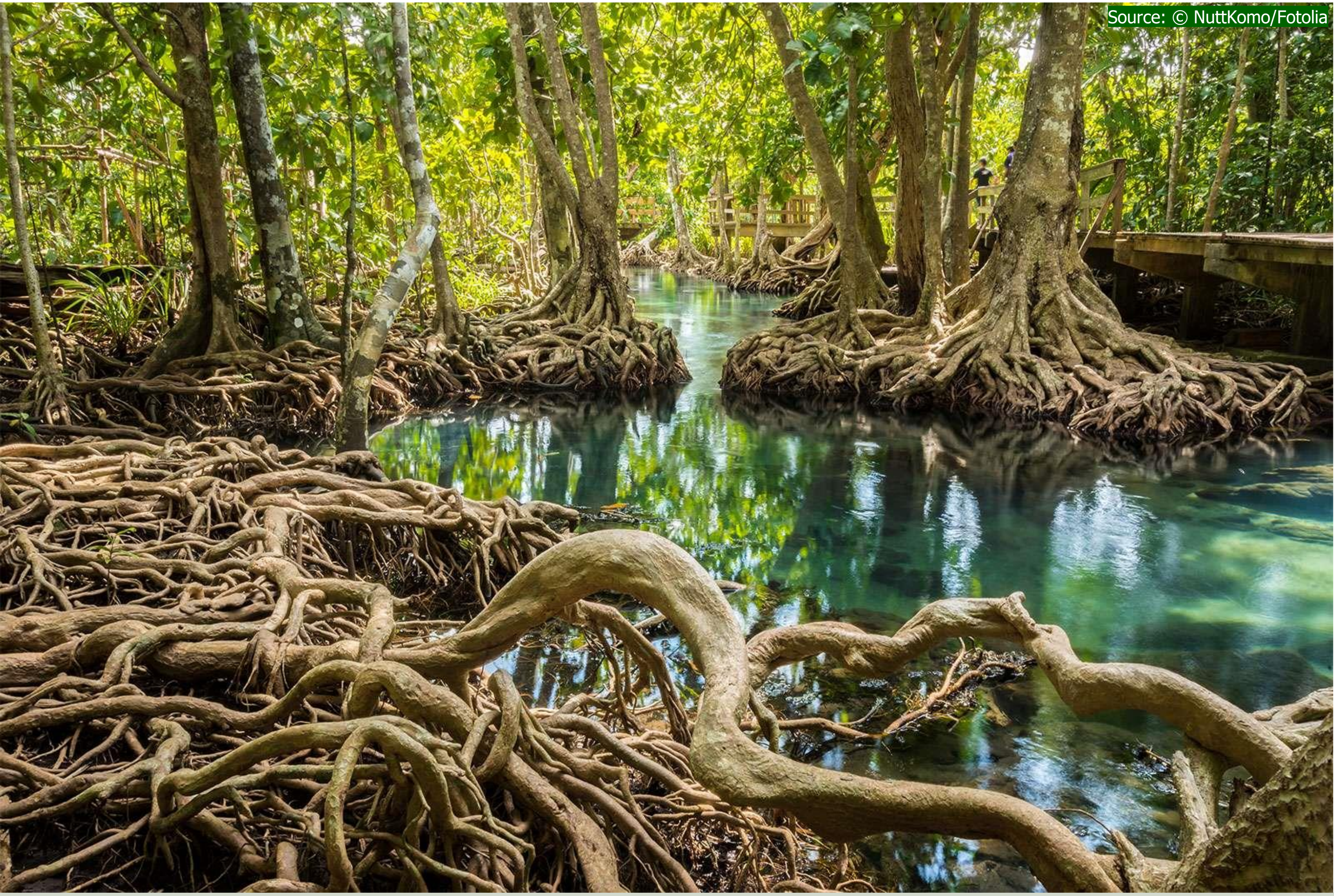

Building barriers

Elucidating the sediment trapping properties of mangroves and their relevance for ecosystem service provision

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Abstract

Mangrove forests in the tropics and subtropics provide a plethora of ecosystem services, among which mitigation of coastal erosion and protection against coastal disturbances and extreme weather events. These forests are however continuously under threat of degradation as the result of direct human actions and the consequences of climate change, especially noting sea level rise. As a way to escape this degradation and continue providing these ecosystems services, mangrove forests are able to expand or migrate. A major factor influencing their capacity to do this is their ability to influence sediment dynamics and consequently stimulate sedimentation. This review therefore aimed to show the ways in which mangroves facilitate this process. Here we start by describing the functional anatomy of mangroves for sediment trapping, together with the conditions necessary for mangrove forest migration. Once these theoretical foundations are established, we highlight a number of experimental studies, both in field and lab settings that have aimed to uncover the biophysical properties of mangroves that underlie sediment trapping, as well as remote sensing studies that describe the influence of sediment capture on mangrove forest migration in various geographical contexts. Subsequently, we describe how this experimental and remote sensing data has been used to create several models that are able to predict how mangrove ecosystems will develop under the influence of various bio-geomorphological factors. Next, we note some Building with Nature projects that have intended to restore degraded mangrove forests by applying the acquired theoretical knowledge of sediment trapping. We then envision the future of mangrove forests, where their survival is influenced by both environmental factors and human (in)actions. In summary, we note that comprehensive understanding of mangrove forests and the complexities regarding their context-dependence, in combination with sustainable usage are crucial in ensuring that these forests are able to provide their ecosystem services far into the future.

Keywords Mangroves – Sediment trapping – Resilience – Field/Lab experiments – Remote sensing – Model simulations – Building with Nature

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Introduction

Mangroves are tropical, subtropical, and temperate tree and shrub species that offer a plethora of ecosystem services. These services include the provision of habitat for fauna and resources for human usage, as well as their function as biofilters, carbon sinks and protectors against coastal erosion due to their sediment binding and wave attenuating abilities (Chen et al., 2018; Spalding et al., 2010, 2014). It is the latter service that will become more valuable in the coming years with both sea levels rising, currently at a rate of 3.4 millimetres per year, and extreme weather events becoming more prevalent as the result of climate change (He & Silliman, 2019; National Aeronautics and Space Administration, 2021).

The mangrove family consists of 73 species that occur on the border between land and sea, a space known as the intertidal zone (Figure 1, Spalding et al., 2010). The term mangrove is used for the trees and shrubs themselves, as well as the forests and ecosystems they form.

Emphasising the protective functions of mangroves is important, since they are currently under threat of destruction (Food and Agriculture Organization of the United Nations, 2020). The degradation of mangroves is predominantly driven by land use change, where mangrove forests are cut down to make space for urbanisation, agriculture, but most commonly aquaculture (Figure 2, Spalding et al., 2010). Other drivers of mangrove forest degradation are overexploitation of its resources, namely wood and fish, as well as excessive pollution dumped in these areas, the presence of artificial structures that limit inland migration and natural disasters (Mentaschi et al., 2018; Spalding et al., 2010)

The global coverage of mangroves was estimated to be around 14.8 million ha in 2020, with the majority being in Asia, especially in Indonesia, where species diversity is also highest

Figure 1. A mangrove tree in the intertidal zone, with its abovewater canopy and underwater root system. Source: https://www.iucn.org/news/marine-and-polar/201907/celebrating-mangroves-super-ecosystem-tropics

Figure 2. Mangrove forest degradation resulting from land use change to aquaculture in Vietnam. Source: Kautz et al., 2011.

(Figure 3, Food and Agriculture Organization of the United Nations, 2020). It has been estimated that from 1980 to 2020 approximately 1.04 million ha of mangrove forest has been lost (Food and Agriculture Organization of the United Nations, 2020). However, it should be noted here that the rate of loss has been declining since the 1980s. The past decade has nevertheless shown an increase in mangrove loss in Asia, with increased loss seen in Indonesia especially (Food and Agriculture Organization of the United Nations, 2020).

Mangroves grow in the intertidal zone, where saline water from the sea encounters freshwater derived from either rivers, groundwater, or precipitation, resulting in varying levels of salinity (Figure 4, Spalding et al., 2010). These areas are also subjected to

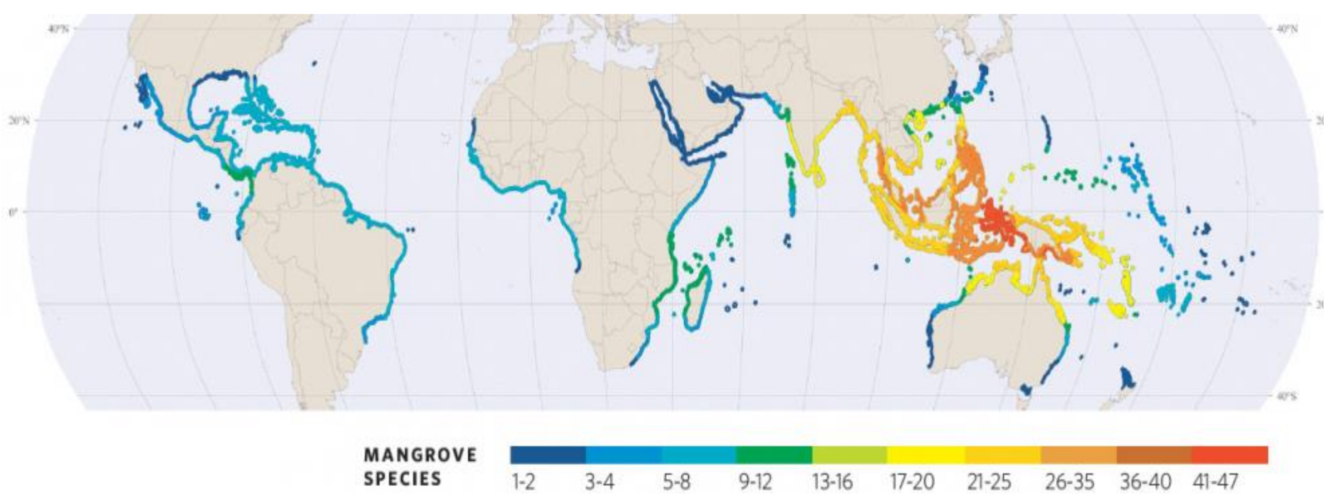

Figure 3. Global mangrove coverage and species diversity. Source: Spalding et al. (2010).

frequent inundation due to the workings of the tides (Spalding et al., 2010). While the capacity for growth in these conditions is dependent on the species of mangrove, the matter that mangroves are able to grow in these saline conditions is in itself quite impressive (Spalding et al., 2010).

In order to ensure protection of mangroves, sustainable exploitation of intact mangrove forests, and restoration of those that have been degraded, it is of utmost importance to further highlight the benefits that healthy mangroves can offer in regard to climate change. In this review, we will therefore elucidate the potential for mangroves in reducing coastal erosion and stimulating soil accretion as a way to counter climate change-induced sea level rise (SLR).

We will first discuss the underlying mechanisms and processes that underlie the sediment trapping capabilities of mangroves. Subsequently, we will note several field and lab experiments, as well as remote sensing studies, that have aimed to uncover the extent to which mangroves are able to trap sediment. We will then highlight models that have tried to simulate mangrove sediment trapping to predict future developments for mangrove forests. Thereafter, we will focus on Building with Nature projects that have incorporated mangroves into their design as a way to reduce coastal erosion and counteract SLR. We will conclude this review by discussing future developments of mangrove ecosystems as well noting the knowledge gaps that still exist in regard to their sediment trapping capabilities.

Data collection

A literature study was conducted using the search terms "mangrove" and "sediment". For

Figure 4. Mangrove trees in the intertidal zones, at the barrier of sea and land. Source: https://wwf.panda.org/wwf_news/?358238/Importance-of-sediment-flow-for-mangrove-conservation-and-restoration

the chapters on field and lab experiments, remote sensing studies, model simulations and building with nature projects, additional search terms were used, respectively "experiment", "remote sensing", "model", and "building with nature". We predominantly made use of articles and reviews that were published in the last 10 years, as a way to highlight recent developments that have occurred within the field of mangroves.

Sediment availability

In order for mangrove forests to expand, the environmental conditions have to allow for expansion. Among other things, a supply of sediment is required for mangrove stabilization and consequent soil accretion to occur (Spalding et al., 2010). Sediment availability is dependent on the workings of the tide, with sediment capture occurring predominantly during flood in comparison to ebb (Chen et al., 2018). Sediment deposition facilitates the establishment of mangrove seedlings and further propagation of mangrove forests (Figure 5, Spalding et al., 2010). Even when sediment is sufficiently available, mangrove soil accretion is relatively slow and is measured in millimetres per year (Krauss et al., 2014).

Many mangrove species prefer softer sediments to grow in, yet there are also species better adapted to harder soil surfaces (Spalding et al., 2010). Mangrove forests can expand rather fast in river deltas and estuaries, where a large amount of sediment is continuously supplied by the river (Spalding et al., 2010). However, sediment can also be supplied on open coastlines, provided that tidal dynamics are sufficiently low (Spalding et al., 2010).

The amount of supplied sediment is dependent on the ecosystem the mangrove is part of (Spalding et al., 2010). When sediment supply diminishes in an area, mangroves will have more difficulties with soil accretion (Mentaschi et al., 2018). Chances of this occurring are increasing as the amount of fresh water input from rivers is decreasing as the result of climate change, consequently reducing the input of fresh sediment. This can also be the result of human activities, such as the building of dams, behind which large amounts of sediment can be trapped (Vörösmarty et al., 2003; Weston, 2014).

With reduced fluvial sediment input, soil accretion will be dependent on the presence of erodible sediments within estuaries, which require significant amounts of energy from wind or tidal workings to become dislodged and resuspended (Schoellhamer, 2011). When sediment is scarce, soil accretion will primarily occur as the result of peat formation and vertical root expansion, processes which are also slowed down when sediment supply is hampered (D'Alpaos et al., 2011). Decreased sediment supply will in this way worsen the resilience of these systems to inundation.

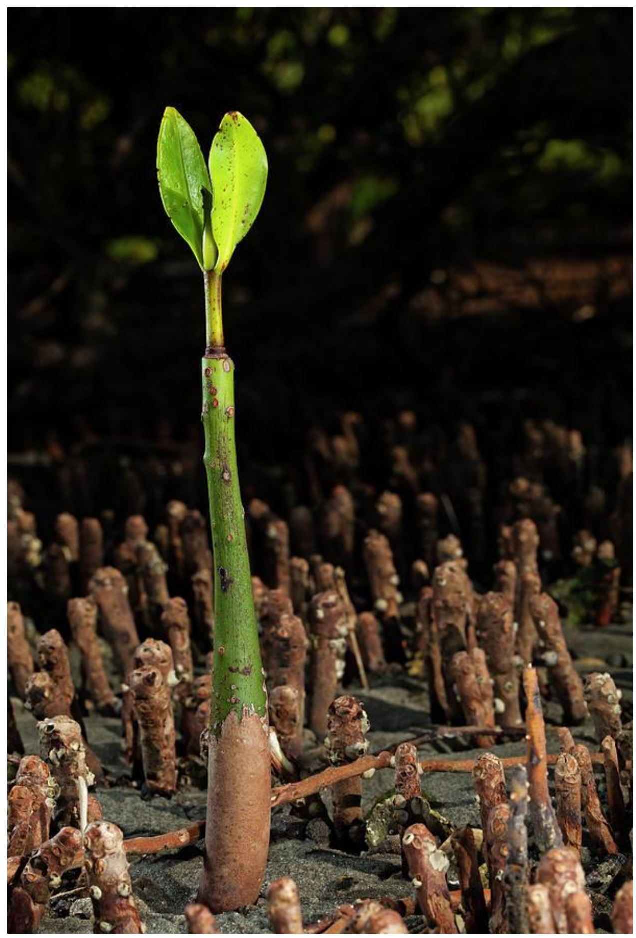

Figure 5. Red mangrove seedling in Baja California, Mexico. Source: https://fineartamerica.com/featured/red-mangrove-seedling-baja-california-mexico-claudio-contreras--natureplcom.html.

Reduced input of sediment is further emphasized in areas where soil subsidence occurs simultaneously. Soil subsidence in mangrove areas can be due to death and consequent compression of mangrove roots, but can also result from human actions, for example after groundwater extraction. Soil subsidence can also increase the degree of inundation in an area, which can negatively influence the development of mangrove forests (Webb et al., 2013).

Previous studies have shown that mangrove soil accretion can keep up with or even exceed SLR, provided that sufficient amounts of sediment are supplied (D'Alpaos et al., 2011; Krauss et al., 2014). Where sediment supply is insufficient and SLR exceeds soil accretion, mangrove forests will be forced to move landward. Landward migration of mangroves can however be hampered by the presence of hard artificial structures, resulting in the squeezing of mangroves between these structures and the rising sea (Spalding et al., 2010). In the case of such coastal squeeze, mangroves will have no habitat to move into, leading to their ultimate disappearance from these areas.

While reduced sediment dynamics can be detrimental for the health of mangrove forests, excessive sediment deposition is not desirable either. When a lot of sediment is built up too rapidly, mangrove mortality is induced due to blockage of the lenticels, necessary for gaseous exchange, which consequently reduces respiration (Figure 6, Ellison, 1999). Sediment availability should therefore be balanced in both amount and frequency.

Mangrove root types

In addition to the availability of sediment, the capturing efficiency of mangroves is also of importance for soil accretion. The capturing of sediment is performed by the root and shoot systems of the mangroves (Srikanth et al., 2016). There are four types of mangrove roots, namely stilt/prop roots, buttress roots, pneumatophores and knee roots (Figure 7).

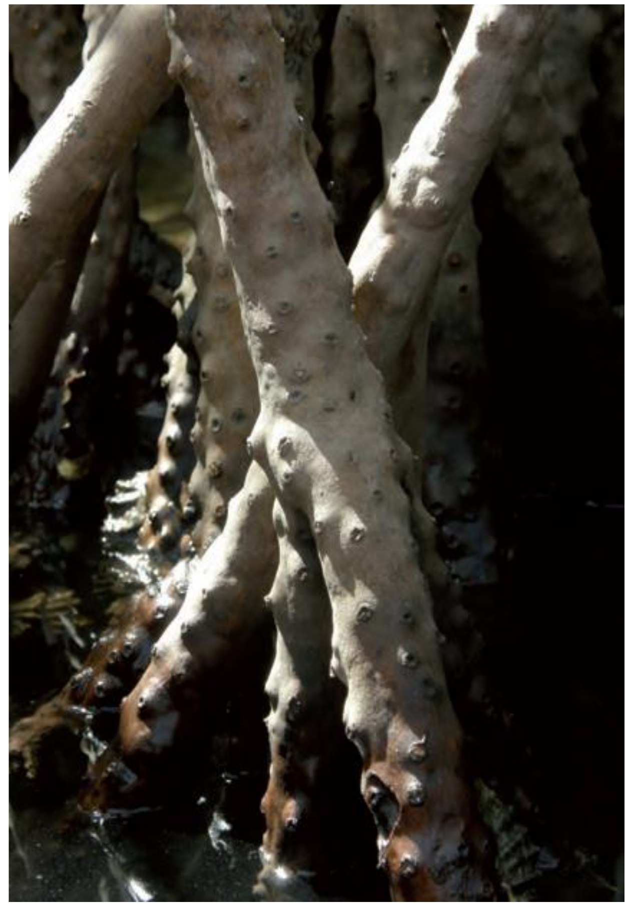

Figure 6. Lenticels covering the shoots of mangroves that mediate gaseous exchange. Source: Spalding et al. (2010).

Depending on the softness of the soil surface, several mangrove species are able to develop aboveground root systems as a way to improve stability (Ong et al., 2004). These roots can be of either the prop or buttress type. The aboveground root systems generally do not develop for mangrove species growing at higher altitudes, since the harder soils do not require additional stability (Srikanth et al., 2016).

Prop roots have high defensive value against EWEs and additionally trap silt and debris that are brought along by the water, further improving stability of the mangroves in the soil (Méndez-Alonzo et al., 2015; Srikanth et al., 2016). Soil accretion is however also influenced by vertical growth of the roots of the mangroves themselves. Noting these bio-geomorphological processes, mangroves can be considered to

Figure 7. The four mangrove root types (from top to bottom): stilt/prop roots, pneumatophores, buttress roots and knee roots. Source: Spalding et al. (2010).

actively contribute to shaping their own physical environment.

Pneumatophores also aid in sediment accretion. In addition to slowing down hydrodynamics, pneumatophores are also thought to be important for the retention of waterborne sediment (Spenceley, 1977). In addition, when the soil accreting properties of prop roots and pneumatophores were compared, it was found that while prop roots had higher soil accretion rates, pneumatophores showed relatively more vertical gain due to reduced soil subsidence in pneumatophore-rich areas (Krauss et al., 2014).

Sediment trapping capabilities

Mangroves can aid in the capture of sediment in several ways (Figure 8, Srikanth et al., 2016). The precise mechanisms behind the sediment trapping are however not completely clear (Krauss et al., 2014). The general concept is that mangroves are able to break waves, inducing drag force which reduces the energy of these waves and consequently facilitates sediment deposition (Mazda et al., 1997).

Suspended sediment is influenced by the settling velocity, indicating the rate with which a particle settles in a fluid, and the shear velocity, which describes the influence of shear stress on particle movement within a fluid (Cheng, 2008). An environment is considered deposition-dominant if the shear velocity is at least a factor 10 greater than the settling velocity (Zong & Nepf, 2010). It is thought that the density of the aerial roots is positively correlated with the degree of shear stress (Chen et al., 2016; Furukawa & Wolanski, 1996).

In addition, mangroves are also proficient at binding fine particles, such as clay and silt (Furukawa et al., 1997). This sediment binding can result in the formation of slopes, which can attenuate hydrodynamics.

In situations where water flow is able to reach the heights of the canopy of the mangroves, their leaves can also trap sediment and increase retention (Chen et al., 2016). Since this requires the water level to be relatively high, this form of sediment trapping does not occur

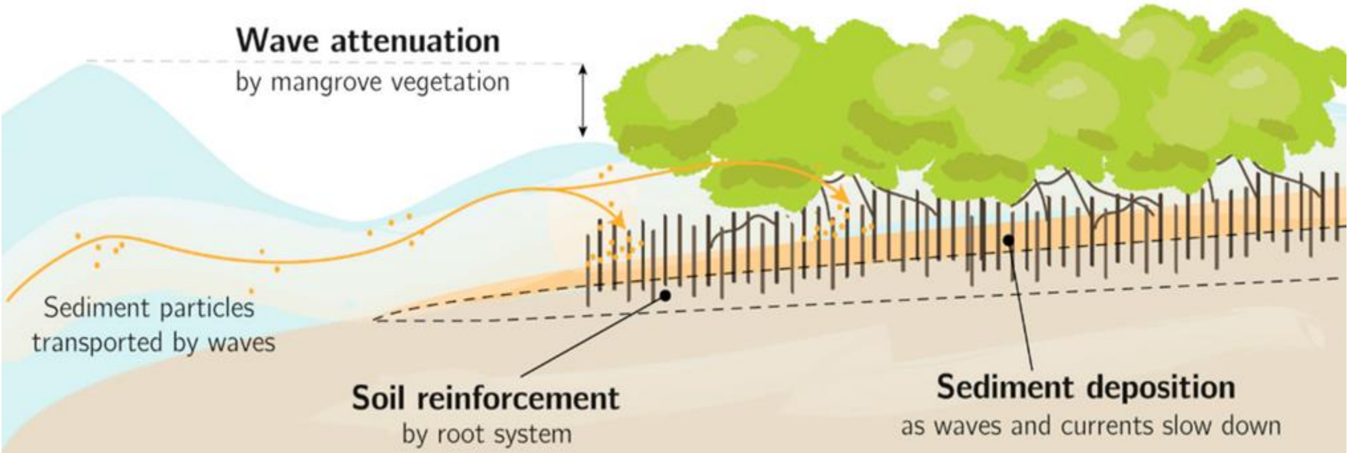

Figure 8. Physical attributes of mangroves influencing sediment dynamics. Source: Mancheño et al. (2021).

often in mature mangroves, but can occur in seedlings, which are of lesser height (Chen et al., 2018).

Furthermore, the type of soil is of influence on the capacity for mangroves to develop roots, with root growth occurring more strongly in softer muddy soils than in harder sandy soils (Lovelock et al., 2007). In addition, variable soil types can negatively affect root growth (Gill & Tomlinson, 1977). A question that therefore remains is what the effect of SLR will be on mangrove trees at different altitudes with different soil types.

Lab and field experiments

We will now describe several studies that have aimed to clarify the mechanisms behind the sediment trapping capabilities of mangroves and have tried to experimentally track sediment dynamics in mangrove forests, starting off with some lab studies.

The main method to investigate fluid dynamics in a lab setting is by using flumes (Figure 9). A flume is a system consisting of a channel in which water currents or waves can be simulated. These can for example be used to test how currents are influenced by obstacles, such as those resembling mangrove roots, and to determine the dynamics of particles within fluids, as in the case of sediment suspended in water.

One way in which flumes can be used is to study the establishment of mangrove seedlings. In order for a seedling to establish, it needs to be able to lodge itself within the soil. This must occur in what has been referred to as a "window of time", starting once the tides deposit the seedling on the soil (Balke et al., 2011). To investigate this window of time, a study made use of field and flume studies and found that, for a seedling to successfully establish, three thresholds have to be crossed, concerning the successive stages of root development to compensate for seedling displacement or dislodgement (Figure 10, Balke et al., 2011). Here each stage has a primary reason for disturbance, with the first being inundation, the second being hydrodynamic forces of waves and currents, and the third being high energy events that would cause erosion around the seedling.

Another study has used flumes to describe the role of porosity in influencing flow velocity and consequent sediment dynamics in mangrove forests (Kazemi et al., 2021). Here porosity is an indicator for the percentage of total space that is uncovered by obstacles (Figure 11). This was studied by using obstacles of various porosities to investigate how flow velocity is affected, as a proxy for the effects of mangrove aerial roots on hydrodynamics. This study found that a porosity of 47% is optimal for transport of sediment while minimizing the occurrence of erosion, resulting in a deposition-dominant area behind the roots.

The effects of sedimentation and inundation can also be investigated by use of mesocosm experiments, in which parameters can be studied in the field under controlled conditions. This has been used to describe the effects of varying sediment dynamics on the survival of seedlings of different mangrove species (Balke et al., 2013). They found that faster-growing seedlings of the one mangrove species are better able to cope with disturbances in sedimentation and erosion than slower-growing ones of the other species. Here sedimentation is compensated for by increasing their overall biomass to outgrow the deposition, and erosion is compensated for by developing their root network to avoid tipping over. Additionally, faster-growing seedlings were found to cope better with the stresses of inundation and disturbance by waves.

Experimental studies regarding mangroves often take part in the field, since much of the influences on mangrove development vary between places. On the basis of a study performed on Iriomote Island in Japan and Hitchinbrook island in Australia, it was hypothesised that hydrodynamics within relatively untouched riverine mangrove forests are only influenced by the slope op the land and the presence of vegetation that exerts drag force (Mazda et al., 1997). The authors state that the hydrodynamics within mangrove forests are therefore mainly influenced by the inundation regime, as well as the plant species composition and density thereof. It is therefore also the case that hydrodynamics differ between tidal rivers, estuaries and the interface between these two regions, with each having their own set of processes influencing sediment dynamics (McLachlan et al., 2017).

Mangrove development is furthermore influenced by the soil conditions of the surface they grow in. A study in the Mekong delta in Vietnam found that a sandy soil results in higher densities of primary mangrove species than muddy soils (Nardin et al., 2016). The reasoning for this is thought to be that the particles that mud consists of are quite small and are therefore resuspended easily by coastal hydrodynamics. Seedlings trying to settle on muddy soils will therefore be more easily disturbed, hampering establishment. The researchers do however note that this finding may be only the case for this

Figure 9. Flume used to mimic hydrodynamics in a mangrove forest. Source: Van Der Stocken et al. (2015).

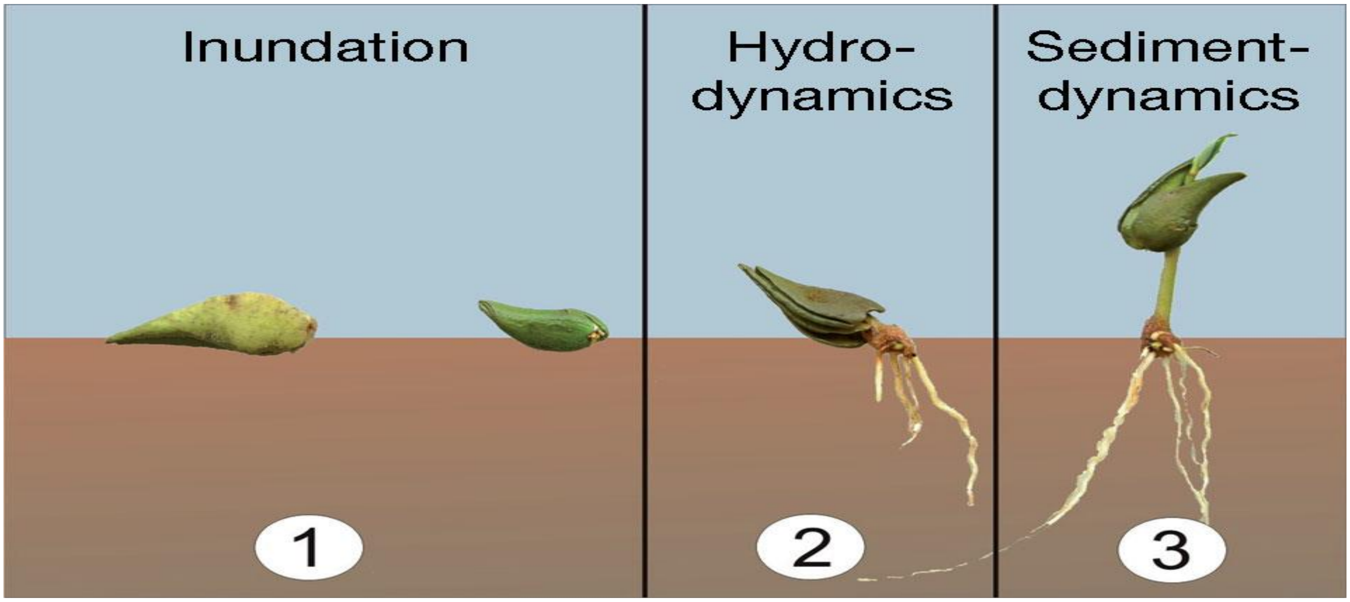

Figure 10. The types of disturbance that mangrove seedlings can handle at each of 3 stages of their establishment. Source: Balke et al. (2011).

study area, since the Mekong delta has high sedimentation supply of both larger and smaller particles.

Additionally, studies can be used to investigate the ways in which vegetation can influence hydrodynamics. A study performed in the Leizhou Peninsula in China found that shear stress was significantly higher in mangrove forests than on unvegetated mudflats (Figure 12, Mai et al., 2022). The degree of sheer stress was furthermore dependent on the species of mangrove that the forest consisted of, with some species exerting more sheer stress than others. It is this sheer stress that mediates sediment deposition and minimizes soil erosion in mangrove forests.

Two parallel studies performed on Cù Lao Dung in the Mekong delta of Vietnam found that turbulence was increased in pneumatophore-dense areas in the mangrove fringes (Mullarney et al., 2017; Norris et al., 2017). This was thought to be due to the pneumatophore-induced drag force that is experienced when coming from the tidal flats. The turbulence associated with this drag force would result in resuspension of fine sediment particles that are then carried further into the forest. It is there that dissipation of the water dynamics gradually increases and deposition of these fine particles is able to occur. The study therefore notes that the role of pneumatophores is more associated with distribution instead of deposition of sediment. The type of wave is also thought to be important for sediment transport within mangrove forests, with infragravity waves being the most probable mediator (Norris et al., 2021).

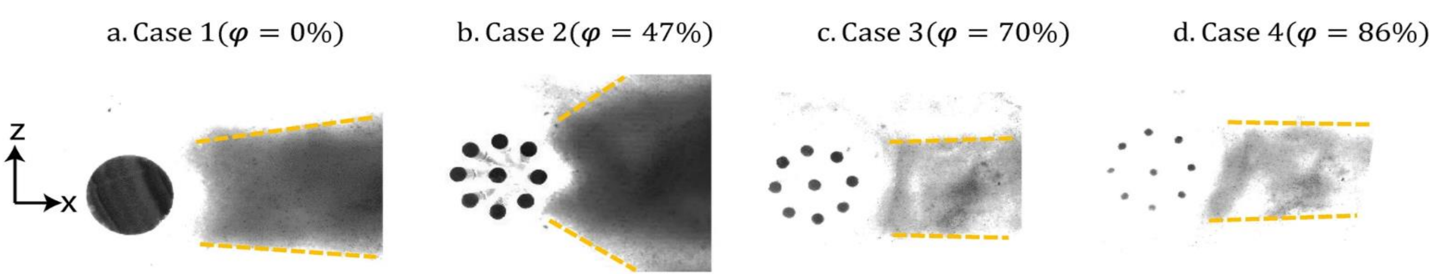

Figure 11. The effect of obstacle porosities on posterior sediment distribution. Source: Kazemi et al. (2021).

Field studies are also used to identify the consequences of aberrances in sediment deposition on mangrove forest development. This is the case for a study performed on the Porong river, Indonesia (Sidik et al., 2016). Here large amounts of sediment are deposited as the result of mud volcanic eruptions, which could accrete the soil up to 10 cm per year at the time of the study. However, these large amounts of deposited sediment did result in reduced survival of the dominant mangrove species in this region, due to it not being able to keep up with the sedimentation.

Another study in the Mekong delta in Vietnam notes the shallowing effect of sediment deposition within smaller channels (McLachlan et al., 2017). This is predominantly the case when river bifurcation occurs, resulting in reduced sediment supply coming from the shallower channel. This will consequently affect the development of mangrove forests downstream of this channel, since sediment will no longer be supplied in sufficient amounts.

Remote sensing studies

In addition to studies performed in the lab or field, studies can make use of remote sensing data as a way to investigate mangrove forests from afar. A selection of such studies is noted in Table 1. Remote sensing data is predominantly utilized to monitor the spatial and temporal changes in mangrove forest coverage of an area (Guo et al., 2017). Monitoring these changes can aid in early detection of mangrove degradation and allows for immediate conservative and restorative action to be taken (Lewis et al., 2016).

The most commonly used form of remote sensing data is optical imagery. Optical imagery makes use of satellites to form an image using sensors for the visible spectrum. Some satellites additionally make use of the near infrared and infrared spectrum. Common indicators to study mangrove forests and their dynamics with optical imagery are vegetation indices. The normalised difference vegetation index (NDVI) is one of such indices and uses the red and near infrared bands of satellite images to determine the amount of

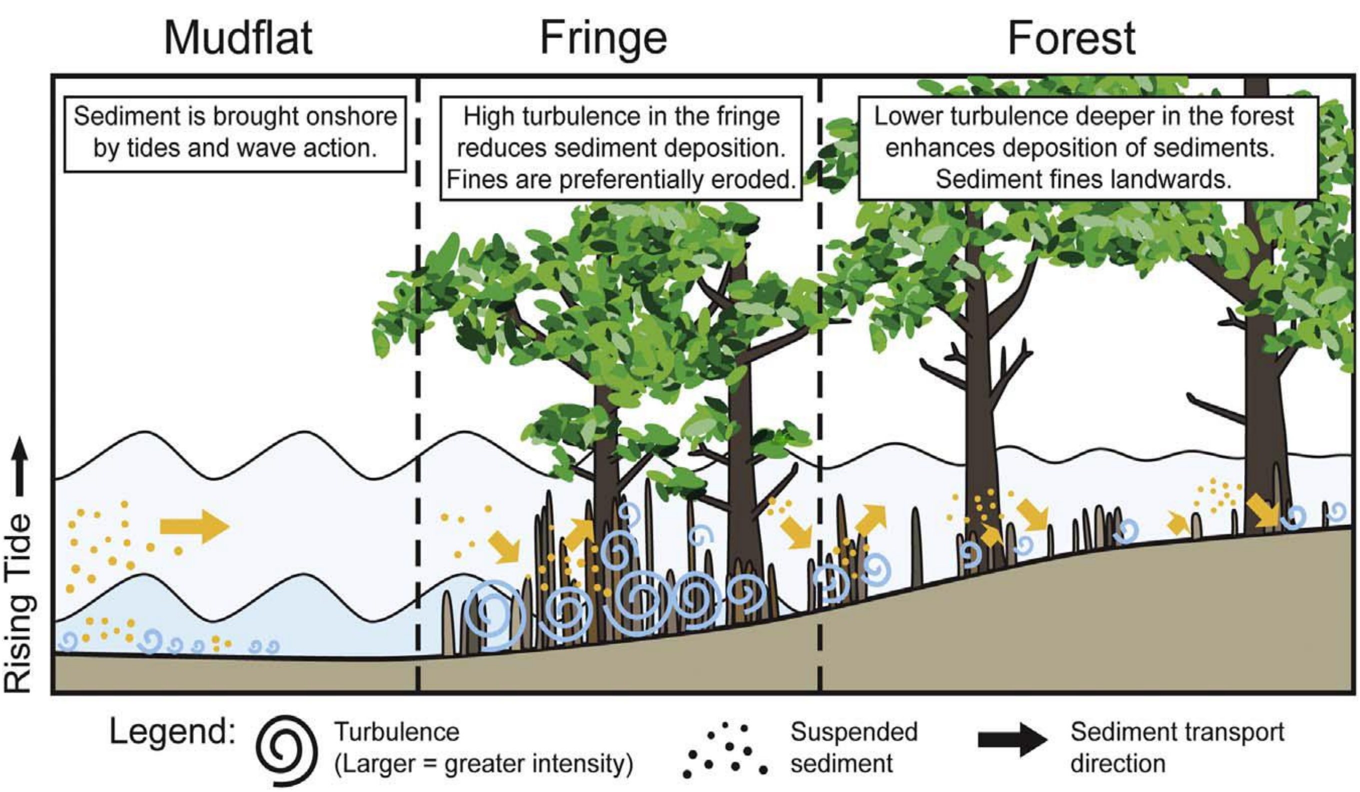

Figure 12. The effect of pneumatophore density on the degree of turbulence and consequent sediment deposition and erosion in different parts of a mangrove forest. Source: Norris et al. (2017).

Table 1. The location, timescale, data type and main findings of the remote sensing studies highlighted in this review.

Location	Timescale	Type	Findings	Reference
Suriname Coast	2000-2018	Optical (Landsat)	Westward migration of mangroves linked to movement of mud bank	de Jong et al., 2021
CùLao Dung Island, Vietnam	1990-2015	Optical (Landsat)	Sonneratia species create habitable conditions for secondary species, notably low wave energy, low forest density, increased elevation, and reduced tidal inundation	Bullock et al., 2017
Saloum Delta and Casamance Estuary, Senegal	2000-2018	Optical (Landsat)	Reduced regeneration of Avicennia germinans, presumably due to lacking sedimentation, results in excessive Rhizophora colonization limiting the expansion of the region	Lombard & Andrieu, 2021
Mai Po, Hong Kong	1991-2015	Optical (SPOT + GF-1)	Increased fluvial sedimentation resulted in migration of the mudflat which allowed mangrove seedlings to establish and resulted in expansion of mangrove forests	Liu et al., 2018
Hinchinbrook Island, Australia	1987-2016	Optical (Landsat + RapidEye) + Radar (ALOS-PALSAR)	Rhizophora species is sensitive to mechanical damage and shows little recovery over time after cyclone	Asbridge et al., 2018
Towamba Estuary, Australia	1949-2016	Optical (Landsat + LPI) + Photogrammetry (drone) + LiDAR	Estuarine habitat stabilisation due to sediment runoff, coastal dynamics and human activities, which may inhibit mangrove development	Al-Nasrawi et al., 2018
East Java, Indonesia	2009-2019	Optical (Landsat + Sentinel) + Photogrammetry (drone)	Continuous sediment supply as a result of mud volcanic eruption results in seaward migration of mangrove forests on average. Migration is season-dependent, with expansion occurring after wet season and regression after dry season.	Besselly et al., 2021
Zhangjiang Estuary, China	2017	Photogrammetry (drone) + LiDAR	Inundation patterns regulate the species composition and consequent spatial formation and elevation of mangrove forests	Zhu et al., 2019

vegetation in an area. By additionally using the normalised difference water index (NDWI), a study was able to distinguish land, water, and mudbanks on the coast of Suriname using optical imagery, as a descriptor of the habitat of mangroves, its boundaries and potential migration (de Vries et al., 2021).

By determining the changes in NDVI in optical imagery, the erosion and colonization of mangrove forests in Suriname during the period of 2000-2018 could be determined (Figure 13, de Jong et al., 2021). They found that the expansion of the mangrove forests was associated with the migration of the mudbank.

A similar finding was found in the Mai Po marshes of Hong Kong (Liu et al., 2018). Instead of using a vegetation index, they made use of machine learning techniques to distinguish different mangrove species on the basis of their spectral reflectance using images from 1991-2015. This study also found that an increase in fluvial sediment supply result in the migration of

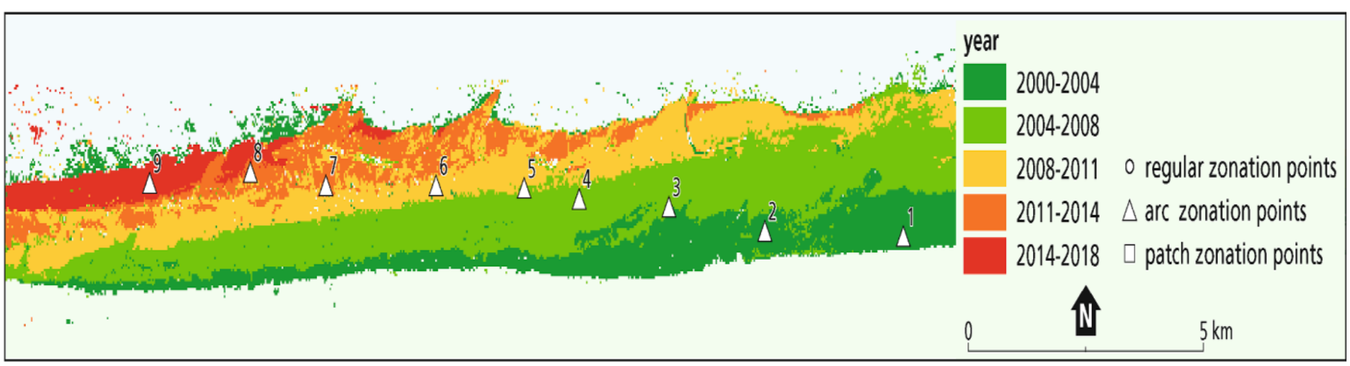

Figure 13. Westward migration of mangrove forest in Totness, Suriname between 2000-2018 following movement of mudbank, as visualised with NDVI. Source: De Jong et al. (2021).

the mudflat, which led to further expansion of the mangrove forests. The aforementioned studies both note the importance of soft soil surfaces for seedling establishment, as a requisite for consequent mangrove forest expansion.

Another study also made use of machine learning, by using a Random Forests classifier to distinguish different mangrove species on Cù Lao Dung in Vietnam (Figure 14, Bullock et al., 2017). This study showed using data from 1990-2015 that the succession of species within a mangrove ecosystem is dependent on bio-geomorphological changes induced by the primary species. The changes made by the primary mangrove species in this ecosystem, *Sonneratia*, included decreased wave energy and low forest density, which resulted in soil accretion and reduced tidal inundation, making the conditions suitable for secondary species.

The importance of the right conditions within a mangrove ecosystem are further corroborated by a study in the Saloum Delta and Casamance Estuary in Senegal (Lombard & Andrieu, 2021). They found using data from 2000-2018 that at locations where sediment deposition had decreased, mangroves of the *Avicennia germinans* species were not able to recover, leading to the colonisation of these locations by mangroves of the *Rhizophora* species. Due to the differing bio-geomorphological effects these two species induce on an ecosystem, the expansion of the mangrove forests at these locations was hampered.

A common disadvantage with the usage of optical imagery is that the images can be hampered by the presence of clouds (Guo et al., 2017). In order to overcome this problem, optimal imagery for sediment dynamics can be used in conjunction with data from other remote sensing sources. These other sources include Phased Array L-band Synthetic Aperture Radar (PALSAR), Light Detection And Ranging (LiDAR), and drone imagery (Dat Pham et al., 2019). Both PALSAR and LiDAR aim to determine topography and geology. Where these methodologies differ is that PALSAR makes use of the time for radio

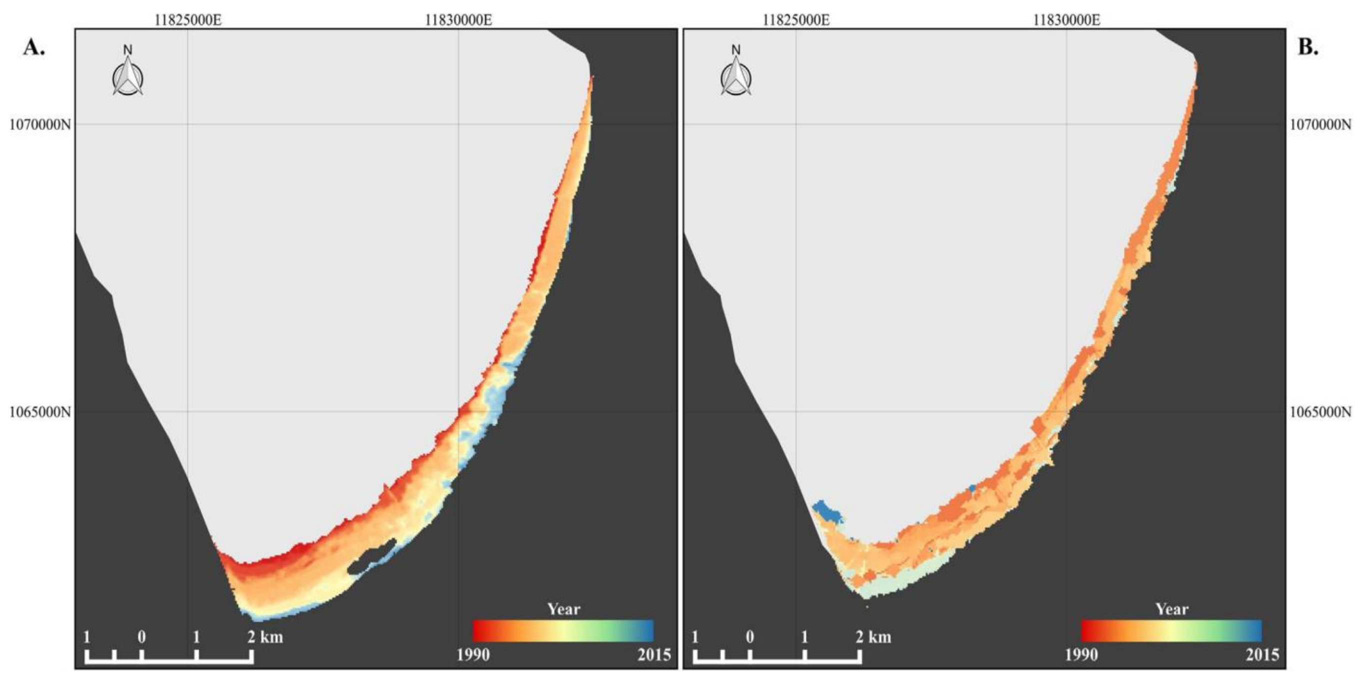

Figure 14. The emergence of the primary (A) and consequent secondary (B) mangrove species in the Mekong delta, Vietnam from 1990-1995 using a random forest classifier on Landsat imagery. Source: Bullock et al. (2017).

waves to reflect, while LiDAR makes use of the time for light of a laser beam to reflect. Drones can be used for imaging below the cloud base, hereby negating the problem.

Combining optical imagery and other remote sensing sources was for example the case for a study on mangrove forests on Hinchinbrook Island in Queensland, Australia. These forests were in large part destroyed by category 5 Tropical Cyclone Yasi, with mangrove foliage protective cover having decreased from > 90% to < 20% (Asbridge et al., 2018). This destruction was felt most strongly for mangroves of the *Rhizophora stylosa* species, which had increased vulnerability due to the fragility of their prop roots. By combining optical imagery and PALSAR data from 1987-2016, the study found that six years after the cyclone the mangrove forests had not shown significant recovery or recolonization by other mangrove species. One explanation the researchers noted for this was reduced sediment dynamics with consequent increased inundation times, resulting in suboptimal conditions for mangrove growth (Asbridge et al., 2018). The lack of recovery in this ecosystem is therefore an indicator of low resilience when sediment is insufficiently available.

A different study, in the Towamba estuary in South-Eastern Australia, found that increased fluvial sediment deposition led to seaward expansion of the land by combining optical imagery with drone imagery and LiDAR data from 1946-2016 (Figure 15, Al-Nasrawi et al., 2018). This landward expansion resulted in increases in mangrove coverage along the shoreline, which led to further stabilisation of the expanded land. The stabilization of the

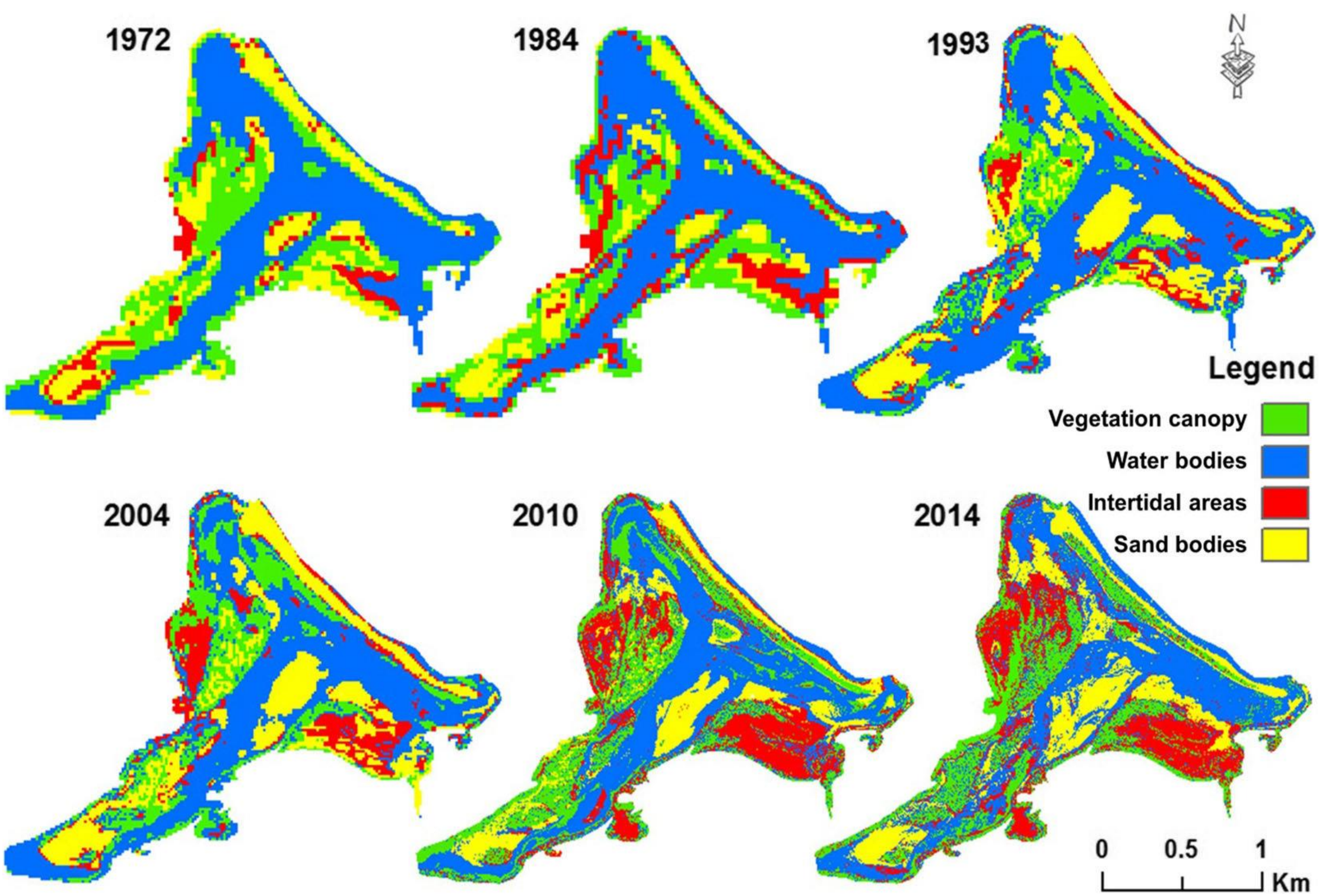

Figure 15. Changes in vegetation and water coverage, intertidal areas, and sand bodies in the Towamba estuary, Australia from 1972-2014 using Landsat imagery. Source: Al-Nasrawi et al. (2018).

ecosystem may however hamper further expansion of the mangrove forests. The remote sensing data of this study in combination with fieldwork sampling and laboratory testing has been used to develop a spatiotemporal model that can predict future development of the Towamba estuary.

By combining optical and drone imagery from 2009-2019, a study in East Java, Indonesia, found yearly mangrove migration as the result of continuous sediment supply stemming from a mud volcanic eruption in the past (Figure 16, Beselly et al., 2021). They did however find that the degree of migration is dependent on the amount of precipitation, with expansion occurring after the wet season and regression after the dry season. This study highlights the importance for mangrove forest expansion of both biological, in the case of mangrove growth resulting from sufficient water and nutrients, and geological processes, in the case of sediment supply.

There are also studies where optical imagery is not used, and only other types of remote sensing data are used. Such is the case for a study on the effects of inundation patterns within a mangrove ecosystem in the Zhangjiang Estuary, China (Zhu et al., 2019). They found using drone imaging and LiDAR data from 2017 that the amount and frequency of inundation within a system regulates mangrove species composition and consequent spatial formation and surface elevation within these mangrove forests.

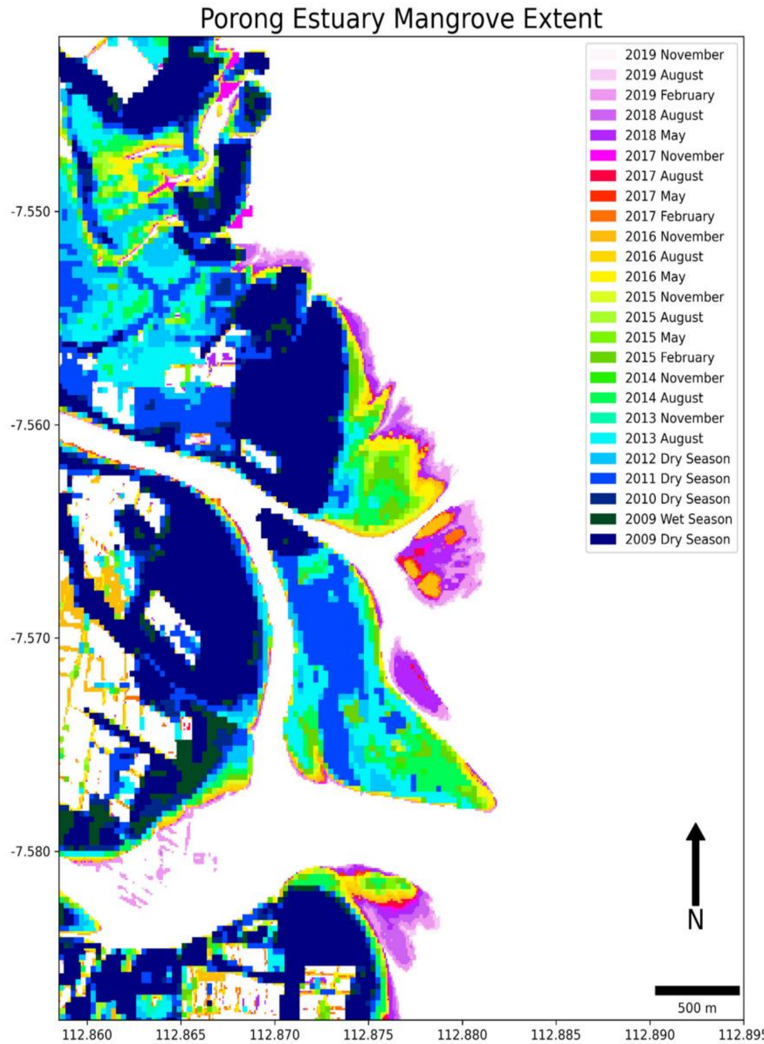

Figure 16. The expansion of the mangrove forest in the Porong Estuary, Indonesia from 2009-2019 as the result of continuous sediment supply, using Landsat and Sentinel imagery. Source: Beselly et al. (2021).

Model simulations

Using the findings from the lab and field studies in combination with remote sensing data, models can be developed to predict future migration of mangrove forests (Fagherazzi et al., 2017). To accurately describe the influence of mangroves on hydro- and sediment dynamics, parameters have to be incorporated in these models. Such parameters can include the underwater profile of the tidal basin, the rate of sediment deposition, the tidal regime, and the density and species composition of the mangrove forest.

These models can be created in a model suite, as is the case for studies that have aimed to identify how mangrove forests respond to SLR and changes in sediment dynamics (Coll et al., 2020). Studies can for example include the presence of mangroves and competition between different mangrove species within a system, as well as the inundation and sediment supply regimes of this system.

One of such studies used the Delft3D model to simulate what the effects would be of both high and low environmental pressures on mangrove expansion (Figure 17, Xie et al., 2020). Here high environmental pressures were represented by a high rate of SLR and reduced sediment supply, while low pressures were represented as a low rate of SLR and sufficient amounts of supplied sediment. The model showed that, in the case of sufficient amounts of sediment supply, seaward migration of the land would occur, with consequent expansion of the mangrove forest in both seaward and landward directions.

The study notes that this migration would be hampered by the presence of artificial structures (Xie et al., 2020). This would result in a reduction of both the overall coverage of the mangrove forest, as well as decrease species diversity. The extent to which real-life mangrove forests will adhere to the simulations of this model is dependent on the overall bio-geomorphology of the areas to which these forests belong.

In addition, the study found that sparse vegetation on the fringes would result in more even sediment distribution along the forest, while dense vegetation in the fringes would result in proximate sediment build-up and creation of a more convex coastal profile (Xie et al., 2020). The latter would be expected to reduce delivery of sediment to higher regions and lead to a consequent reduction in species diversity within mangrove forests.

A similar finding on sediment dynamics throughout the tidal basin was derived from a model formed on the basis of two transacts of a mangrove forest on Cù Lao Dung in Vietnam (Bryan et al., 2017). These two transects differ in mangrove density on the fringes of the tidal basin, which has consequently led to the development of a more convex profile for the densely vegetated, and a more linear profile for the sparsely vegetated fringes. On the basis of this model, the study noted that the dissipation of water currents would not be primarily due to the presence of vegetation, but instead due to elevation changes. The presence of vegetation would however play a secondary role in this process by stimulating soil accretion.

A different study using the Estuary and Lake Computer Model (ELCOM) elucidated that, on sandy soil surfaces, the mangrove properties that mediate flow resistance and raise the threshold of erosion, could additionally mediate channel development in the tidal basin (Figure 18, Van Maanen et al., 2015). Channel development results from water flow becoming concentrated in the space between vegetated patches, which results in the scouring of the soil surface. In this modelled system, the number of channels was positively correlated with the

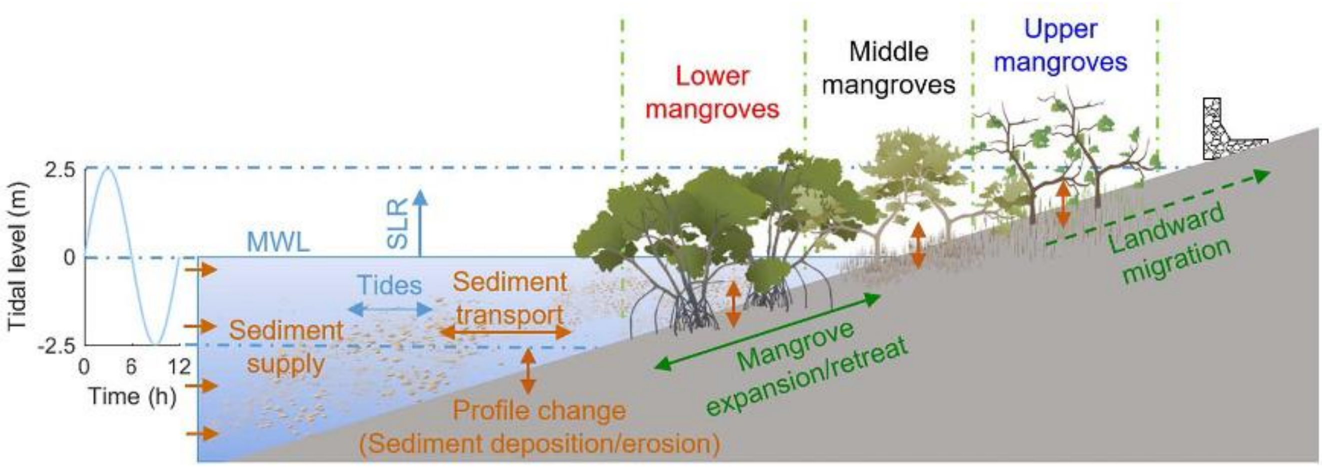

Figure 17. Various environmental parameters that can be included in a bio-geomorphological model of mangrove forests. Source: Xie et al. (2020).

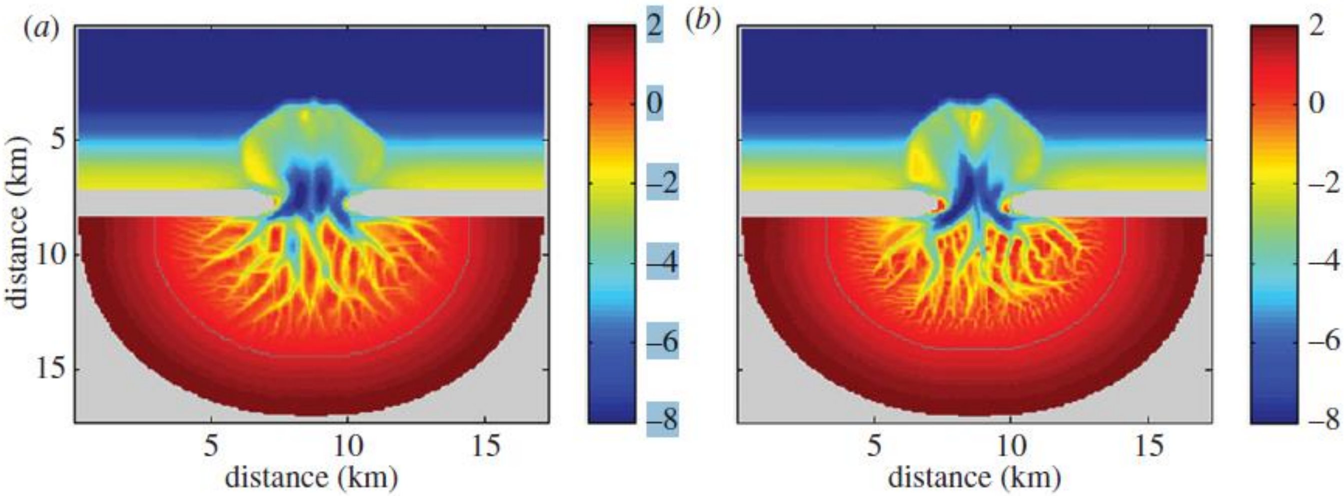

Figure 18. Simulation of tidal basin development over a period of 160 years either without (A) or including mangroves (B). Notes the role of mangroves for the formation of tidal channels. Source: Van Maanen et al. (2015).

vegetation density. This degree of channel formation decreased the further in the tidal basin one was, as hydrodynamics gradually became weaker and insufficient to form tidal channels.

Furthermore, this study notes the effect of rising sea levels on the formation of these tidal channels. In the case of SLR, which forces the tidal channels to move landward, creation of new channels would be hampered in areas completely covered in mangroves. The reason for this is that flow concentration would become ineffective in such mangrove-dense areas. The previous two studies hereby emphasized the role mangroves play in bio-geomorphologically altering their environment.

Models can also be used to investigate how mangrove ecosystems would be able to develop in regard to the threat of SLR. In this manner, a model describing mangrove forests flanking the regions of the Indo-Pacific, showed that their survival against SLR is dependent on the width of the intertidal zone and sediment supply in an area (Lovelock et al., 2015). They found that mangrove forests in areas with a broad tidal range will be able to survive, even when sediment deposition rates are low and SLR is high. How well a forest is able to survive is related to the inundation regime of a system, and the amount of relative elevation that would have to be lost for parts of the forest to be at or below mean sea level.

However, the usage of models also has some limitations. The simplicity of models, while making them useable, is simultaneously also where they lack predictive value. When a model is developed, the developers have to decide which parameters to include. A model will therefore be largely influenced by the assumptions made during its development. By disregarding aspects that are in actuality important, a skewed representation of the system is created. Simulations of such an inaccurate model will therefore also result in predictions that may not be representative of the modelled system.

In the case of modelling sediment- and hydrodynamics in mangrove forests, there are several aspects that are often left out of the model. Which aspects are excluded is often dependent on the main aim of the study, and can include aspects such as wave types, wind, temperature, nutrient availability and the amount of salt stress. This highlights the need for validation of these types of models prior to usage (Mogensen & Rogers, 2018).

In addition to incorrect assumptions that are made in the developmental stages, models are often not suitable for predicting non-linear feedback relationships within a system and becomes less accurate for predicting long-term relationships far into the future.

Building with Nature projects

Knowledge on the mechanisms and processes behind the sediment trapping of mangroves can be put into practice with Building with Nature (BwN) projects. These projects mostly focus on the restoration of degraded mangrove forests as a way to continue making use of the ecosystem services they supply, especially the continuous limitation of coastal erosion and protection against SLR and EWEs (Figure 19, Gijsman et al., 2021). In this way they can decrease the dependence on, or even completely replace, artificial structures such as seawalls (Aiken et al., 2021).

There are however some common issues that BwN projects encounter, which are mostly associated with the habitat having become unsuitable for mangrove facilitation. This habitat unsuitability is predominantly due to increased coastal dynamics and longer inundation times. Many mangrove restoration projects immediately aim to plant mangroves, instead of first focusing on creating a hospitable environment, which leads to the failure of a large amount of these projects (Bosire et al., 2008). One reason for failure is that the environmental conditions will not be suitable for the establishment of the seedlings, negating mangrove succession and the potential for consequent forest expansion (Bosire et al., 2008).

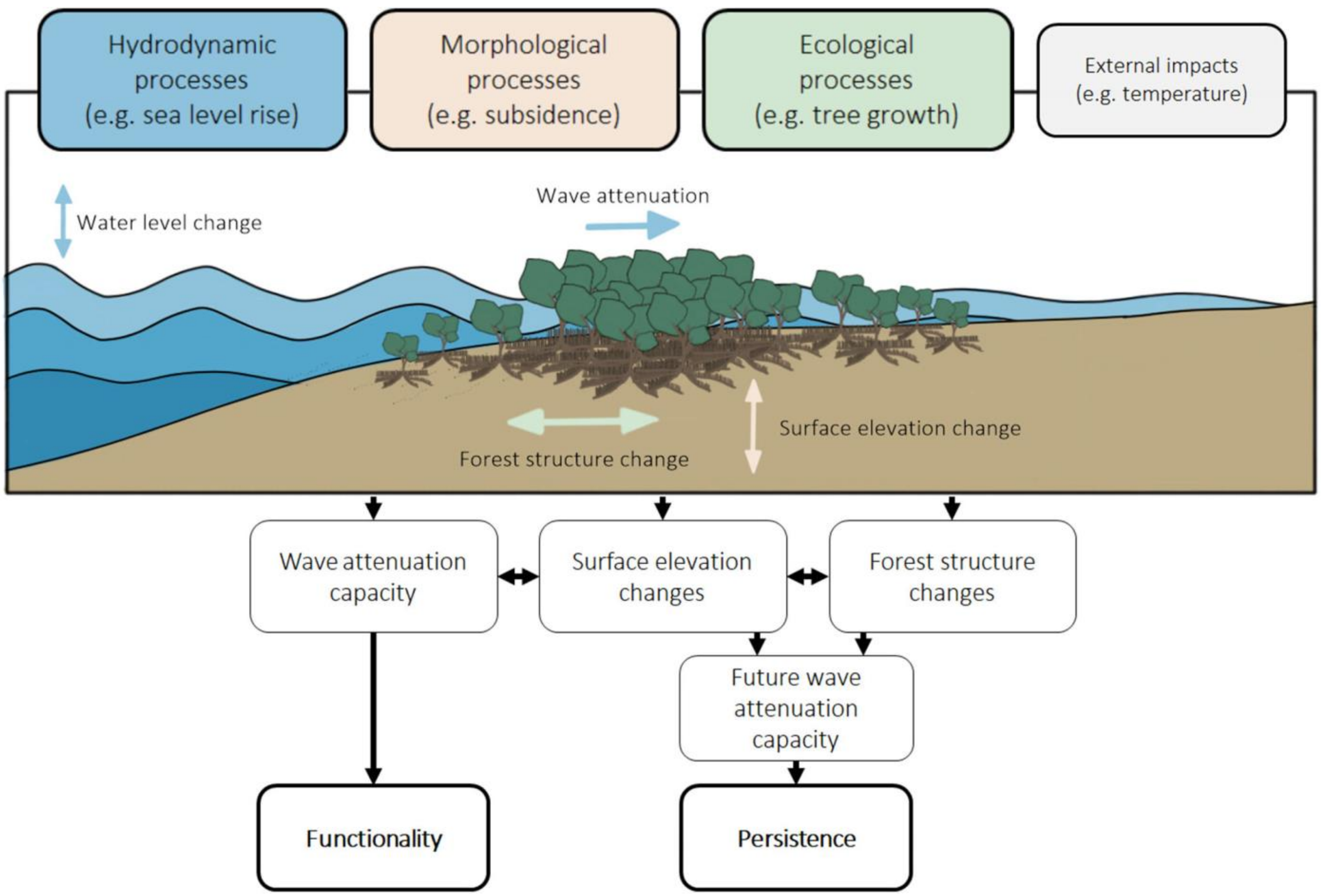

Figure 19. The hydrodynamic, morphological and ecological processes and external impacts that underlie the development of mangrove ecosystems, and have to be taken into account for Building with Nature projects to succeed. Source: Gijsman et al. (2021).

It must be noted that the degree of unsuitability of an environment for mangrove forest establishment and expansion is context-dependent (Krauss et al., 2014). There are a lot of conditions influencing the potential for mangroves to successfully grow, which can be variable between different study sites.

A study in Demak, Indonesia focused on the restoration of mangrove forests in abandoned ponds used for aquaculture (Figure 20, van Bijsterveldt et al., 2020). This study found that in order for successful restoration to occur, stability of the soil surface and decreases in inundation times are required (below 40% of the time), as they increase the success rate of seedling establishment. The study hereby notes the importance of focusing on these environmental conditions when aiming to restore mangrove forests.

This can for example be seen in Leizhou Bay in China, where in areas with severe mangrove degradation, no natural restoration had occurred within 20 years due to the environmental conditions having become unsuitable for the native species (Ren et al., 2008). The simultaneous growth of an invasive mangrove species in this region can however allow for the growth of the native species, due to the formers ability to positively influence the environmental conditions (Ren et al., 2008). Nevertheless, this only occurs in early stages of mangrove growth, since the invasive species will hamper the natural succession within the system, and therefore have to be removed for successful restoration of the mangrove forest (Ren et al., 2008).

There are however projects that aim to actively increase the suitability of environmental conditions to facilitate mangrove growth. One of these projects is the Building with Nature Indonesia project, which was a joint venture of multiple organisations and individuals, including Ecoshape and Wetlands international. The project, which ran from 2015-2021, focused on creating a stable coastline at Demak, Indonesia by using BwN strategies (Wilms et al., 2017).

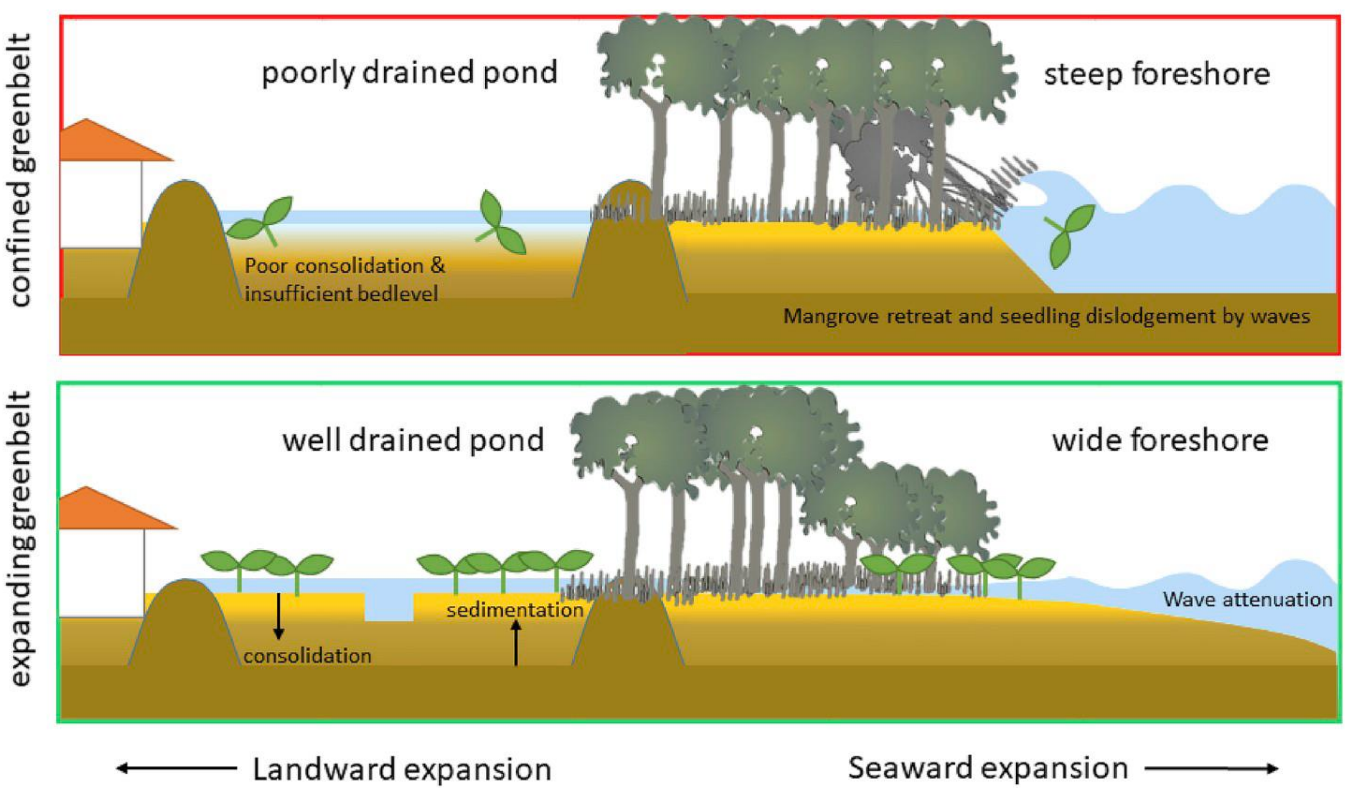

Figure 20. Drainage of old aquaculture ponds and restoration of mangrove forests with reduced steepness of the foreshore can mediate seaward land expansion. Source: van Bijsterveldt et al. (2020).

This region had previously seen a huge loss of land due to coastal erosion, associated with mangrove degradation and soil subsidence due to groundwater extraction (Tonneijck et al., 2015). Since these conditions no longer allowed for natural growth of mangroves, it was these conditions that the project focused on as a way to combat coastal erosion in these areas.

The Building with Nature Indonesia project hereby aimed to diminish coastal dynamics and consequently stimulate sediment deposition and soil accretion (Tonneijck et al., 2015). To achieve this, the project made use of semi-permeable structures that induced drag force and captured sediment (Figure 21, Wilms et al., 2017). Once sufficient sediment had been deposited, this resulted in conditions that were suitable for mangroves, after which the mangrove forests could again become self-sustaining (Wilms et al., 2017).

The emphasis of this project was placed on the understanding of the workings of the structures, which was achieved through continuous monitoring of their functionality and adapting them when necessary (Wilms et al., 2017). Knowledge of the workings of the structures could furthermore be distributed within the community to facilitate their participation in achieving success for the project throughout its duration (Wilms et al., 2017).

However, not all mangrove restoration projects are successful. Projects that aim for quick and cheap restoration of mangrove forests do this by planting monocultures of exotic mangrove species (O'Connell et al., 2021). These projects hereby do not take into account the initial species composition and biodiversity of these areas. The services that restored ecosystems can provide over time may therefore be subpar compared to those of the initial ecosystems.

This is for example the case for mangrove forests in the Mai Po Marshes in Hong Kong, the Yunxiao wetlands in Fujian, China, and the Lake Sihwa and Saemangeum tidal flats in Korea (Lee & Khim, 2017). Due to the lack of knowledge about the systems prior to restoration, these studies have introduced exotic species. The success rate of these projects over longer periods of time are therefore difficult to judge, and should therefore continuously be tracked (Lee & Khim, 2017).

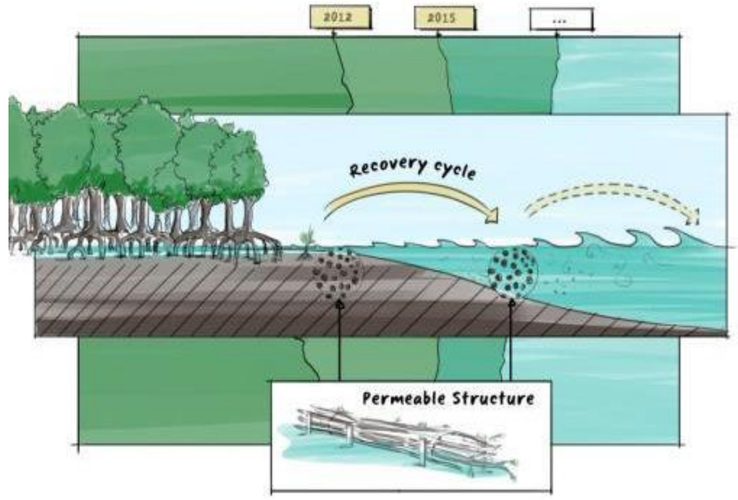

Figure 21. The semi-permeable structures that aid in sediment deposition at mangrove restoration sites by inducing drag force and capturing sediment. Source: Wilms et al. (2017).

According to the World Bank (2017) the success of BwN projects should be assessed on the basis of 5 principles: 1. consideration of the larger system scale, 2. assessment of the risks and benefits of the project, 3. development of a standardized performance evaluation, 4. integration with the principles of ecosystem conservation and restoration, and 5. Adaptive management of the ecosystem (Gijsman et al., 2021). These principles highlight the points that knowledge on the system prior to action and continuous assessment and adaptation over time are required for successful restoration projects (Aiken et al., 2021; Bosire et al., 2008).

Future prospects

Although the rate with which mangrove forests are declining globally is decreasing, they are still under threat of degradation (Food and Agriculture Organization of the United Nations, 2020). Sea levels are estimated to keep rising over the next century, which will force mangrove ecosystems to migrate landward (He & Silliman, 2019).

Moreover, human actions will place additional pressures on the habitat of mangroves (Spalding et al., 2010). The building of dams will reduce fluvial sediment supply, hampering seaward expansion of mangroves, while the placement of artificial structures, such as roads, will block landward expansion (Mentaschi et al., 2018; Weston, 2014). In addition, many coastal regions are experiencing soil subsidence as the consequence of groundwater reserve depletion (Webb et al., 2013). Taking all of these factors into account, it is expected that mangrove ecosystems will become squeezed between rising sea levels and landward blockades, leading to large losses in forest coverage (Spalding et al., 2010).

In the case of large-scale degradation, mangrove forests will not be able to continue providing their ecosystem services, among which the prevention of coastal erosion and protection against coastal disturbances and EWEs (Spalding et al., 2010, 2014). The loss of such services will be accompanied by large socio-economic and ecological costs (Sarhan & Tawfik, 2018).

It is therefore of utmost importance to ensure that destruction of mangrove forests is halted. Degradation should be detected when still in early stages, so that swift conservative and restorative measures can be taken (Lewis et al., 2016). Degradation can be detected using a combination of field observations and remote sensing data (Dat Pham et al., 2019). This combination can help identify the amount of degradation, the stressors causing the degradation and the amount of degradation a system can handle before diverting to an alternative state (Lewis et al., 2016).

When conservative measures are not viable, communities should aim for sustainable usage of mangrove forests, as well as aid in the recovery of damaged and the planting of new forests. In order to stimulate this, economic policies can be introduced (Lavieren et al., 2012). By creating incentives for local communities to make sustainable use of these systems and the resources they supply, instead of overexploiting them, mangrove ecosystems will hereby be able to provide their services for years to come (Figure 22, Su et al., 2021).

The Building with Nature Indonesia project is a good example hereof, as the project incorporated aquaculture at several sites along their study area. They found that combining aquaculture with mangrove forest restoration resulted in similar or increased overall yield, even though the area allotted to aquaculture had decreased (Figure 23, Building with Nature Indonesia, 2022). This means that the economic

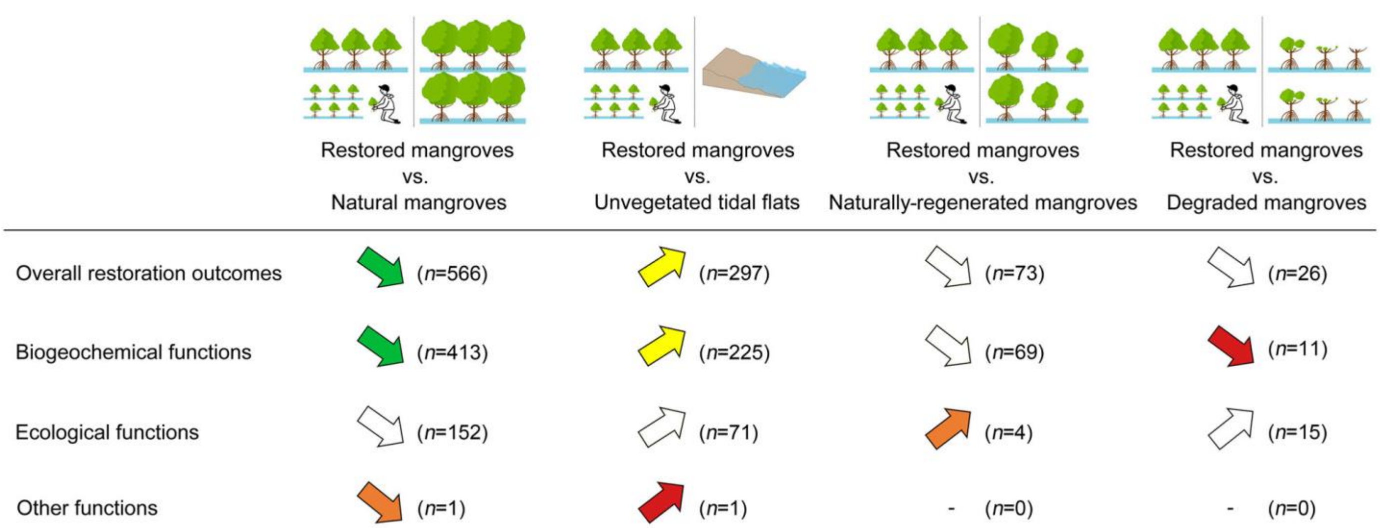

Figure 22. The outcomes of mangrove restoration on ecosystem functioning in comparison with other options on the basis of a meta-analysis. Here the arrows indicate whether the restored mangroves perform better or worse and the colours indicate the effect size (white = no large effect, green = 0 – 0.3, yellow = 0.3 – 0.6, orange = 0.6 – 0.9, and red = > 0.9. Source: Su et al. (2021).

value generated within the system is sustained, while the system is better protected due to the presence of mangroves.

The findings of this study highlight the necessity of mangroves as mediators for correct ecosystem functioning (Lavieren et al., 2012; Spalding et al., 2010). Working together with mangroves instead of against them will stimulate local economies, and simultaneously offer the involved communities protection against coastal disturbances, erosion of the land, and SLR (Wilms et al., 2017). The knowledge gap filled by the Building with Nature Indonesia project can be used to set up mangrove restoration projects in other regions that suffer from mangrove forest degradation and its consequences.

It should however be noted that conditions do differ between degraded mangrove forests. Restoration projects that are successful in one area, can for that reason fail when implemented in another (Bosire et al., 2008). It is therefore important to acquire knowledge about the functioning of a system before applying any restorative measures. Once the constraints of a system are identified, one can plan restoration projects with a higher rate of success (Gijsman et al., 2021; Wilms et al., 2017).

Summary

In this review we have highlighted some ecosystem services of mangrove forests, mainly their sediment trapping and binding capabilities. It is these capabilities that regulate two important ecosystem services, being the mitigation of coastal erosion and protection against coastal disturbances and EWEs.

We first noted the roles that the distinct mangrove root types play in sedimentation, by either influencing hydrodynamics and stimulating sediment deposition, or by actively trapping sediment. Secondly, we emphasised the environmental conditions that underlie the potential for mangrove expansion or regression, with the most important factors being the availability of fluvial sediment and the inundation regime.

Figure 23. Visualisation of the dream scenario of the Building with Nature Indonesia project for 2030. Source: Building with nature Indonesia / Frederik Ruijs

Once the theoretical foundations had been laid, we looked at several lab, field, and remote sensing studies that investigated various factors influencing mangrove sediment trapping in different contexts. The findings of such studies can be implemented in models to predict future changes in mangrove forest ecosystems. In addition, they can be used for the development of Building with Nature projects that put the theoretical background behind sediment trapping to use for restoration of degraded mangrove forests.

Collectively, these studies show that mangroves are able to manipulate their environment to a certain extent by influencing hydrodynamics and consequent stimulating sediment deposition, provided that sufficient is supplied. This process is essentially the precursor for the soil accretion we see in mangrove forests, which mediate the mitigation of coastal erosion and facilitate the formation of a protective barrier.

For the sedimentation process and consequent expansion of mangrove forests to occur successfully, their environment has to adhere to certain conditions. Since these conditions vary between coastal locations, this suggests that expansion of mangrove forests is context-dependent. Areas with broader intertidal zones, sufficient sediment supply, and a lack of artificial barriers will be more resilient to the rising sea than areas with narrow intertidal zones, a lack of sediment supply and the presence of artificial blockades that hamper landward migration.

This context-dependency is emphasised within the five principles for Building with Nature, being that understanding of the area is necessary before implementing anything. In order for communities to be able to predict the success rates for mangrove conservation, restoration, and afforestation, knowledge on the workings of the system is first and foremost required.

Although the concepts regarding mangrove sediment trapping are generally clear, here noting their ability to influence their environment, the future for many specific mangrove ecosystems that will have to deal with a multitude of pressures is less clear. Considering the context-dependency of it all, it is important to identify and characterise mangrove ecosystems that are least resilient to these pressures, so that money and energy can be diverted here. Only then can suitable solutions be developed to ensure the survival of these ecosystems, as well as the animal and human communities that rely on them.

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Layman's Summary

Mangroves are tree and shrub species growing in the tropics and subtropics that offer a variety of ecosystem services, such as providing habitat to various animal species and resources for human usage. They also function as biofilters, carbon sinks and protectors against coastal erosion. Mangrove forests are however under threat of succumbing to rising sea levels as the result of climate change. Sediment trapping by mangroves and the consequent soil accretion can offer a solution to the dangers of the rising sea. It is therefore that this review has aimed to describe what is currently known about the influence of mangroves on sediment dynamics in order to paint a picture of how mangrove ecosystems will develop in the future.

We start this review by laying a theoretical foundation of the general workings of mangrove sediment trapping, including how different root types stimulate sediment deposition either directly or indirectly, and the conditions that are necessary for mangrove forest expansion to occur. Afterwards, we highlight multiple studies from recent years that have investigated mangrove sediment trapping. We first discuss the experimental studies, performed either in the field or in the lab, that show the different factors that influence the capacity for mangrove forests to influence sediment dynamics. Other studies have used satellite imaging to study how factors related to sediment availability have influenced the movement of mangrove forests over time, in a variety of geographical contexts.

The information from these experimental and remote sensing studies can be used to create models that simulate how mangrove ecosystems will develop in the future, a few of which we describe in this review. The acquired information can also be applied in a more practical way, as is the case with Building with Nature projects that apply concrete understanding of the workings of mangrove ecosystems to devise plans for restoring degraded mangrove forests. We therefore note projects that have succeeded and ones that have been less successful, as well as the potential causes for the varying levels of success.

Taking all of these studies into account, we then paint a picture of the future of mangrove forests. Here we note that although mangrove ecosystems are able to adapt to sea level rise in theory, they are continuously being influenced by factors regarding sediment availability and inundation, as well as by human actions. These factors may negatively influence the ability for mangrove ecosystems to cope with these environmental changes and have to be taken into account for conservation and restoration efforts to be successful. We conclude the review by summarizing that to ensure continued usage of the services mangrove ecosystems provide, we need to have a better understanding of mangroves, as well as understand that not all ecosystems with mangroves can be treated the same. Only once this is understood and we make use of mangrove ecosystems in a sustainable way, can we secure that we will be able to make use of their services for years to come.