough et al., 1997; Hallé et al., 1978), such as the

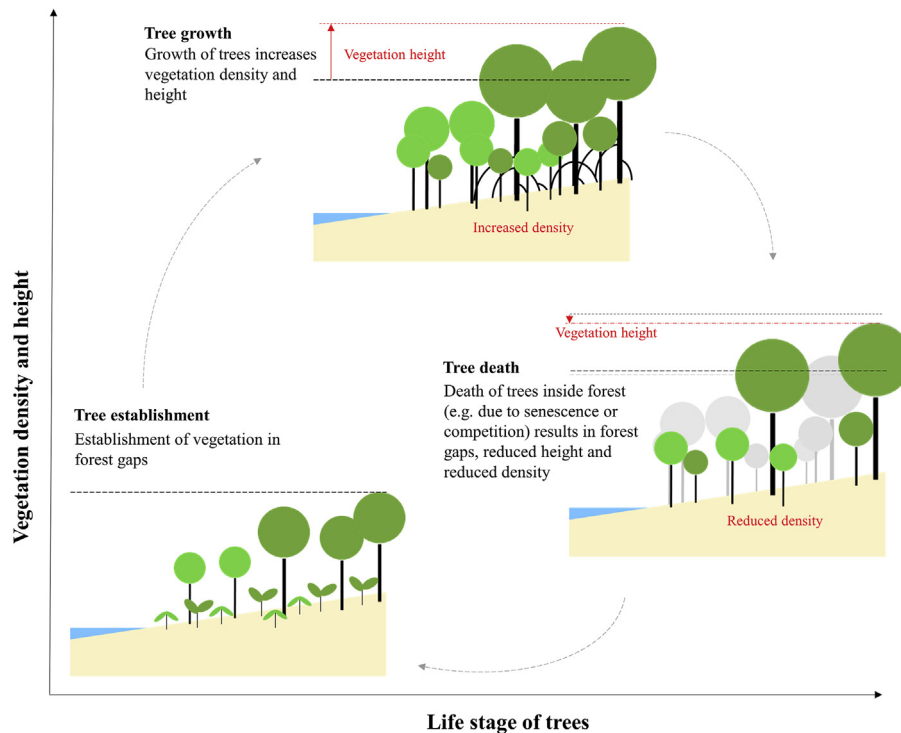


Fig. 5. Simplified overview of vegetation density and height as a function of tree development (life stage). Initial establishment does not affect the effective vegetation density and height immediately, as seedlings cannot yet provide coastal protection. When seedlings mature, the effective vegetation density and height increase, while they can decrease when trees die. Life stage progression (establishment, growth, and mortality) is species-specific and depends on environmental settings such as physical drivers. Arrows suggest possible directions in which forest changes can take place.

shapes of specialised aerial root systems (Tomlinson, 2016). Architectural differences may affect not only wave and surge attenuation but also sediment transport and resulting bed-level dynamics, as some aerial root systems may reduce the water flow more strongly, causing more sediment deposition or preventing more resuspension (Xie et al., 2020).

Over time, the species composition of a forest may change, potentially altering its capacity for coastal protection (Koch et al., 2009). For example, wood volume increases with mangrove species diversity (Njana, 2020). Species composition will largely be determined by (1) which species is currently present, and (2) which of those are able to establish and survive in the future. Global change that imposes major shifts in physical drivers (such as temperature or salinity) can affect local species compositions, as some species are no longer able to survive (Ward et al., 2016). For example, shifts in tidal inundation due to sea-level change can cause shifts in species composition, where species with wider tolerances are more likely to tolerate sea-level rise (Ellison et al., 2022; Watson, 1928). Similarly, increases in soil salinity can cause more stresses for species with lower salinity tolerance (Rahman, 2020). Furthermore, recovery from storm damage varies between species, possibly resulting in changes in species composition, particularly if storms increase in frequency or intensity (Krauss and Osland, 2020).

5.2. Modelling forest development with individual-based models

Despite being important drivers of wave and surge attenuation, vegetation height and density have not been studied in much detail in the context of nature-based coastal protection. However, there is potential to do so. There is a wealth of long-term ecophysiological data on mangroves (e.g. Putz and Chan, 1986; Sillanpää et al., 2017; Uddin et al., 2022). These data can be combined with models that can simulate mangrove forest dynamics to obtain increasingly realistic projections of forest structure. These simulations models (also known as individual-based models (IBMs)) allow for simulating tree recruitment, establishment, growth, allometry, productivity, and mortality, and can account for light and nutrient availability, soil pore water salinity, and competition between individuals, among others (Berger et al., 2008). Many IBMs assume that these abiotic factors are constant in time, but a push is expected toward models that can consider dynamic environmental conditions (Peters et al., 2020), which will allow for a more realistic prediction of forest structure under changing environmental conditions.

6. Conclusions and outlook

Mangroves can effectively attenuate waves and hence effectively contribute to nature-based flood defence (Fig. 2). In combination with engineering structures, wave attenuation by mangroves allows for lower structures and consequently lower construction costs (van Zelst et al., 2021). This perspective evaluates the current state of science on the processes that determine long-term resilience and functioning of mangroves

as part of a nature-based flood defence (Fig. 1). We uncovered the forest properties that are most important for coastal protection. That is, mangrove forests can effectively attenuate (storm) waves, provided that the forest is wide and dense enough and that the vegetation height matches the water level (Horstman et al., 2014; Menéndez et al., 2020; Quang Bao, 2011). Furthermore, we showed how biophysical and ecological processes alter these properties. However, it is currently still unclear how sensitive the (modelled) wave attenuation capacity is to changes in forest structure. The capacity of mangroves to contribute to surge attenuation is still poorly understood and requires better understanding of the role of morphology and vegetation patterns inside estuaries or deltas, combined with field observations of storm surges across a variety of forest structures.

The mechanisms that drive forest expansion are increasingly well understood, with a wide knowledge base on the tolerance of mangrove seedlings in a range of environmental settings. However, further mechanistic model development specifically for mangroves is needed to predict forest expansion in increasingly detailed environmental scenarios, such as changing tidal regimes and variable bed-level dynamics. New monitoring tools (SED sensors) could link daily and long-term bed-level dynamics and biogeomorphic forest dynamics and improve understanding of seedling establishment at the forest fringe. Forest retreat is relatively well understood thanks to empirical studies on extreme weather events, and mangrove retreat can even be modelled for a range of sea-level rise scenarios. However, mechanistic modelling of other stressors, particularly repeated and combined stressors, remains limited. Ultimately, the current state of science allows for the development of modelling tools that can estimate how the cross-shore width and structure of a specific forest will develop over time, while allowing for uncertainty in global change pathways due to unpredictability of future human choices. For example, individual-based models (Berger et al., 2008; Peters et al., 2020) could be combined with mechanistic simulation models that capture how physical drivers determine forest expansion (Balke et al., 2015; Hu et al., 2015, 2021a) and retreat (Asbridge et al., 2015; Xie et al., 2020, 2022), to estimate changes in forest structure and size. Such mangrove forest simulation models require input on relevant physical drivers under global change, which can be achieved by downscaling global climate models to provide local estimates, for example, of sea-level change or shifts in salinity. The predicted forest structure and size could then be combined with models, such as the one presented in Maza et al. (2021), to predict changes in the hydrodynamic attenuation capacity of a forest over time.

This paper provides a perspective on the current state of science for predicting future coastal protection capacity of mangrove forests. Nevertheless, implementing nature-based flood defence requires more than in-depth understanding of physical drivers and ecological processes alone. Mangrove forests sit in a socio-political and socio-economic environment, comprising of local pressures such as land use or plastic pollution (Bryan-Brown et al., 2020; van Bijsterveldt et al., 2021), as well as the triple planetary crisis (climate change,

biodiversity loss, and air pollution; UNEP, 2020). Mangrove forests offer multifunctionality by providing ecosystem services beyond flood protection, such as global climate regulation or trapping pollutants (Temmink et al., 2022; Waryszak et al., 2021), and have been perceived by fishers to increase fishery yields after their establishment (Debrot et al., 2022). Hence, it is worthwhile to consider when nature-based solutions should be designed to deliver specific ecosystem services like flood protection or be designed to optimize delivery of multiple services at the same time at potentially lower capacity (Section 4 of Appendix A). Finally, important constraints to the deployment of nature-based solutions in tropical coasts are practical in nature, such as a lack of guidelines or on the ground experience. Adaptive management can be used to obtain practical knowledge about mangrove functioning in coastal flood protection and develop field experience in restoring and protecting mangrove forests (Gijsman et al., 2021; Walters, 1986). Further research should focus on advancing interdisciplinary understanding through development of open-source models and accessible science that can be translated to applicable guidelines.

Declaration of competing interest

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

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