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The response of mangrove soil surface elevation to sea level rise

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The Nature Conservancy's **Natural Coastal Protection** project is a collaborative work to review the growing body of evidence as to how, and under what conditions, natural ecosystems can and should be worked into strategies for coastal protection. This work falls within the Coastal Resilience Program, which includes a broad array of research and action bringing together science and policy to enable the development of resilient coasts, where nature forms part of the solution.

The **Mangrove Capital** project aims to bring the values of mangroves to the fore and to provide the knowledge and tools necessary for the improved management of mangrove forests. The project advances the improved management and restoration of mangrove forests as an effective strategy for ensuring resilience against natural hazards and as a basis for economic prosperity in coastal areas. The project is a partnership between Wetlands International, The Nature Conservancy, Deltares, Wageningen University and several Indonesian partner organisations.

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Executive Summary

Coastal ecosystems such as mangroves can reduce risk to people and infrastructure from wave damage and flooding. The continued provision of these coastal defence services by mangroves is dependent on their capacity to adapt to projected rates of sea level rise. This report explores the capacity of mangrove soil surfaces to increase in elevation in response to local rises in sea level.

Historical evidence suggests that mangrove surface elevations have kept pace with sea level rise over thousands of years in some places, such as Twin Cays, Belize. Rates of surface elevation increase ranged between 1 mm/yr and 10 mm/yr in different locations and settings. Key controls on this include external sediment inputs and the growth of subsurface roots.

Recent evidence based on measurements using the Surface-Elevation Table – Marker Horizon methodology (from studies published between 2006 and 2011) suggest that mangrove surfaces are rising at similar rates to sea level in a number of locations. However, surface elevation change measurements are available for a relatively small number of sites, and most records span short time periods. Longer term mangrove surface elevation datasets are needed from more locations, and these need to be analysed relative to sea level changes over the same periods of measurement.

Six sets of processes are known to influence surface elevation change in mangroves: sedimentation/resuspension; accretion/erosion; faunal processes (e.g. burrowing of crabs); growth/decomposition of roots; shrinkage/swelling of soils in the presence/absence of water; and compaction/compression/rebound of soils over time and under the weight of soil/water above. A variety of factors affect the rates of these processes, including the supply of external sediment, the types of benthic mats that bind surface sediments together, vegetation characteristics such as tree density and aerial root structure, nutrient availability to sub-surface roots, storm impacts, and several hydrological factors such as river levels, rainfall and groundwater pressure. The sum of these processes results in surface elevation change.

The number and complexity of processes involved in surface elevation change create significant challenges to the modelling and prediction of future elevation change in the face of sea level rise. It is likely that negative feedbacks exist between sea level change and surface elevation change, but evidence for these feedbacks is currently lacking. Such feedbacks might enable mangrove soil surfaces to maintain their surface elevation with respect to local sea level over the longer term. Threshold rates of sea level rise are also likely to exist, beyond which mangrove surfaces are no longer able to keep up. An improved understanding of the different processes and feedbacks involved in surface elevation change will increase our ability to predict the response of surface elevation to sea level rise, and to manage mangrove areas in ways that enhance their ability to keep pace with sea level rise.

Monitoring and management of mangrove areas is recommended to ensure continued provision of coastal defence services into the future. In particular, sediment inputs need to be maintained, mangroves should be protected from degradation, and space should be allowed for mangroves to colonise landward areas. In many areas, short term anthropogenic losses of mangroves represent a greater threat to the provision of coastal defence services by mangroves than the longer term effects of sea level rise.

Contents

1. Introduction

Coastal ecosystems such as mangroves can reduce risk to people and infrastructure from wave damage and flooding. The continued provision of these coastal defence services by mangroves is dependent on their capacity to adapt to sea level rise, either through an increase in soil surface elevation (Figure 1), or by colonising more landward areas. In this report we review the response of mangrove soil surface elevation to sea level rise. For a discussion of the factors affecting the landward migration of mangroves, see Woodroffe (1990), Ellison (1993), Woodroffe (1995), Gilman *et al.* (2007), Gilman *et al.* (2008) and Soares (2009). Lovelock and Ellison (2007) and Ellison (2012) review other potential effects of climate change on mangroves, which will also affect the long-term provision of coastal defence services by mangroves.

An understanding of how mangrove surface elevation is likely to respond to changes in sea level is needed in order to predict whether mangroves will be able to survive in their current position as sea levels rise, and to manage mangrove ecosystems in ways that increase their chance of surviving in the face of rising sea levels. In this report we present the current state of knowledge, starting with basic descriptions of the key concepts, then describing available data and discussing various factors that may affect surface elevation change, before finishing with a description of a sediment development model that could be used to predict future surface elevation change in mangroves. The information and discussion provided here are by necessity incomplete, as relatively few studies have explored this topic, few data are available, and many important questions remain unanswered.

In the first section of this report, we briefly explain how sea level is changing, why this varies locally, what is meant by “surface elevation change” in mangroves, and how mangrove surface elevation may be able to keep pace with local sea level rise. In Section 2, we examine historical and recent evidence for mangrove surface elevation keeping pace with sea level rise. In Section 3, we summarise the processes involved in mangrove surface elevation change and the factors that affect these processes. In Section 4, we explore the relative contribution of surface and subsurface processes to elevation change, and look at factors known to affect surface elevation change rates. Section 5 then considers the factors affecting the response of mangrove surface elevation to sea level rise, including possible feedbacks and thresholds. Section 6 briefly considers a sediment development model that aims to predict surface elevation change in mangroves. Section 7 concludes by considering what more we need to know in order to better predict when and where mangroves may be able to maintain their surface elevation in the face of sea level rise.

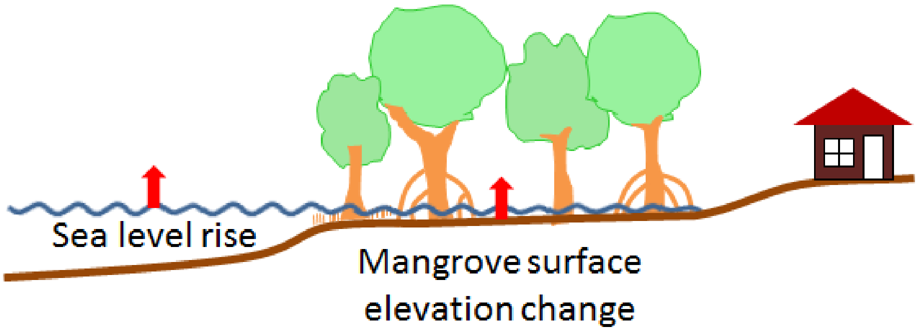

Figure 1. Schematic diagram showing how, when mangrove soil surface elevation can keep pace with sea level rise, mangroves will be able to continue to protect people and infrastructure from waves.

1.1 The tidal environment, mangroves and accommodation space

Mangrove forests include a variety of species of trees and shrubs that are able to live in tidally flooded areas. Mangrove forests occur in intertidal areas, at heights between **mean sea level** (MSL) and high tide (mean high water; exact tidal levels vary with species and location; Ellison, 2009). Therefore they occupy the upper part of the **tidal frame**, where the 'tidal frame' refers to the area that is flooded by the tides (i.e. it does not include areas that are always under water or which are only flooded during storms).

Due to the shifting and dynamic nature of the tidal environment, intertidal mudflats both form and are washed away over relatively short periods of time (a single storm can radically alter a muddy coastline). When the height of a mudflat reaches a height above mean sea level suitable for mangroves, and providing mangrove propagules (i.e. seeds) are available, then mangroves are expected to colonise such an area (Figure 2a). Once mangroves have established, they may change the environment: by slowing water flows and reducing wave energy, they may allow further deposition of sediments, and through the growth of subsurface roots, they may increase the soil volume. Both processes can further increase the height of the soil surface. If a time comes when soil inputs and losses approximately balance such that the soil surface height (i.e. the **surface elevation**) remains relatively stable (e.g. Figure 2b), then mangroves may remain as the climax vegetation for many years (sometimes thousands of years e.g. in Twin Cays, Belize). If the height of the soil surface continues to increase due to soil inputs exceeding soil losses, then the soil surface height may continue to rise until it reaches the upper limit for mangroves to survive; ultimately, terrestrial vegetation may outcompete mangroves.

The difference in height between the current soil surface height within a mangrove forest and the maximum soil surface height that can be achieved with mangroves present (limited either by the balance of soil inputs and losses, or by mangrove vegetation being outcompeted by terrestrial vegetation) is referred to as the mangrove **accommodation space** (Figure 2a). More generally, the term 'accommodation space' describes the available space for soil expansion or growth, both vertically and laterally, given the current position of the soil surface, the tidal frame, and erosive forces[1]. Over a particular stretch of coast, an accommodation volume may also be defined as the volume of space above the substrate that could be filled with sediment and allow mangroves to grow there; this allows for a 'lateral accommodation space', meaning seaward areas where mangroves could live if sediment filled the space (limited also by bathymetry and wave conditions eroding sediment; these factors limit the seaward edge of the accommodation space shown in Figure 2). The accommodation concept is widely used in geology (e.g. Schlager, 1993; Miall, 1996); in relation to coastal ecosystems, it has been applied more frequently to coral reef systems (e.g. Pomar, 2001; Kennedy and Woodroffe, 2002; Montaggioni, 2005), but only occasionally in relation to saltmarshes (e.g. French, 2006) and mangroves (Spencer and Möller, 2013).

When sea level rises or land subsides, the volume of accommodation space increases (Figure 2c), as the difference in height between the height of the substrate and mean sea level has increased. This volume can now be filled with soil if soil inputs are high enough, allowing the

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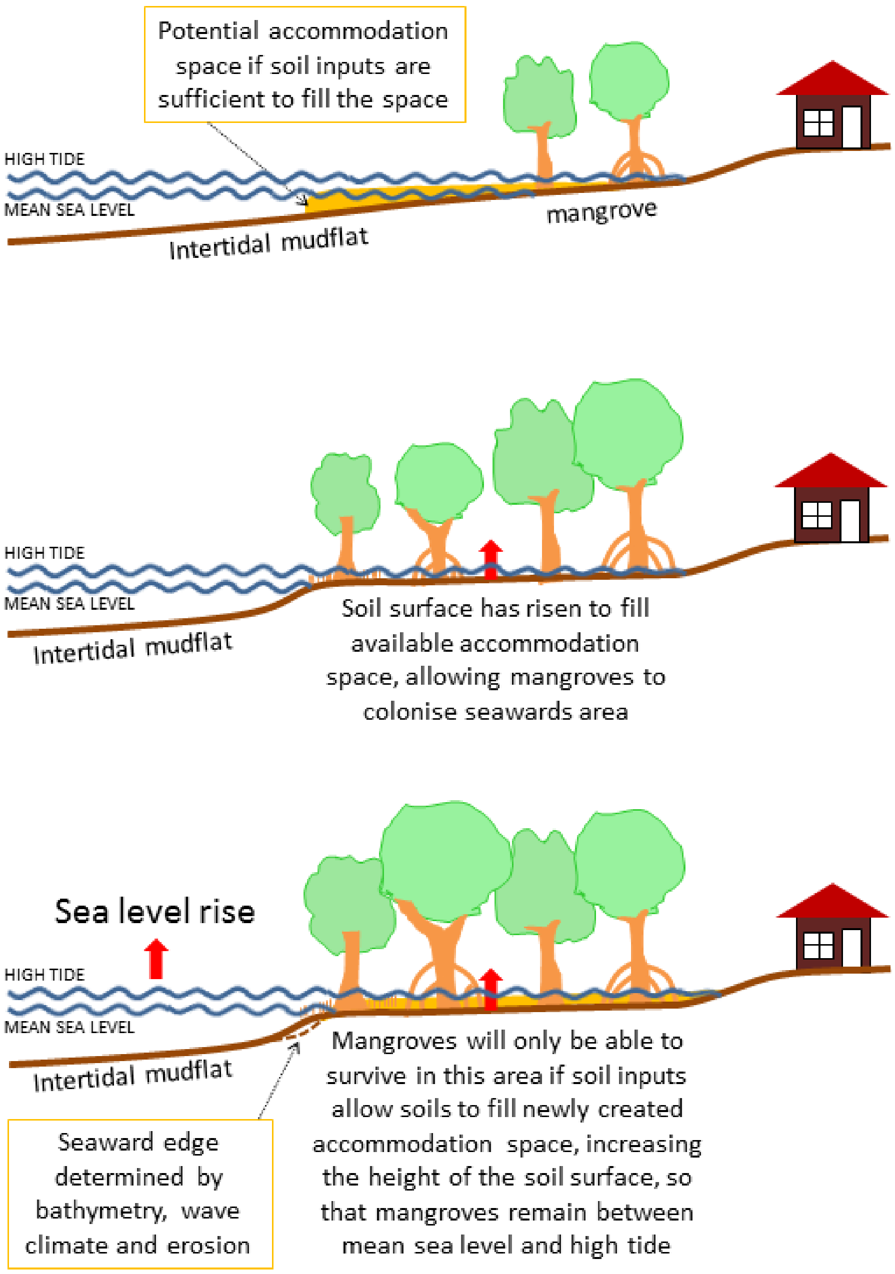
[1] The concept of accommodation space is fundamental in the study of sequence stratigraphy in geology, and Miall (1996, p. 456) offers the following definition from Jervey (1988): "the space made available for potential sediment accumulation [where] in order for sediments to be preserved, there must be space available below base level (the level above which erosion will occur)". In other words, accommodation space refers to the space between the level of the substrate and the highest level that sediment could remain without being eroded away.



Potential accommodation space if soil inputs are sufficient to fill the space

Soil surface has risen to fill available accommodation space, allowing mangroves to colonise seawards area

Mangroves will only be able to survive in this area if soil inputs allow soils to fill newly created accommodation space, increasing the height of the soil surface, so that mangroves remain between mean sea level and high tide

Seaward edge determined by bathymetry, wave climate and erosion

Figure 2. Schematic diagram illustrating the concept of accommodation space (see text for further description).

soil surface to rise until the newly created accommodation space has been filled. Soil inputs include organic or inorganic sediments and subsurface roots. The increase in height of the mangrove soil surface can result in mangroves remaining in their preferred part of the tidal frame, i.e. between mean sea level and high tide. Without such an increase in soil surface height, the mangrove surface could end up below mean sea level, creating stress on mangrove trees, and probably resulting in their death. If the change in soil surface height exactly matches the change in sea level, this results in the relative height of the mangrove surface remaining constant within the tidal range (Figure 2b and c).

In Sections 2 to 7, we explore whether mangrove soil surfaces tend to rise in response to rises in sea level, the mechanisms underlying this, and the factors affecting it.

1.2 Sea level rise

Globally, mean sea levels are rising as a result of both the thermal expansion of sea water, as temperatures rise with climate change, and the melting of the polar ice caps and other land ice, which add additional water to the sea (Cazenave *et al.*, 2008). Both thermal expansion and melting of ice increase the volume of water in the oceans, and the resulting rise in sea level is called **eustatic sea level rise**. Recent estimates of mean global sea level rise are 3.4 ± 0.4 mm/year over the 14 year period from 1993 to 2007, based on satellite measurements of sea surface level (Beckley *et al.*, 2007). Taking a longer term perspective, sea levels have been relatively stable over the last 7,000 years (global mean sea level rose by 3 to 5 m over this period, i.e. rise rates of 0.4 to 0.7 mm/yr; Fleming *et al*., 1998). Over the last 20,000 years, sea levels have risen by more than 100 m, and sea levels have fluctuated widely over the last 250,000 years (Curray, 1965; Chappell and Shackleton, 1986). These fluctuations are largely related to periods of glaciation, when more water is locked up as ice on land, resulting in a fall in global mean sea level.

There is significant spatial and temporal variation in eustatic sea level (Cazenave *et al.*, 2008). Spatial variation in recent sea level trends is shown in Figure 3. Some areas have experienced much higher rates of sea level rise (e.g. parts of the Philippines), while others have experienced falls in sea level (e.g. parts of the west coast of North America). The main cause of regional variation in sea level change is the regional variation in thermal expansion (Cazenave *et al.*, 2008). Temporal variation in sea levels also occurs, caused by temporary reorganisation of ocean currents and associated oscillations in regional ocean temperatures which affect thermal expansion, such as those seen with the El Niño Southern Oscillation (ENSO), which affects large areas of the Pacific Ocean (Lombard *et al.*, 2005).

Mean sea level rise as measured by tide gauges along the coast also varies because of vertical land movements, such as glacial isostatic adjustments and lithospheric flexural subsidence (Pugh, 2004; Yu *et al.*, 2012). These changes in land level result from a wide range of factors, such as earthquakes and tectonic movements, consolidation of coastal sediments (e.g. in deltas), the extraction of oil or water, and a change in loading (i.e. weight) on the land surface or sea floor (e.g. from the melting of glaciers and ice caps or the deposition of sediments around large deltas) (Pugh, 2004; Mitchum *et al.*, 2010). Rates of uplift/subsidence vary geographically: for example, uplift rates of up to 20 to 30 mm/yr have been observed in northeast Canada, while subsidence rates of up to 6 to 7 mm/yr have been observed between Greenland and northeast Canda (Pugh, 2004).

The combination of eustatic and isostatic changes in sea level results in sea level rise rates which vary significantly along coasts and over time. The net effect of eustatic and isostatic sea level changes in a particular location is referred to as **Relative Sea Level Rise (RSLR)** (Figure 4, top). It is this local change in sea level that affects coastal ecosystems such as mangroves and the people who live along these coastlines. Therefore, for the purpose of understanding the relationship between sea level change and mangrove surface elevation change, local measurements of sea level are needed.

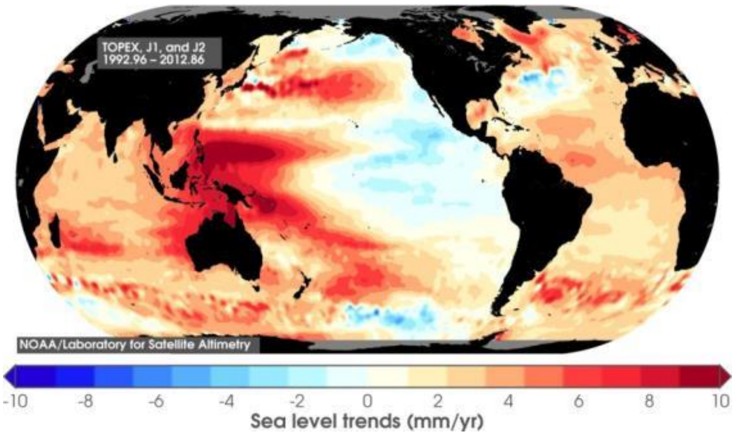


Figure 3. Global map of eustatic sea level trends between 1992 and 2012. Map and altimetry data are provided by the NOAA Laboratory for Satellite Altimetry (http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/LSA_SLR_maps.php).

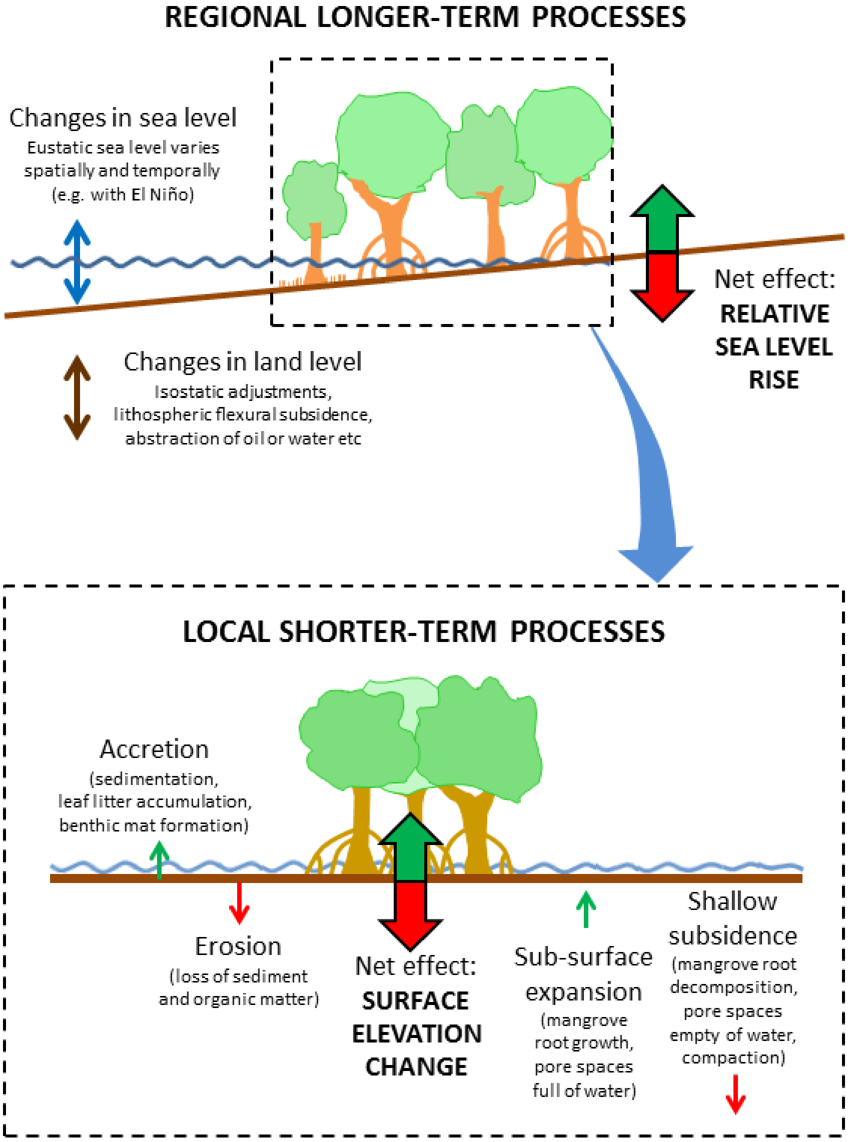


Figure 4. Regional and local processes affecting the elevation of the mangrove surface relative to local mean sea level.

1.3 Surface elevation change in mangroves

The elevation of a point on the Earth's surface is the height of that point measured with respect to a reference point or **datum**. The elevation of the soil surface within a mangrove area is referred to as the **surface elevation** within the mangrove, and is the height of the mangrove substrate, usually measured with respect to a local datum such as mean sea level. **Surface elevation change** refers to a change in height of the soil surface over a defined period of time (Figure 5); such changes in surface elevation are usually not referenced to a local datum, because of the practical difficulties of doing so.

A number of processes may result in changes in the mangrove surface elevation, and these are illustrated in Figure 4 (lower part). These processes may be divided into surface processes and sub-surface processes. For the purposes of this report, the **soil surface** refers to the interface between the soil and the air (or water, when the tide covers the soil) (Figure 5). **Surface processes** refer to those processes which occur at or above the mangrove soil surface, including sedimentation (the deposition of material on to the surface of the soil), accretion (the binding of this material in place), and erosion (the loss of surface material). **Subsurface processes** refer to processes that occur below the soil surface but above the basement or consolidated layer (Figure 5); these include growth and decomposition of roots, swelling and shrinkage of soils related to water content, and compaction, compression and rebound of soils due to changes in the weight of material above.

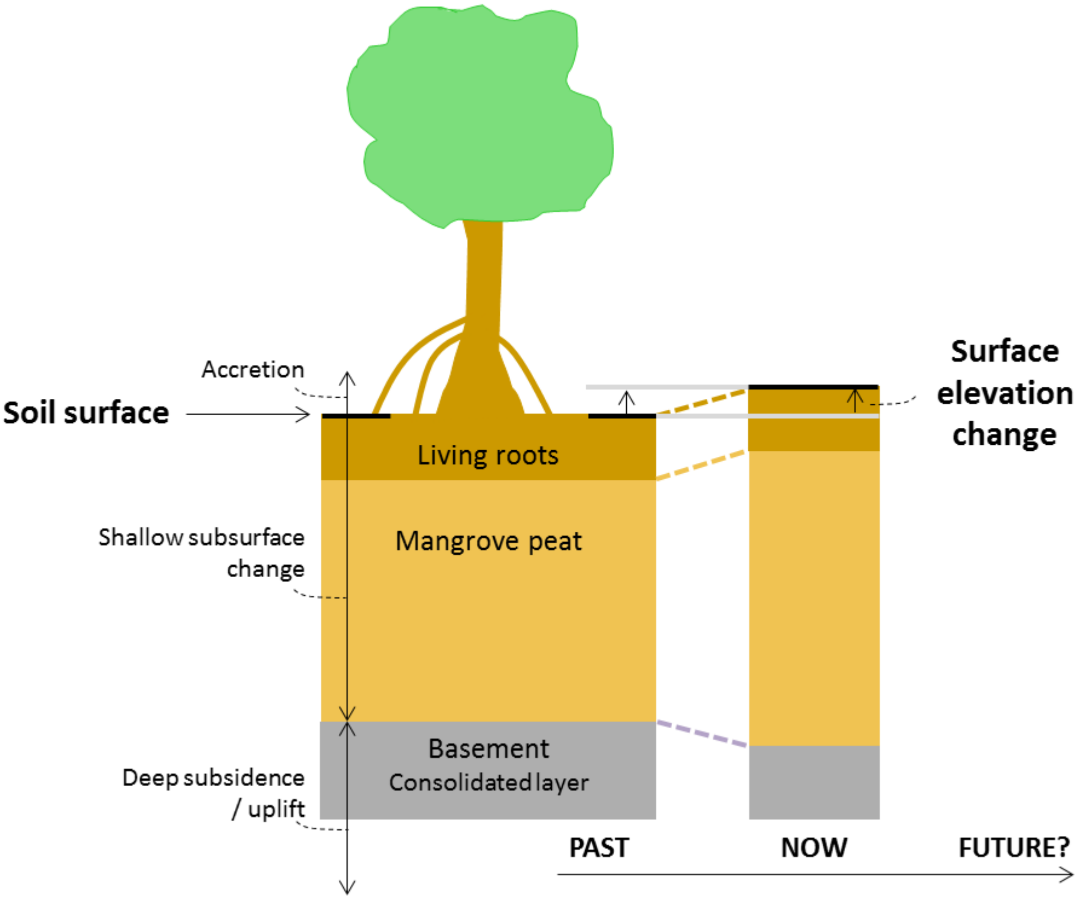


Figure 5. Schematic diagram of a mangrove tree and the soil beneath it, showing where accretion, shallow subsurface change and deep subsidence/uplift occur in the profile, and illustrating how surface elevation change may occur over time.

When sub-surface processes result in a change in volume of the soil, this is called **sub-surface expansion** or **shallow subsidence**. Shallow subsidence refers to the loss of elevation caused by these sub-surface processes, which act above the bedrock or consolidated layer; it is called **"shallow"** to distinguish it from **"deep" subsidence**, caused by longer-term geological processes (Cahoon *et al.,* 1995a), which are accounted for in relative sea level rise rates (described above in Section 1.2).

These surface and subsurface processes are described in more detail in Section 3; the combined effect of these processes results in surface elevation change, as described in Section 4.

1.4 How mangrove surface elevation varies with sea level rise

The following scenarios describe how mangrove surface elevation may change as mangroves are exposed to sea level rise (some of these are shown schematically in Figure 6):

1. In areas with very high rates of sedimentation, mangrove soil surfaces may rise at a rate which exceeds the local rate of sea level rise, such that terrestrial species invade landward areas, and progradation occurs (i.e. new land is formed seaward of the current mangrove area, which mangroves then colonise); this is likely to occur around the deltas of large rivers that bring high volumes of sediment to the coast.
2. Sea level rise rates may be matched by a rise in mangrove soil surface elevation, allowing mangroves to remain in the same location, possibly also colonising more landward areas if such areas have suitable substrate and topography (this scenario is illustrated in Figure 6d). An example of where this has occurred is Twin Cays in Belize, as discussed in Section 2.1.
3. Mangroves soils may be unable to rise as fast as the local rate of sea level rise, resulting in death of trees in the lower areas and at the seaward edge of the mangrove area (Figure 6b). Mangroves are likely to invade landward areas which now fall within the tidal frame, providing suitable substrate and topography are present there. The deeper water in mangrove areas may also allow waves to penetrate further into the mangrove area, resulting in erosion particularly at the seaward edge.

Which of these scenarios is observed in any particular location is likely to depend on rates of sedimentation and sub-surface soil inputs in combination with rates of sea level rise. A variety of positive and negative feedbacks between changes in sea level and the rates of surface and subsurface processes that influence soil volume may also be at play (these are discussed in Section 5).

A useful measure of how mangrove surface elevation is changing relative to local sea level change is the elevation surplus/deficit (Cahoon *et al.*, 1995a), which is calculated as:

$$\underset{\text{(mm/yr)}}{\text{elevation surplus/deficit}} = \underset{\text{(mm/yr)}}{\text{surface elevation change}} - \underset{\text{(mm/yr)}}{\text{relative sea level rise rate}}.$$

An elevation surplus occurs if surface elevation rises more quickly than sea level, while an elevation deficit reflects that sea level is rising at a faster rate than the mangrove surface.

If both the mangrove surface elevation and the sea level are changing, another useful measure is the rate of sea level rise relative to the mangrove surface, which we term the "**mangrove-surface-relative sea level rise**" (MSR-SLR). While this is calculated in the same way as the elevation surplus/deficit outlined above, it is useful to be able to describe changes in water level with respect to the mangrove surface, particularly when considering feedbacks between

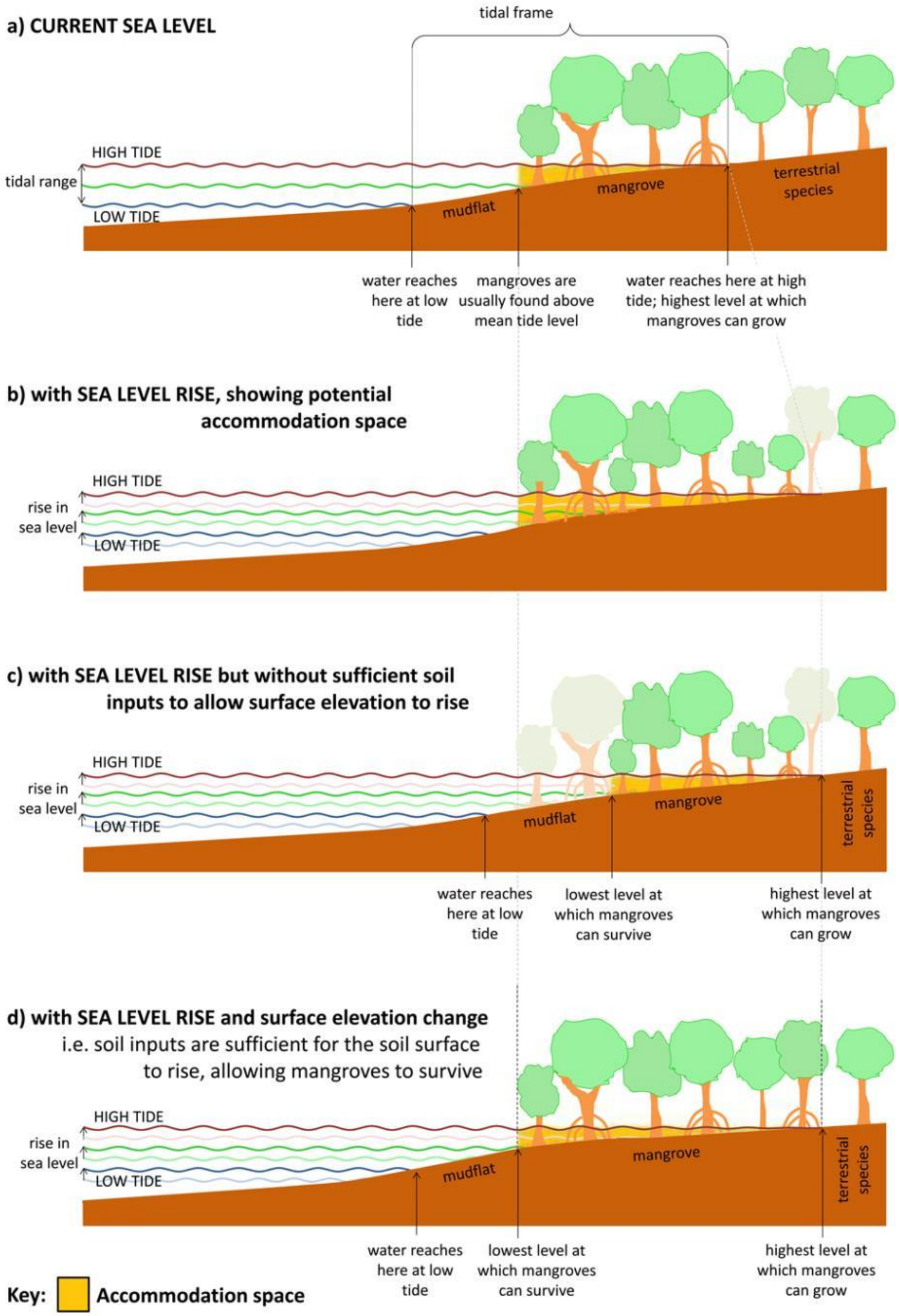


Figure 6. Schematic diagram of mangroves to demonstrate tidal range, tidal frame, accommodation space, and possible scenarios following sea level rise with or without surface elevation change.

water levels and the rates of surface and sub-surface processes (Section 5). A positive value means that local sea levels are rising more quickly than the mangrove surface resulting in deeper water over the mangrove substrate and more frequent inundation; a negative value would indicate that mangrove surfaces are more than keeping pace with sea level rise and being inundated less often (scenario 1 above).

The following section explores historical and recent evidence for mangrove surfaces keeping pace with sea level in different locations.

2. Can mangrove surface elevation keep pace with sea level rise?

There are two sources of evidence for whether mangrove surface elevation can keep pace with sea level rise: historical evidence of mangrove persistence in the face of sea level rise over thousands of years, and recent measurements of surface elevation change that can be compared with known rates of sea level rise over similar periods and in nearby locations. We will consider these two sources of evidence in turn.

2.1 Historical evidence

In some areas, mangrove surface elevation has kept pace with sea level rise over thousands of years. The most compelling evidence that mangrove surface elevation is able to keep pace with sea level rise comes from areas with deep mangrove peats under existing mangroves, such as in Twin Cays and the Tobacco Range Islands, Belize. The peat layer can be several metres thick, formed from dead mangrove material that has accumulated over many years. The age of the peat layers can be estimated using radiocarbon dating techniques (described in Toscano and Macintyre, 2003). Dating of the deepest layers of peat show that some peat layers are more than 7000 years old; for example, mangrove peat found at a depth of 8.7 m in Twin Cays was estimated to be between 7,430 and 7,580 years old (McKee *et al.*, 2007; Figure 7).

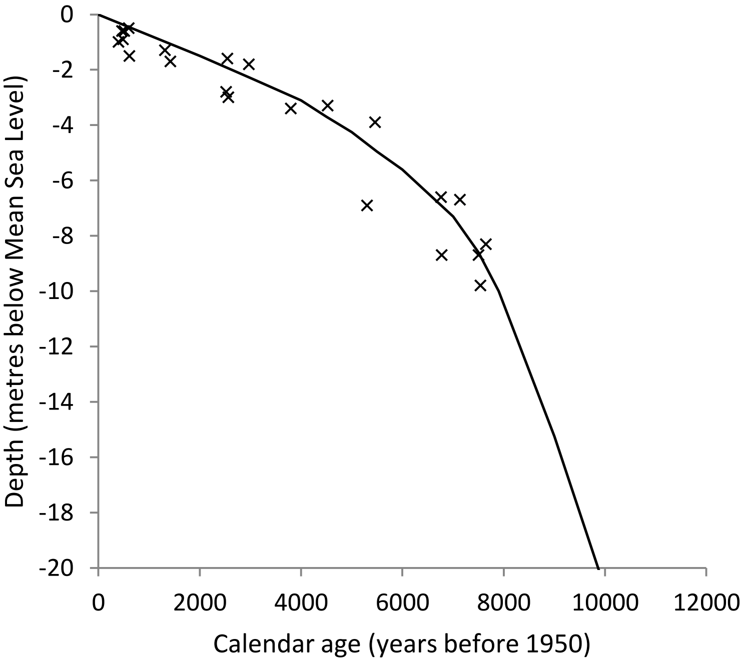


Figure 7. Mangrove peat depth-age data (x) from Twin Cays, Belize (McKee *et al.*, 2007) plotted on top of a sea-level history curve (line) derived from separate studies of the age of mangrove peat and coral material at different depths from the Caribbean region (Toscana and Macintyre, 2003).

The age of the mangrove peat at different depths gives an indication of the sea level at the time that the peat was formed, provided that there has not been significant compaction of peat layers. Mangroves can only live in the intertidal zone, so the age of mangrove peats at different depths has been used to construct sea level rise curves (Scholl, 1964; Woodroffe, 1990; Toscano and Macintyre, 2003). Dating of mangrove peat formed by the red mangrove *Rhizophora mangle,* in combination with coral material formed by the reef crest coral *Acropora palmata,* was used to reconstruct a sea level rise curve for the Western Atlantic region (including the Caribbean) (Toscano and Macintyre, 2003); the curve is shown in Figure 7. More recent dating of mangrove peats from Twin Cays by McKee *et al.* (2007) is in close agreement with the original data used to construct the curve by Toscano and Macintyre (2003); the data from McKee *et al.* (2007) are also shown in Figure 7.

The Twin Cays data show that mangroves were not present before 7,600 years BP[2], when sea level rise rates were greater than 3.5 mm/yr (McKee *et al.*, 2007). After this time, the mangroves accumulated peat at rates of 3 mm/yr between 7,600 and 7,200 years BP, 1.3 mm/yr between 7,200 and 5,500 years BP, and 1.0 mm/yr between 5500 and 500 years BP, matching sea level rise rates in the region (McKee *et al.*, 2007). This demonstrates that mangroves in this area have been capable of increasing in surface elevation at a rate of at least 3 mm/yr. If the mangrove surface elevation had not kept pace with sea level rise, the substrate would now be several metres below sea level and mangroves would no longer be present. The absence of mangrove peat more than 7,600 years old could be related to a number of factors, including an absence of suitable substrate, unsuitable climatic conditions, a lack of mangrove seeds arriving in the area, or an inability of mangrove surface elevation to keep pace with the higher rates of sea level rise before this date.

Similar studies exist in other areas (Table 1). These studies show that mangroves in different areas have been able to keep pace with sea level rise for long periods; some of them were then drowned as sea level rise rates increased beyond a critical threshold for that site, and others were replaced by terrestrial vegetation following high rates of sedimentation. These studies are reviewed in Ellison (2008 & 2009).

Mangrove peat found in cores taken from the sea bed (e.g. Parkinson, 1989; Ellison, 1993; Ellison, 2008) provides evidence that mangroves may be submerged by rising sea levels. For example, Parkinson (1989) took sediment cores from a number of locations within Ten Thousand Islands in Florida, and found a layer of mangrove peat buried beneath other sediments in areas of open water up to 6 km from the coast and 5 m below mean sea level. Radiocarbon dating indicated that this peat layer was more than 3,500 years old.

Therefore historical records show that in some locations, mangrove surface elevations have kept pace with rising sea levels over thousands of years until the present day. In other locations, surface elevations kept pace with sea level rise for a period of time, but mangroves were eventually drowned when the rate of sea level rise exceeded some threshold that mangrove surface elevations could not keep pace with. These thresholds vary with location and are likely to depend on local conditions (thresholds are discussed further in Section 5.3).

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[2] BP stands for “Before Present”, where the year 1950 A.D. is taken as the reference point for “Present”.

Table 1. Locations and periods where mangroves kept pace with sea level rise.

Location	Period during which mangroves persisted	Relative sea level rise rate that mangroves kept pace with	Additional information	Source
South Alligator River, Australia	Between 8,000 and 6,000 years BP	6 mm/yr (12 m rise in relative sea level during this period)	Mangrove swamp replaced by terrestrial vegetation after 5,500 BP as a result of sedimentary landfill	Woodroffe, 1990; Ellison, 2009
Mary River, Australia	Between 6,500 and 4,000 years BP	Up to 10 mm/yr	Sedimentation caused mangrove forest to be replaced by freshwater wetlands	Woodroffe and Mulrennan, 1993; Ellison, 2009
Twin Cays, Belize	Since 7,600 years BP	Up to 3 mm/yr	Described in text above	McKee *et al.*, 2007
Hungry Bay, Bermuda	Since 2,000 years BP	0.85 to 1.1 mm/yr	Mangrove lost 26% of its area over previous century due to retreat of seaward edge	Ellison,1993 & 2009
Fanga'uta Lagoon, Tonga	Between 7,000 and 5,500 years BP	1.2mm/yr	Became submerged after 5,500 years BP with more rapid sea level rise, but re-established in new locations when rates slowed	Ellison, 2009
Kosrae, Federated States of Micronesia	Since 2000 years BP	1 to 2 mm/yr	During rapid sea-level rise (10 mm/yr) between 4,100 and 3,700 years BP, mangrove forests retreated landwards	Fujimoto, 1997, in Ellison, 2008

2.2 Recent evidence

Recent evidence relating to whether mangrove surface elevation can keep pace with sea level rise comes from direct measurements of changes in surface elevation using the Surface Elevation Table – Marker Horizon (SET-MH) methodology, which is described in more detail in Box 1. This method can measure surface elevation change over periods of months to years, and measurements made using this methodology are used throughout the rest of this report. Other methods have been used to measure surface accretion[3] in mangroves, including the use of marker horizons alone and the aging of sediment layers using radionuclides; however these methods do not account for sub-surface changes in soil volume e.g. due to compaction, which also affect the level of the soil surface, and therefore they cannot be used to compare surface elevation change rates with sea level rise rates.

2.2.1 Measurements made using the SET-MH methodology

Cahoon *et al.* (2006) brought together available mangrove surface elevation change data that had been measured using the SET-MH methodology for at least a year (Cahoon and Hensel, 2006, also refer to these data). These data were measured in 19 geographical locations in seven countries (United Sates, Mexico, Belize, Honduras, Costa Rica, the Federated States of Micronesia and Australia). In each location, a number of different SET-MH stations were set up to explore elevation change in different forest types (e.g. fringe, basin, riverine or overwash forests) or in different energy settings (i.e. exposed or protected forests), and altogether 60 settings were included in the analysis.

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[3] Accretion refers to the addition of material to the soil surface, and is described in more detail in Section 3.

Box 1. The SET-MH methodology

Surface elevation change is now standardly measured using the Surface Elevation Table – Marker Horizon (SET-MH) method (also called the Sedimentation-Erosion Table – Marker Horizon method). The Surface Elevation Table – Marker Horizon methodology combines a marker horizon (used to measure accretion) with a measurement of the height of the soil surface above a base layer underground, usually a layer of consolidated material that a rod or pipe is driven into to the point of refusal (Figure 1.1). The method thus allows the measurement of surface elevation change relative to the bedrock or consolidated layer, which becomes the underground benchmark (Cahoon and Lynch, 1997). The combination of surface elevation change and accretion measurements allows the magnitude of sub-surface change to be calculated (described below).

The apparatus consists of a long pipe driven into the sediment to the point of refusal, which is left permanently within the sediment, and the measuring apparatus is attached to the top of the pipe when it is time to take a reading (Figure 1.1). The pipe thus acts as a reference point, which is expected to remain stable over time (it will only be affected by geological uplift or subsidence of the underlying bedrock or consolidated layer).

(continued on next page)

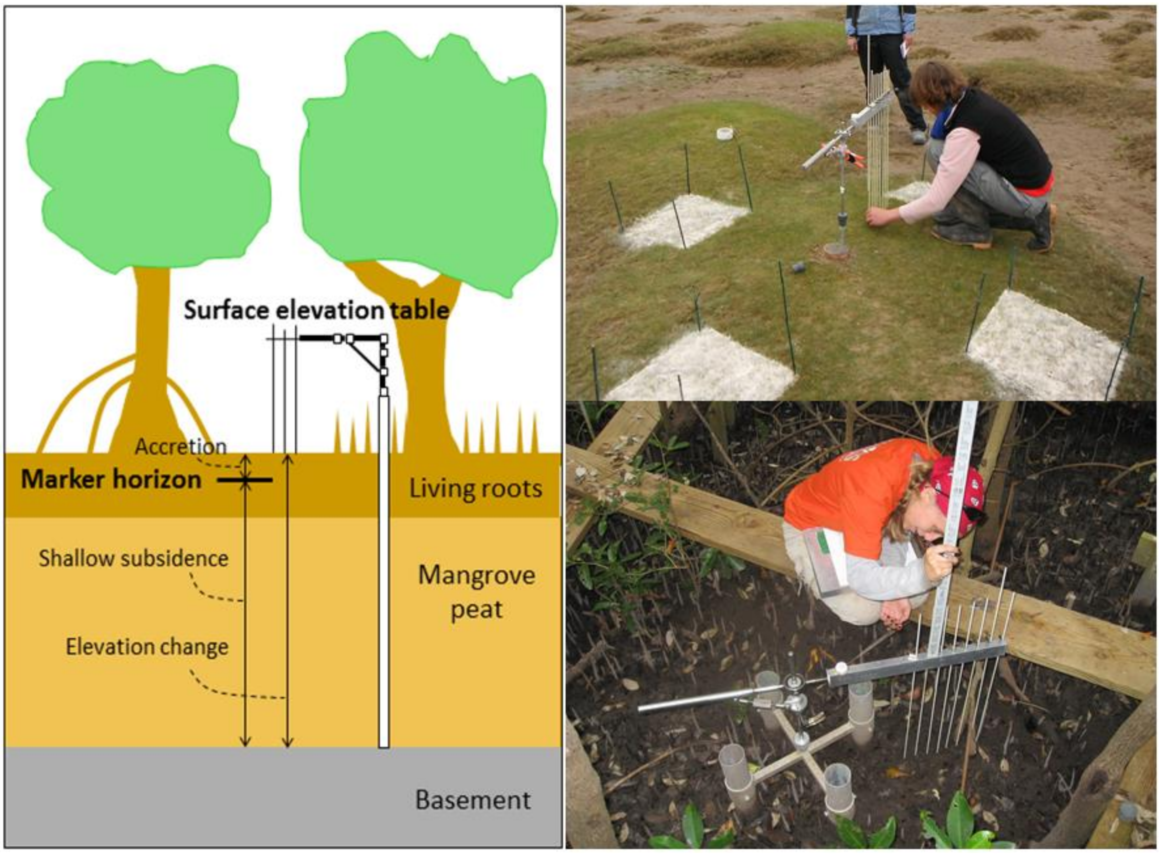


Figure 1.1. The Surface Elevation Table - Marker Horizon apparatus, shown schematically (left) and in use in a marsh (top right, showing Iris Möller measuring marsh surface elevation, and fresh kaolinite layers to be used as marker horizons, at Cartmel Sands, Morecombe Bay) and mangrove (bottom right, showing USGS hydrologic technician Karen Balentine measuring surface elevation in a mangrove forest near Lostmans River, Everglades National Park). Photos by Ben Evans (marsh) and USGS (mangrove; used with permission from Thomas J Smith).

Box 1. The SET-MH methodology *(continued)*

The measuring apparatus consists of an arm attached to the reference pipe (Figure 1.1). The arm holds up a small table through which nine plastic rods can be lowered gently onto the substrate surface; the distance from the surface to the table is then measured for each of the rods, in each of four directions from the pipe, at time intervals ranging from months to years. These measurements are used to calculate the rate of change of the surface elevation with reference to the benchmark.

Nearby, markers are placed on top of the sediment in patches (often 50 by 50 cm). The markers consist of lighter-coloured material such as feldspar or kaolin. After a period of time, a core is taken through the patch in order to measure the depth of sediment that has accreted above the patch. This gives a rate of accretion. By subtracting the rate of accretion from the rate of surface elevation change, it is possible to calculate the rate of sub-surface change, based on the following equation:

surface elevation change (mm/yr) = accretion (mm/yr) + sub-surface change (mm/yr).

Section 4 describes the range of measurements recorded at several different mangrove sites.

Full details of this method can be found in the original paper by Boumans and Day (1993) and on the USGS Surface Elevation Table web-site (Cahoon and Lynch, 2003). The methodology has been developed more recently to allow measurements of expansion in different sub-surface layers (Whelan *et al.*, 2005; Cahoon *et al.*, 2011), and different versions of the SET-MH apparatus now exist such as the rod SET (Cahoon *et al.*, 2002).

Cahoon *et al.* (2006) compared the change in surface elevation with long term rates of relative sea level rise measured as close as possible to the SET-MH sites, and found that in most sites, surface elevation change lagged behind relative sea level rise, resulting in an elevation deficit (i.e. surface elevation fell with respect to local sea level; see definitions in Section 1.4). They did not find a relationship between elevation change rates and relative sea level rise rates, except in embayments (one of five geomorphic classes that the sites were divided into), where elevation change increased with relative sea level rise (however, the significance level was low at $p = 0.07$, n = 8).

We repeated their analysis with more recent data from 15 geographical locations (including 31 settings), using data from 5 studies published between 2006 and 2011 (Table 2, raw data given in Appendix A). Five sites showed an elevation surplus, while 10 sites showed an elevation deficit with respect to relative sea level rise for the area (Figure 8 shows the frequency distribution of elevation surplus/deficit). The mean elevation surplus/deficit was -1.26 mm/yr (mean of 15 values), and this was not significantly different from zero ($t = -1.59$, d.f. = 14, p-value = 0.13) (surface elevation change rates varied between -2.6 and 5.64 mm/yr, with a mean value of 0.69 mm/yr; relative sea level rise rates varied between -0.47 and 4.1 mm/yr, with a mean value of 1.95 mm/yr). These more recent data suggest that mangrove surface elevations are keeping up with relative sea level rise rates in some locations.

Table 2. Mangrove locations where surface elevation change has been measured and where rates of relative sea level rise are available.

Location	**Surface elevation change (mm/yr)**	**Record length (years)**	**Relative sea level rise rate (mm/yr)**	**Source**
Rookery Bay and Naples Bay, Florida, US	+0.61 to +3.85	3	2.1	McKee, 2011
Twin Cays, Belize	-3.7 to +4.1	3.5	2.0	McKee *et al.*, 2007; McKee, 2011
Various sites on Kosrae and Pohnpei, Micronesia	-5.8 to +6.3	1.4 or 3*	1.8	Krauss *et al.,* 2010
Moreton Bay, Australia	+1.4 to +5.9	3	2.4	Lovelock *et al.*, 2011a
Several sites in Australia	-2.6 to +5.64	3	-0.5 to +4.1	Rogers *et al.*, 2006

* Krauss *et al.* (2010) measure surface elevation change over 1.4 or 3 years, and 5 or 6.6 years. Here we use the shorter period of measurement because accretion and sub-surface change measurements were measured concurrently (described in more detail in Sections 3 and 4).

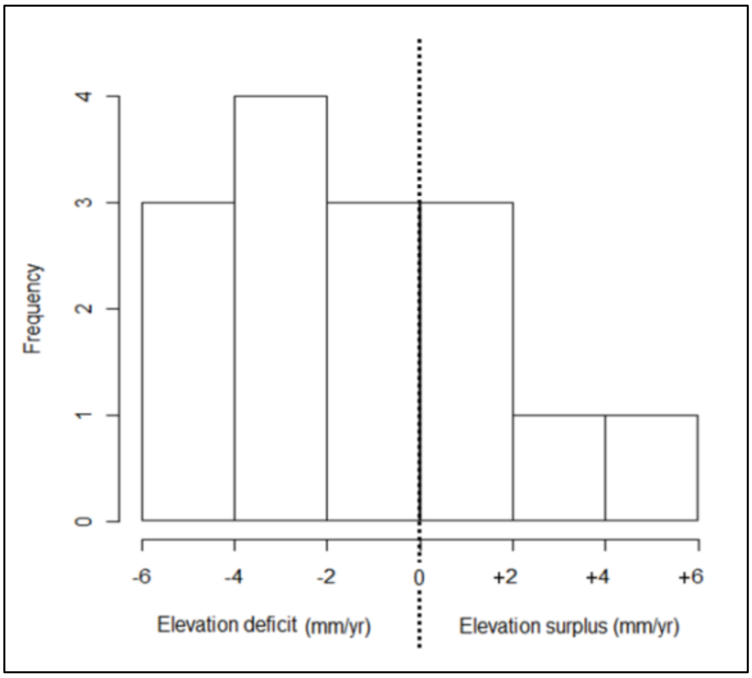


Figure 8. Histogram showing the distribution of elevation surplus/deficit values at 15 locations described in Table 2 and Appendix A (mean values have been taken for each location, with the exception of Kosrae and Pohnpei in Micronesia, which are treated as two separate locations).

Figure 9 plots these surface elevation change measurements against relative sea level rise rates as measured in nearby tide gauges (distance to tide gauges given in Appendix B). Figure 9 shows that there was a high level of variation in surface elevation change measurements in most sites (raw data given in Appendix A). There was no significant relationship between surface elevation change and relative sea level rise (linear regression: $F_{(1,13)} = 2.81$, $p = 0.12$).

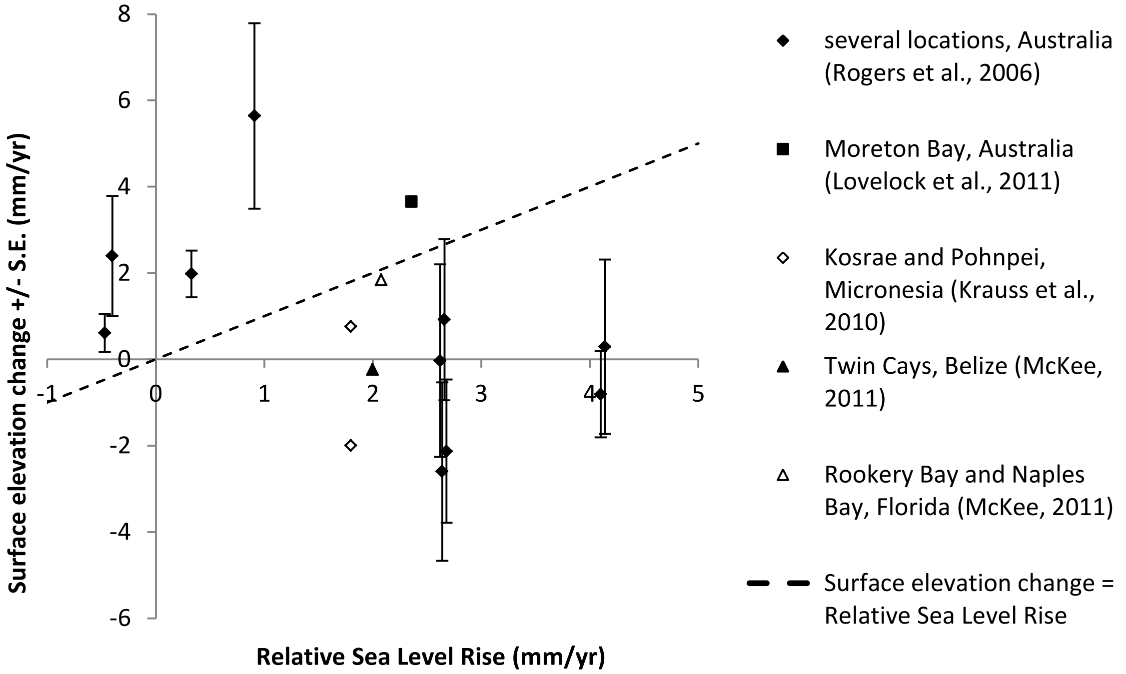


Figure 9. Surface elevation change plotted against relative sea level rise at different locations. The dashed line shows the case where the rate of surface elevation change equals the rate of sea level rise. Points above this line represent sites where surface elevation change is more than keeping pace with sea level rise, while below the line, sites are not keeping pace. Where several points have the same Relative Sea Level Rise, the points have been slightly staggered to make the error bars visible. Standard errors are not shown for data points from Moreton Bay, Kosrae, Pohnpei, Twin Cays or Rookery Bay and Naples Bay, Florida, as the raw data from which to calculate the standard error of these mean elevation change measurements were not provided in the respective source papers.

2.2.2 Comparing surface elevation change data with sea level rise data

When comparing surface elevation change data with sea level rise data, several potential issues need to be taken into account, including:

- high temporal variability in both surface elevation change and sea level change measurements, combined with different measurement periods. Temporal variation in sea level change can be large. e.g. Church *et al.* (2006) estimate that sea level varied by more than 300 mm over a 2 year period on the island of Pohnpei in Micronesia (coinciding with the beginning of Krauss *et al.*'s (2010) study of surface elevation.change there). Similarly, surface elevation can both rise and fall over relatively short periods: e.g. Gilman *et al.* (2007) measured surface elevation changes of 50 to almost 200 mm over less than 6 months using stakes in American Samoa.

  In the studies in Table 2, surface elevation change was measured over periods of 3.5 years or less, while sea level rise was measured over periods of 10 years or more (data in Appendix A and B). Even if surface elevation at a particular location closely tracked sea level rise, any relationship might well be obscured by the different measurement periods combined with the temporal variability. Ideally both would be measured over the same period and this period would be several decades, to average out inter-annual and inter-decadal variation, due to natural oscillations such as the El Niño Southern Oscillation (ENSO) and the 18 year tidal cycle. If surface elevation responds to sea level rise following a time lag, this will further complicate the interpretation of such data; longer term datasets with regular measurements are needed to explore whether time lags exist in surface elevation responses to sea level rise.

Another issue relates to the acceleration of sea level rise rates over the past 140 years (Church and White, 2006). This could make long term sea level rise measurements less suitable for comparing with recent short term rates of surface elevation change.

- high spatial variability in surface elevation change measurements. The small-scale variability in surface elevation change measurements is shown by the large error bars in Figure 9; standard errors of surface elevation means ranged between 0.44 and 2.23 mm/yr (Rogers *et al.,* 2006; Appendix A). Calculating a mean surface elevation change from these measurements may not provide an accurate spatial average of elevation change across the site: French and Spencer (1993) demonstrated that spatial averaging of accretion data across a marsh site provided a poor estimate of total accretion because accretion varied with height of the substrate and distance from channel margins; a numerical integration taking these factors into account provided a better accretion estimate across the marsh habitat.

- spatial variability in relative sea level change, combined with variable distances between SET-MH stations and tide gauges: small-scale variation in relative sea level rise rates can be caused by local geomorphology and bathymetry (e.g. larger rises in sea level may be observed in an estuary relative to neighbouring open coast). Larger-scale variation is caused by regional variation in rates of thermal expansion of sea water and isostatic adjustments (as discussed in Section 1.2). This spatial variability in relative sea level rise means that SET-MH stations need to be placed as close as possible to the tide gauges measuring relative sea level rise. Most SET-MH stations used in the studies in Table 2 were less than 25 km from tide gauges (Appendix B). However the nearest tide gauges to the SET-MH stations on Twin Cays, Belize and Kosrae, Micronesia were 1075 and 550 km away respectively, and relative sea level rise rates in these SET-MH locations may differ significantly from the nearest tide gauge in Key West, Florida and on Pohnpei, Micronesia.

Confounding factors

It is also important to note that other controls on surface elevation change may or may not be linked to sea level rise, such as changes in sediment supply, and altered wave action or tidal currents which affect sediment routing and deposition. Where other controls are dominant, there may not be any correlation between sea level rise and surface elevation change, and even where the two are correlated, they may not necessarily point towards a direct causal link.

2.2.3 Conclusion

In conclusion, recent studies suggest that surface elevation change rates are not significantly different from sea level rise rates, indicating that mangrove surfaces are rising at similar rates to relative sea level rise in their respective locations. There is high variability in surface elevation change rates even within sites, indicating that some areas within each site may be keeping pace with local sea level rise, while other areas may be lagging behind. More surface elevation data measured over longer time periods are needed to better understand whether surface elevation change rates are correlated with local sea level rise rates.

3. Processes

In order to understand when and where mangrove surface elevation is likely to be able to keep pace with sea level rise in the future, we need to understand the processes involved in surface elevation change. These processes can be divided into surface processes (sedimentation, accretion and erosion) and sub-surface processes (growth/decomposition of roots, shrink/swell of soils, and compaction/compression/rebound of soils) (Section 1.3). These processes are described in turn below, first giving a brief description of the process, followed by factors that are likely to affect it. The following sections give an overview of current knowledge, but do not attempt to provide an exhaustive review or bibliography of relevant publications because of the large number of processes involved.

It is important to note that surface processes interact with subsurface processes, and both sets of processes may be influenced by local sea level fluctuations (amongst many other factors, as described below). We consider some of the likely interactions between surface processes and subsurface processes in Section 4.2, and interactions with sea level rise are considered in Section 5.

3.1 Surface processes

Surface processes include all processes which affect the material arriving at the sediment surface and the fate of this material. Here we divide these processes into sedimentation, accretion, erosion and faunal processes (i.e. processes mediated by animals that live within mangrove areas).

3.1.1 Sedimentation

Sedimentation refers to the deposition of inorganic sediments and organic matter onto the soil surface. The deposited material can be allochthonous (i.e. derived from outside the mangrove area) or autochthonous (i.e. created within the mangrove area).

Allochthonous material can be:

- terrigenous material from the land brought down by rivers; for example, the Sundarbans receive billions of tonnes of sediment per year from the Ganges-Brahmaputra-Meghna system (Woodroffe and Davies, 2009); small rivers can also deliver significant quantities of sediment;
- brought in through the creeks during high tides and then deposited when the creeks overspill onto the surrounding area; such sediment may have been carried along the coast (long-shore transport), as seen along the coast of French Guiana, north of the Amazon delta (Allison and Lee, 2004), or advected from offshore by wave and tidal processes, particularly in macrotidal systems (i.e. systems with a large tidal range), such as those along the coast of northern and north-western Australia (Woodroffe and Davies, 2009); large quantities of off-shore material may also be brought in during high-magnitude storm or tsunami events (Ellison, 2009);
- biologically produced, for example coral sand generated in nearby coral reef ecosystems; or

- precipitated, for example, solid calcium carbonate can be precipitated from dissolved carbonate in the water, and the calcareous muds of the Great Bahama Bank are produced in this way (Woodroffe and Davies, 2009).

When mangrove sediments are made up of predominantly coral sands or precipitated carbonate, the mangroves are classed as being in a carbonate setting (Woodroffe and Davies, 2009); examples include mangroves in Florida, Caribbean islands and many other low-lying islands. Alternatively mineral sediment inputs may dominate, and most often this is made up of terrigenous material brought down by rivers; such settings are classed as minerogenic, to distinguish them from carbonate settings. Examples include many mangrove areas in Australia and south-east Asia.

Autochthonous material includes leaf litter, dead twigs, branches and roots from the mangrove vegetation, as well as the benthic mats that grow on the sediment surface (Cahoon *et al.* 2006; McKee, 2011). These materials may become incorporated into the soil by bioturbation e.g. by crabs, or be buried under deposited sediments. The build-up of this material is influenced by detritivores such as crabs, amphipods and gastropod molluscs, which consume leaf litter (Middleton and McKee, 2001; Nagelkerken *et al*., 2008) (see Section 3.1.4 on faunal processes).

Excess sedimentation, for example during storms or caused by construction projects, may result in reduced vigour of mangrove trees or even death, depending on the amount and type of sedimentation (Ellison, 2009). This topic is reviewed in Ellison (2009).

Factors affecting sedimentation

The factors likely to affect sedimentation rates in mangroves are shown in Figure 10. The most important influences on sedimentation rates are likely to be the amount of incoming sediment and locally generated material, the period of inundation when external material can settle out, and factors affecting whether particles are able to settle out or are quickly resuspended, including flow rates and flocculation of particles.

Factors affecting the amount of incoming material

The most important factor affecting the amount of incoming allochthonous material is likely to be proximity to a source of material, e.g. a river mouth. The delivery of this sediment into mangrove areas will depend on water currents and flow pathways, and may vary seasonally or during storms. For example, Saad *et al.* (1999) found that seasonal variation affected the rate of sedimentation and accretion rates in Kememan, Terengganu, Malaysia: accretion rates were 2.6 mm/month (equivalent to 31 mm/year) during the monsoon period between November and January, compared to 1.2 mm/month outside the monsoon period (equivalent to 14 mm/year). This may be explained by the higher river discharge and river sediment load during the monsoon season, with suspended sediment concentrations in the river between 50 to 100 ppm (parts per million) at this time, compared to 8 to 20 ppm outside the monsoon season.

Storms and hurricanes (and particularly the storm surges associated with them) can bring in large pulses of sediment: for example, after Hurricane Wilma in 2005, a mangrove area on Shark River, Florida, increased in elevation by 48 mm (Smith, unpublished data, in Cahoon, 2006), due to an influx of sediment (accretion was 77 mm, accompanied by 29 mm of shallow subsidence). Cahoon (2006) notes that the degree of sediment mobilization is usually related to the intensity of the storm, the size of the storm surge and the local geomorphic

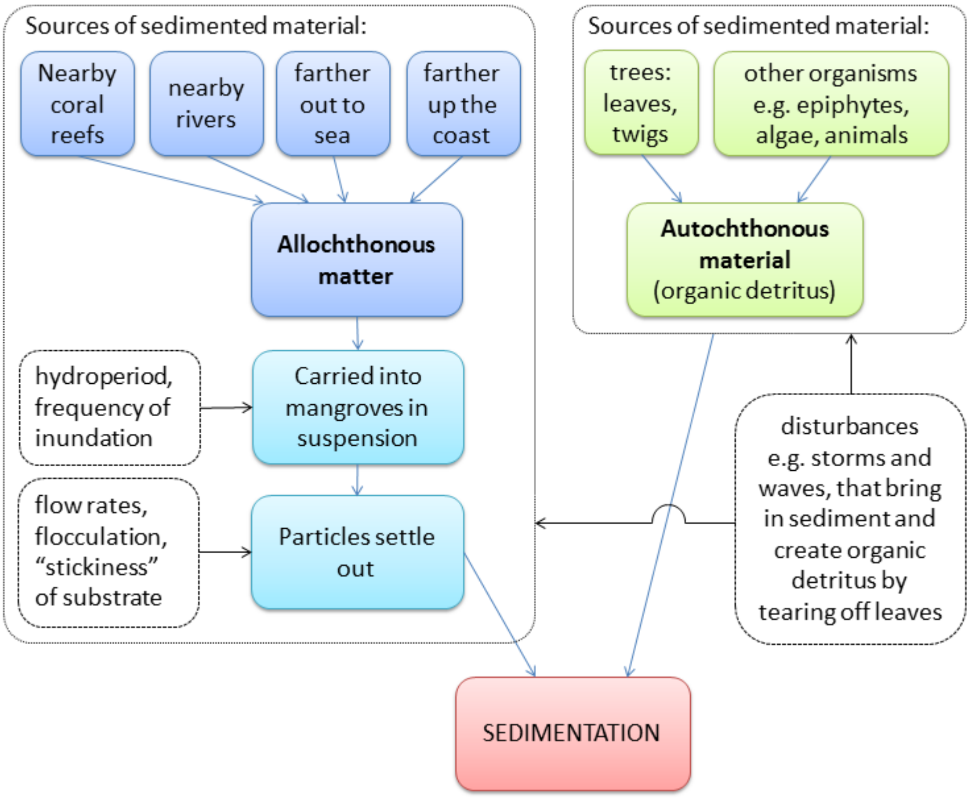


Figure 10. Sources of sediment and processes affecting sedimentation. Disturbances such as storms and waves can either increase sedimentation or carry away material, resulting in unpredictable effects of storms on sedimentation/erosion.

setting combined with the storm track. For example, while the storm surge from Hurricane Wilma deposited 77 mm of sediment in mangroves along Shark River, mangroves at Big Sable Creek, located to the south of Shark River, on the lee side of Cape Sable and therefore more protected from the surge, received only 1 mm of sediment (Cahoon, 2006). In marsh settings, single storms can deposit more sediment than would otherwise be deposited annually, and such low frequency pulses of sediment may be critical for maintaining surface elevations in areas with low sediment inputs and high rates of subsidence (Cahoon *et al.*, 1995b). The relative importance of such sediment pulses in mangroves is not known, but is likely to be similar.

Factors influencing the amount of incoming autochthonous material include forest characteristics and the local climate: Saenger and Snedaker (1993) found that litterfall was related to both height of vegetation and latitude. Storms can also result in large quantities of autochthonous material being dislodged and arriving on the substrate, e.g. if leaves are blown off trees or epiphytic algae are washed off tree roots. However some of this organic detrital material may be carried out to sea by the ebb tidal currents: Wolanski *et al.* (1980) note that the outgoing tide at Coral Creek, Queensland, Australia, was strong enough to carry all leaves into tidal creeks and hence out to sea. The amount of litterfall that accumulates also depends on how much is consumed by detritivores such as crabs and amphipods, and on rates of microbial decomposition (Middleton and McKee, 2001).

Processes involved in particle settling

Flocculation

Suspended particulate matter entering mangrove forests includes particles of various sizes, from clay particles (particle diameter less than 3.9 µm) to aggregated flocs (aggregations of smaller particles) that can be very large (sometimes more than 100 µm in diameter). Particle size is important because it influences the rate at which particles settle in water; very small particles settle very slowly, and may not have time to settle during tidal inundations. Large particles settle rapidly, even in slowly flowing water. In fast flowing turbulent water, large flocs usually break up as the forces holding them together are relatively weak. The size and nature of flocs varies in different mangrove settings: in calcareous settings, flocs may be much larger than in clay-dominated settings, where floc density is higher and flocs are stronger (i.e. they do not break up as easily) (Wolanski, 1995).

Flocculation rates (i.e. the rate at which small particles stick together to form larger particles) are dependent on the concentration of suspended particulate matter: Verney *et al.* (2009) observed maximum floc sizes above concentrations of 0.1 g/l, and no flocculation was observed below concentrations of 0.004 g/l (this was measured in an estuarine environment in France). They noted that diatom blooms speeded up rates of flocculation. Flocculation rates depended on the types of particles present and on the content and concentration of organic matter. Turbulence limited the maximum floc size. Salinity was found to have less effect on flocculation than suspended particulate matter concentration.

Settlement of flocs

Furukawa *et al.* (1997) measured particle sizes over three spring tides in mangroves at Middle Creek, Cairns, Australia. They found that the median particle size of flocs entering mangroves on the flood tide was 20 µm, with individual flocs often exceeding 100 µm in diameter. At ebb tide, no large flocs were seen; median floc size was 2 µm with the largest flocs still less than 20 µm. This suggests that the large flocs had settled during the high tide period. Furukawa *et al.* (1997) measured the exact timing of settlement using an upward-looking nephelometer (this measures the thickness of a sedimented layer by measuring the reduction in light level; the nephelometer wiped the sediment off the sensor every 5 minutes, enabling continuous measurements of sedimentation). Sedimentation peaked sharply approximately 30 minutes before high tide (slack water), and the bulk of sedimentation occurred over a 20 minute period.

Furukawa *et al.* (1997) also explored the currents within the mangrove area at Middle Creek. Using observations of fine-scale flow patterns around *Rhizophora* prop roots and a numerical model (VORTEX) to simulate flows around mangrove trunks and roots, they estimated flow rates among the roots. The field observations showed that the roots generated eddies, jets and stagnation zones. Using the model, they found that at a flow rate of 0.2 m/s, particles remained within the mangrove area for longer than when the flow rate was lower at 0.05 m/s, due to particles being trapped in stagnation zones behind roots; these stagnation zones resulted from a reduction in laminar flow at the higher flow rates. This implies that the faster flow rates resulted in higher rates of sedimentation as particles become trapped in these stagnation zones.

Distance from coast or creek

In tidal areas of southeast Queensland, Australia, sedimentation was highest in the seaward fringe mangroves (Adame *et al.*; 2010); however in riverine settings, Adame *et al.* (2010) observed a more homogeneous pattern of sedimentation across the intertidal zone. This is likely to be related to a longer hydroperiod (i.e. time under water), during which time sediment can settle out of the water column. Saad *et al.* (1999) also noted that the mean particle size of sedimented material was highest in the fringe zone (because the largest heaviest particles settle out first), and decreased further into the mangrove area in Kemaman, Malaysia.

Furukawa *et al.* (1997) found that net sedimentation rates during spring tides in mangroves surrounding Middle Creek, Cairns, Australia decreased exponentially with distance from the tidal creek. Sedimentation rates were measured with sediment traps, and were as high as 300 g/m^2/spring tide next to the creek, decreasing to almost zero 200 m from the creek. They estimated that 10.4 kilograms of sediment per metre length of tidal creek per spring tide were retained in the mangroves, out of a total incoming sediment load of 12.5 kg/m length creek/spring tide.

Sediment trapping by roots

Mangrove aerial root architecture may influence sediment trapping in mangroves: Kathireesan (2003) found differences in sediment trapping efficiency in the Vellar estuary, India, between mixed stands of *Avicennia* and *Rhizophora* and areas with just one species or the other, and he suggests this relates to the different aerial root structures (*Avicennia* spp. have pneumatophores, pencil like projections sticking out of the substrate, while *Rhizophora* spp. have prop roots). In areas with both *Avicennia* and *Rhizophora*, 30% of the total suspended sediment received at high tide was trapped at low tide, while in areas with only one species, only 20 to 25% of the suspended sediment was trapped. The trapping effect probably relates to flow modifications around aerial roots; if stagnant areas form (as suggested by Furukawa *et al.* (1997) above), then particles can settle out and are likely to be retained in the mangroves.

Furukawa and Wolanski (1996) modelled the influence of tree species on sedimentation rate, and predicted that most sedimentation should occur around trees that form a complex matrix of roots, such as *Rhizophora* spp., and least sedimentation around isolated trees such as *Ceriops* spp. that lack extensive aerial roots.

3.1.2 Accretion

Sedimentation contributes to surface accretion, which occurs when the deposited material becomes fixed in place (i.e. it can no longer be washed away by the tides or waves). It is usually measured relative to a marker horizon (Box 1).

Processes which contribute to accretion include:

- the growth of surface mangrove roots into the newly deposited layer, binding sediments in place (Cahoon and Lynch, 1997), and preventing them from being washed away by waves and tidal flows;
- the formation of benthic mats, made up of single-celled organisms (diatoms and bacteria), filamentous algae and cyanobacteria, mineral sediment, leaf litter and other organic matter (McKee, 2011), which cover and incorporate sediments, holding them in place;
- dewatering and consolidation of fluid muds, increasing soil shear strength and ability to resist resuspension/erosion by waves (Wells and Roberts, 1980).

The distinction between sedimentation and accretion is often unclear, and the terms are sometimes used interchangeably in the literature. The difference lies in their temporal scale:

sedimentation can be measured over a period of hours or days (and may be followed by resuspension of deposited but unbound material), while accretion can only be measured over months or years, when the deposited material is more firmly bound in place.

Factors affecting accretion

The rate of accretion depends on the balance of the rates of sedimentation and resuspension, and on processes which bind deposited material so that more force is required to resuspend it. The factors affecting sedimentation have been discussed in the previous section; resuspension rates are likely to be affected by waves and currents, and are discussed further in the following section on erosion. The binding of deposited material will depend on the growth of near-surface roots into the newly deposited material, and the formation of benthic mats and mucilaginous layers, both of which can 'fix' the material in place.

Benthic mats

Benthic mats can form on the soil surface of wetlands, and they may consist of filamentous algae, plant roots, microbial communities or any combination of these (Cahoon *et al.*, 2006).

McKee (2011) recognized three types of benthic mat in Caribbean mangrove systems: turf algal mats, consisting of filamentous algae; leaf litter mats, containing a higher proportion of mangrove leaf litter alongside filamentous algae; and microbial mats, containing mixtures of cyanobacteria, diatoms, other microalgae and other amorphous organic matter. Turf algal mats accreted faster than leaf litter mats, and at similar rates to microbial mats, but there was high variability across sites (McKee 2011). McKee (2011) found different types of benthic mat in different forest types in Caribbean mangrove systems; for example, microbial mats were common in dwarf mangrove forests and in shallow protected ponds where the tree canopy was open or absent and the soil surface remained flooded. Turf algal mats are often seen in *Rhizophora mangle* forests throughout the Caribbean (Cahoon *et al.*, 2006).

Rates of vertical mat growth can vary from 1 mm/yr (e.g. turf algal mats along the shoreline) to 6 mm/yr (microbial mats in interior dwarf mangrove stands) (Cahoon *et al.*, 2006). Variation in accretion rates of different types of benthic mat may contribute to different rates of accretion and elevation change.

McKee (2011) also noted that benthic mats in Belize contained up to 30% (by volume) live mangrove roots.

Factors affecting sedimentation and/or accretion

Several studies report factors that have been shown to affect accretion rates, but it is likely that these factors affect accretion primarily through their influence on sedimentation rates.

Aerial root type and density

Krauss *et al.* (2003) investigated the influence of root type on vertical accretion in three river basins in Micronesia. They looked at three different functional root types: prop roots in *Rhizophora* spp., knee roots in *Bruguiera gymnorrhiza*, and pneumatophores in *Sonneratia alba.* In the Enipoas River basin, Pohnpei, accretion rates were higher among prop roots (11.0 mm/yr) than among pneumatophores (7.2 mm/yr), knee roots (9.3 mm/yr) and bare soil controls (9.4 mm/yr).

Young and Harvey (1996) placed arrays of artificial pneumatophores within mangroves in the Hauraki Plains, New Zealand, to investigate how accretion rates are affected by the density of pneumatophores. Accretion rates were 4 mm/yr with 100 pneumatophores/m^2, and 25 mm/yr with 350 pneumatophores/m^2. They also measured accretion along 2 transects within the mangroves: 102 accretion measurements were taken along the 500 m length transects over a 5 month period, with maximum accretion rates of 14 mm. They found a significant positive correlation between the density of *Avicennia marina* var. *australasica* pneumatophores and accretion rates, but the correlation between mangrove stem density and basal area with accretion was not significant.

It is likely that the prop roots of Krauss *et al.*'s (2003) study, and the higher densities of pneumatophores in Young and Harvey's (1996) study, are more effective at promoting sedimentation and reducing resuspension through slowing water flows from waves or currents.

Tree density

Mangrove seedling density can influence accretion rates: in an experiment where *Rhizophora mucronata* seedlings were planted at different densities in Palakuda, Sri Lanka, accretion rates were highest among the highest densities of mangrove seedlings over a period of 3 years (Table 3; Huxham *et al.*, 2010; Kumara *et al.*, 2010). However such high densities are only possible with seedlings; older trees could not exist at such densities.

Table 3. Accretion rates and surface elevation change rates measured over 3 years at different seedling densities of *Rhizophora mucronata* in Palakuda, Sri Lanka (from Kumara *et al.*, 2010). Older plants could not survive at the higher densities used here.

Seedling density (no. of seedlings/m^2)	Accretion rate (mm/yr)	Standard error	Surface elevation change (mm/yr)	Standard error
0	5.7	0.3	-0.3	0.1
0.95	6.9	0.5	0.6	0.2
1.93	8.4	0.3	1.1	0.2
3.26	10.5	0.9	1.6	0.1
6.96	13	1.3	2.8	0.2

Amount of mangrove leaf litter present

Cahoon *et al.* (2006) found that the standing stock of litter present on the mangrove surface in a forest in southwest Florida affected vertical accretion in basin forests, with a significant positive correlation between litter biomass (g/m^2) and vertical accretion (mm/yr). However no relationship was seen in fringing mangroves, where tidal action may wash leaves away and the drier conditions may allow leaves to decompose more quickly.

Frequency and period of inundation (hydroperiod)

The period of time that mangroves are flooded (hydroperiod) and the frequency of flooding affects sedimentation and accretion rates because allochthonous sediment arrives suspended in the water column. Rogers *et al.* (2005) found that sediment accretion rates were directly related to inundation frequencies in Homebush Bay, Australia: in areas inundated by 5% of tides per year, sediment accretion rates varied between 1 and 2.6 mm/yr, while in areas inundated by 13% of tides per year, accretion rates varied between 4.6 and 8.6 mm/yr.

Forest type

Cahoon and Lynch (1997) measured elevation change and accretion in fringe, basin and island mangroves of Rookery Bay, Florida. They identified three distinct accretionary environments based on hydroperiod and soil properties: fringe forests with regularly-flooded mineral soils, basin forests with irregularly-flooded organic soils, and overwash island forests that were flooded regularly and had mixed mineral-organic soils. Accretion rates were highest in the fringe forests (7.2 and 7.8 mm/yr) and lowest in the overwash forest on the sheltered island (4.4 mm/yr).

Tidal range

Rogers *et al.* (2006) found a significant positive relationship between mangrove surface accretion and tidal range using data from 10 wetland sites in south-eastern Australia; they attribute this to stronger tidal currents in areas with larger tidal ranges, which can re-suspend sediments and facilitate deposition within wetlands. Cahoon *et al.* (2006) also found a significant positive relationship between accretion and tidal range in a global dataset including 38 mangrove locations.

3.1.3 Erosion

Erosion refers to the loss of surface material caused by the top layer of the sediment surface being sheared off by water flows, leading to a loss in elevation. Surface erosion can occur when waves or currents scour the sediment surface, for example during intense storms. Small waves (even capillary waves) can also result in erosion of the very fine muds found in some mangroves areas (Winterwerp *et al.,* 2005).

Surface erosion is sometimes called “sheet erosion” to distinguish it from lateral or bank erosion, which occurs at the edge of the mangrove where it borders the sea or a tidal channel.

Factors affecting surface erosion

Surface erosion is difficult to measure as surface markers are lost (Cahoon and Lynch, 1997) and any lowering of surface elevation as measured using the SET-MH methodology (Box 1) could also have been caused by shallow subsidence resulting from sub-surface processes (Section 3.2). Therefore, in order to understand the factors affecting surface erosion, we are obliged to study the factors affecting the erodibility of the mangrove surface and the bottom shear stresses (i.e. the hydrodynamic forces) acting on the surface. These are reviewed in Le Hir *et al.* (2007) in relation to a wide range of coastal systems.

The rate of erosion ε_r (m/s) can be described by the following equation (Hanson and Cook, 2004):

$$\boldsymbol{\varepsilon_r = k_d(\tau_e - \tau_c)} \qquad \text{(Equation 1)}$$

where k_d is the erodibility or detachment coefficient (m^3/N-s), τ_e is the effective hydraulic stress (Pa) and τ_c is the critical stress (Pa). This equation shows that the rate of erosion depends on a coefficient of erodibility, and on the difference between the hydraulic stress τ_e (i.e. the shear force acting on the substrate as the water flows over it) and a critical or threshold stress level (τ_c) above which the substrate gives way and starts to be eroded.

In mangroves, several studies have measured the shear strength of soils using a device which measures the torque required to shear or deform the soil (McKee and McGinnis, 2002; McKee and Vervaeke, 2009; Cahoon *et al.,* 2003a&b; McKee, 2011; these studies are described below). The shear strength of a soil is thus related to the critical stress (τ_c) in Equation 1. Soils with higher shear strengths have higher erosion thresholds above which erosion will occur.

Waves and currents generate hydraulic stress (τ_e) at the sediment surface (also referred to as bed shear stress). Factors which result in reduced currents or waves, and thus reduced hydraulic stress, are also expected to reduce the rate of erosion at the mangrove surface.

Factors that either increase the shear strength of mangrove soils or decrease the flow rates within mangroves will reduce erosion rates. The factors affecting the shear strength of mangrove soils and the water flows within mangroves are discussed below.

Factors affecting the erodibility of mangrove soils

McKee and Vervaeke (2009) measured the shear strength of mangrove soils on mangrove islands in the Pelican Cays and Twin Cays Ranges, Belize; the main mangrove species was *Rhizophora mangle*. They found that the shear strength of undisturbed mangrove soils was higher than that of degraded soils (mangroves were classed as degraded in areas where clear-cutting of mangroves had taken place, followed by filling with sediment dredged up from nearby coastal areas). The substrate in the undisturbed mangrove forests consisted of a strong matrix of living and dead fibrous roots, with mats of filamentous algae on the soil surface. This material was extremely resistant to shearing and retained its integrity even when agitated in water (McKee and Vervaeke, 2009). These results imply that the network of living and dead roots of healthy mangroves increase the shear strength of the mangrove soil surface, presumably by binding the soil together (Scoffin, 1970; Spenceley, 1977; Cahoon and Lynch, 1997).

McKee and McGinnis (2002) studied the shear strength of mangrove soils 14 months after the passage of Hurricane Mitch in 1998; they found that impacted sites had lower shear strength than unimpacted sites, and this was associated with reduced sub-surface root densities or death of the root system. The effect of hurricane impacts on soil shear strength varied with the level of impact, the depth of the soil, and whether the soil was in a fringe or basin forest. Soil shear strength was highest in fringe forests, in deeper soil layers (5 cm and below) and in less impacted forests (Cahoon *et al.*, 2003b). Reduced shear strength of soils is expected to make the soils more vulnerable to erosion.

Benthic mats that form on mangroves soils also affect the shear strength of the surface (Cahoon *et al.*, 2006; McKee, 2011). Based on a study in Belize, Cahoon *et al.* (2006) found that the soil shear strength of algal mats made up of filamentous algae and roots was generally higher than for microbial mats (soil shear strength of filamentous algae and roots varied between 0.25 and 0.45 kg/cm^2, while for microbial mats it was less than 0.05 kg/cm^2). McKee (2011) compared the shear strength of different types of benthic mat found on the mangrove soil surface in sites in Belize and Florida; she also found that benthic mats made of “turf algae” (primarily filamentous algae) had higher shear strength than benthic mats containing more leaf litter or microbial matter. Turf algal mats were found in fringe, scrub and restored forests.

Factors affecting the hydraulic stress on mangrove soils

The hydraulic stress (or bed shear stress) on mangroves soils is caused by the water flows within surface wind and swell waves, and flows caused by water currents related to tides or storm surges. These vary according to local or distant weather systems. Generally, mangroves only receive small wind and swell waves, as they live in sheltered areas. However, during storms, both waves and currents may generate stronger water flows. The presence of mangrove vegetation such as aerial roots and trunks can reduce wave energy and height (Massel *et al.*, 1999; Mazda *et al.*, 1997 & 2006; Quartel *et al.*, 2007; reviewed in McIvor *et al.*, 2012a). Likewise, the mangrove vegetation slows water flows during storm surges, resulting in peak water level reductions (Krauss *et al.*, 2009; Zhang *et al.*, 2012; reviewed in McIvor *et al*., 2012b). Therefore the mangrove vegetation reduces the hydraulic stress on the sediment surface, reducing the frequency of occasions when the shear stress exceeds the critical threshold (τ_c) for erosion to occur (as described in Equation 1 above).

However, mangrove roots and trunks may also create eddies and jets in flowing water (Furukawa *et al.* 1997), resulting in very localised areas that may experience higher shear stress, possibly scouring out sediment and increasing erosion rates in these areas.

3.1.4 Surface faunal processes

The soil surface of mangrove forests hosts a wide variety of animal species, amongst which crabs and molluscs are very common. These organisms affect surface processes in a variety of ways:

- sesarmid (Grapsidae) and fiddler (Ocypodidae) crabs consume mangrove leaf litter, reducing export of such leaf litter by outgoing tides, and retaining nutrients contained in the leaf litter within the mangrove ecosystem (Kristensen, 2008; Nagelkerken *et al.*, 2008; Alongi, 2009). Molluscs, particularly snails such as the mud whelk *Terebralia*, and other organisms such as copepods and nematodes, play a similar role, recycling nutrients within the system (reviewed in Spalding *et al.*, 2010). These nutrients can then be taken up by mangrove trees, enhancing growth, including the growth of above and below ground roots.
- many crabs live in burrows in the mangrove substrate, into which they drag the leaves (reviewed in Spalding *et al.*, 2010). These burrows alter the surface topography, potentially altering the shear strength of soils, water flows over the surface and sedimentation rates.
- Crabs may also affect benthic mat formation and persistence: Kristensen and Alongi (2006) found that the fiddler crab, *Uca vocans*, depressed the abundance and productivity of microalgal mats in an *Avicennia* forest in experimental mesocosms in Queensland, Australia.

The importance of faunal processes may vary in different mangrove regions; for example, crabs avoid eating mangrove leaves and seeds in temperate Australian mangrove-salt marsh ecosystems and in some Caribbean mangroves (Alongi, 2009).

3.2 Subsurface processes

Various subsurface processes have been discussed in the mangrove surface elevation change literature; the names given to these processes vary to some extent between authors. In this report, we consider the following three groups of subsurface processes:

- the growth and decomposition of mangrove roots and other organic matter;
- the swelling and shrinkage of soils and the live mangrove roots within them in the presence or absence of water or changes in groundwater pressure (also referred to as dilation water storage);
- the compaction or compression of soils, due to the sorting of particles or the weight of material above them (sediment, organic matter, or water e.g. a storm surge), followed

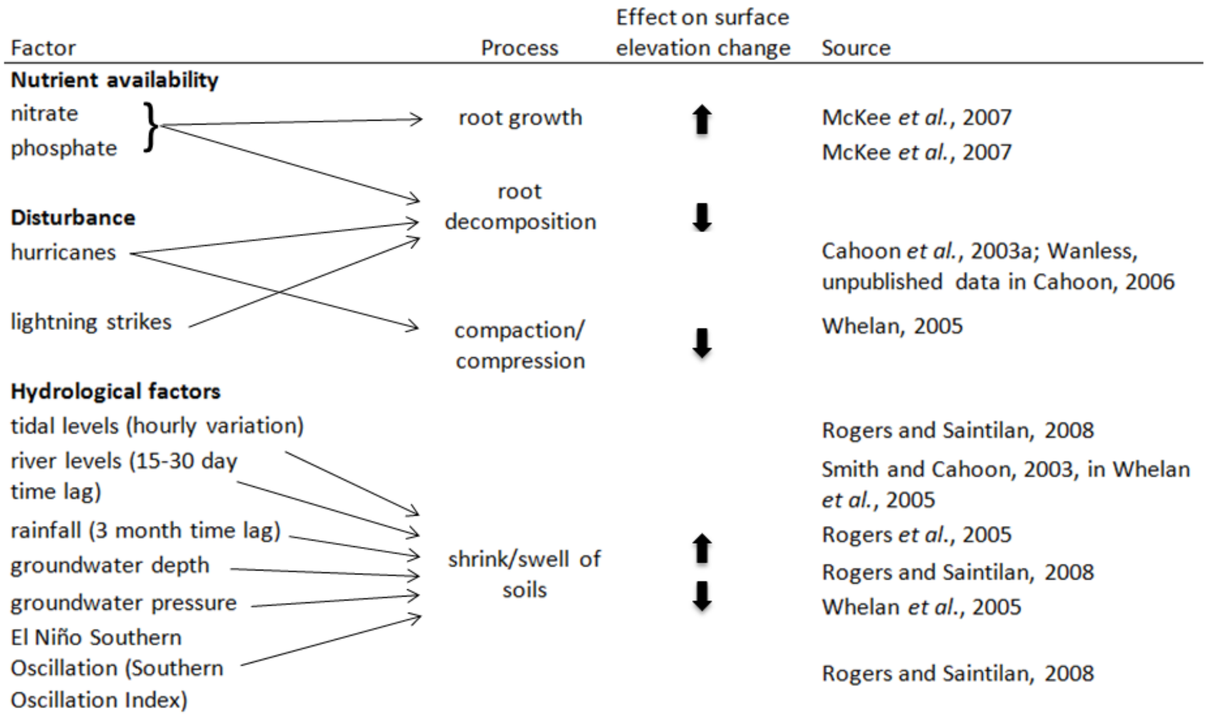
in some cases by the rebound of soils when this weight is removed (e.g. after a storm surge).

While changes in sub-surface thickness (depth below marker horizon to benchmark; Box 1) can be measured using the SET-MH methodology, it is not possible to measure the contributions of different sub-surface processes using this methodology. Therefore our understanding of the different subsurface processes has to be derived from other measures, such as the mass or volume of live and dead root matter in soil samples, or it has to be based on correlations, such as changes in subsurface volume in different soil layers that are correlated with rainfall or groundwater levels. Our understanding of these processes is growing, but there remains much to learn about how these processes work and their contribution to surface elevation change in mangroves.

Of these processes, the shrink-swell response and the compression-rebound responses of mangrove soils to local weather-related and tidal events (rainfall, tidal flows, droughts, floods, storm surges) are expected to act over short time-scales of hours to months, while root growth, organic matter decomposition and soil compaction are expected to have long-term consequences for surface elevation over many years. Our interest here is primarily in the longer-term processes affecting mangrove surface elevation. However we also consider the short-term processes because of their potential effects on other longer-term processes; for example, a drought may reduce surface elevation through the shrinkage of soils, which will result in an increased hydroperiod when soils are flooded by tides, possibly causing increased sedimentation and accretion.

The processes described below and the factors affecting their contribution to surface elevation change are summarized in Table 4.

Table 4. The factors affecting sub-surface processes within mangroves, and their effects on surface elevation change. These processes and factors are described in more detail in the text.



Factor	Process	Effect on surface elevation change	Source
Nutrient availability			
nitrate	root growth	⬆	McKee *et al.*, 2007
phosphate			McKee *et al.*, 2007
	root decomposition	⬇	
Disturbance			
hurricanes			Cahoon *et al.*, 2003a; Wanless, unpublished data in Cahoon, 2006
lightning strikes	compaction/ compression	⬇	Whelan, 2005
Hydrological factors			
tidal levels (hourly variation)			Rogers and Saintilan, 2008
river levels (15-30 day time lag)			Smith and Cahoon, 2003, in Whelan *et al.*, 2005
rainfall (3 month time lag)			Rogers *et al.*, 2005
groundwater depth	shrink/swell of soils	⬆	Rogers and Saintilan, 2008
groundwater pressure		⬇	Whelan *et al.*, 2005
El Niño Southern Oscillation (Southern Oscillation Index)			Rogers and Saintilan, 2008

3.2.1 Root growth and decomposition

The growth of mangrove roots results in an increase in soil volume and sub-surface expansion (Cahoon *et al.* 2006; McKee, 2011). Conversely, when roots decompose, they take up less space, causing a reduction in soil volume and resulting in shallow subsidence (Cahoon *et al.*, 2003b). In a study in Twin Cays, Belize, McKee *et al.* (2007) found that root inputs explained more than 50% of the variation in surface elevation change (42% from fine roots and 10% from coarse roots), with subsidence (compaction) and accretion explaining 36% and 2% respectively. In a separate study, McKee (2011) found that both fine and coarse root mass accumulation was positively correlated with elevation change in mangrove sites in Belize and Florida. Cahoon *et al.* (2006) also found a positive correlation between subsurface root production and elevation change, using data from 18 mangrove forests in different geographic locations and three soil types (mineral, organic and peat).

Factors affecting sub-surface root growth and decomposition

The growth and decomposition of mangrove vegetation, including sub-surface roots, are influenced by tree health, salinity (mangroves usually grow faster in lower salinities), temperature (mangrove species are generally intolerant of cold temperatures), nutrient availability (related to riverine inputs and regional geological influences), tree species, and soil aeration, amongst many other factors. Some of these factors are explored in more detail below.

Evidence for the importance of tree health comes from areas where trees have died following lightning strikes or the passage of hurricanes. After Hurricane Mitch hit Honduras in 1998, mangrove areas where trees had been destroyed by the high winds experienced peat collapse; Cahoon *et al.* (2003a) measured a fall in elevation of 11 mm between 18 months and 33 months after the hurricane. They attributed this to the death and decay of sub-surface mangrove roots leading to shallow subsidence.

After Hurricane Andrew in 1992, some mangroves in southwest Florida lost 20 mm elevation because of peat decomposition (Wanless, unpublished data in Cahoon, 2006). The likelihood of peat collapse may be related to the organic content of soils; those with higher organic content may be more likely to suffer collapse following tree death (Cahoon *et al.*, 2003a). Gaps in the mangrove canopy caused by lightning strikes to trees can also lead to localised elevation losses of up to 60 mm in Everglades National Park, Florida (Whelan, 2005).

Availability of nutrients may also affect root growth and decomposition. In Twin Cays, Belize, McKee *et al.* (2007) found that application of fertilizers altered both the direction and rate of change of surface elevation through the effects on root growth. Addition of phosphorus as superphosphate increased rates of root accumulation in interior mangrove zones: fine roots contributed substantially to soil volume and explained a significant amount of the variation in elevation change. Conversely, when a nitrogen fertilizer (in the form of urea) was applied in the same zone, there was a significant increase in root mortality, and these plots had higher rates of shallow subsidence. The effect of nutrients on subsurface change and elevation change varied with mangrove zone, and addition of nutrients to transition and fringing zones did not produce the same effect as in interior zones (e.g. in the fringing zone, addition of both nitrate and phosphate resulted in shallow subsidence, while the control zone still showed sub-surface expansion; fertilized plots showed a smaller increase in surface elevation than control plots in this zone). Elevation change was significantly correlated with sub-surface change in these sites ($r = 0.94$; $p < 0.0001$), showing that sub-surface processes were the primary controls on surface elevation change

(McKee *et al.*, 2007). It is unknown if natural variation in nutrient inputs has similar effects on root growth and decomposition.

The importance of root growth contributions is not limited to organic or peat soils, but is also important in mineral soils (i.e. soils with a greater percentage of non-organic material): Cahoon *et al.* (2006) found that in 5 out of 7 mineral settings, root growth contributed to soil expansion, compared with 15 out of 17 peat settings.

Decomposition rates are also affected by the degree of aeration of the soil: most mangrove soils are anaerobic, reducing rates of decomposition. However air may reach further into mangrove soils via tree roots, or if the soils dry out, or through the action of burrowing invertebrates, such as crabs.

3.2.2 Shrink-swell of soils (dilation water storage)

Dilation water storage refers to the expansion or contraction of soils when the soil water content increases or decreases respectively (Cahoon *et al.*, 2011). Dilation water storage results in the shrink-swell response of wetland soils to flooding and drying. Mechanisms for this are likely to include changes in the osmotic pressure within mangrove roots in the shallow soil layers, and increases in groundwater pressure in the deeper soil layers that result in an increase in volume in these layers. The effect may also be more pronounced in soils with a higher organic content.

Cahoon and Hensel (2006) suggest that the effects of water availability on surface elevation are usually transitory and may not affect longer-term trends in surface elevation. However, this may not be the case where water flows have been permanently altered through drainage, diversion, the building of dams upstream and abstraction, or where precipitation patterns are changing as part of on-going climatic changes.

Factors affecting soil swelling and shrinkage

Soils swell and shrink in response to the presence of water and groundwater pressure over a variety of timescales, from very rapid changes related to tidal levels, to changes over months to years in response to longer-term climate variations, such as those associated with the El Nino Southern Oscillation (ENSO).

Tidal levels

Rogers and Saintilan (2008) measured surface elevation repeatedly over a four hour period on 23 January 2004 between high tide and low tide in a mangrove at Homebush Bay, Australia. During the first 210 minutes (over which time measurements were taken approximately every hour), surface elevation decreased by 3.7 mm; the reduction was almost linear, and this equates to a fall in surface elevation of 1.1 mm/hr. Over the last 15 minutes of observation, surface elevation started to rise again. This demonstrates that tidal levels can cause short term changes in surface elevation of relatively large magnitude compared to annual surface elevation changes, which are often of a similar order of magnitude (between 2000 and 2003, the surface elevation change rate in Homebush Bay was measured as 5.6 mm/yr by Rogers *et al.*, 2006). Rogers and Saintilan (2008) note that similar short term changes in surface elevation have been measured in tidal marshes by Paquette *et al.* (2004), where they are attributed to changes in soil water content (and hence soil volume) influenced by tidal inundation and evapotranspiration.

Rainfall and groundwater level

Smith and Cahoon (2003, in Whelan *et al.*, 2005) measured surface elevation in a mangrove forest along Shark River in the Everglades National Park, Florida, over a 3 year period. They found that mangrove surface elevation increased linearly with increasing water levels in the Shark River as measured 15 to 30 days previously, indicating that water levels can strongly influence mangrove surface elevation.

Rogers *et al.* (2005) monitored surface elevation in a mangrove area in Homebush Bay at approximately 6 month intervals over a 43 month period between 2000 and 2003 (the following discussion refers only to the control area of their experimental design). They found that surface elevation varied significantly over the measurement period: after an initial increase which then plateaued (a 12 mm increase over 3 years), surface elevation then rose again sharply (by 10 mm over 6 months) at the end of the measurement period. The change in surface elevation correlated with rainfall, where rainfall was adjusted to include a 3-month time lag (this time lag was introduced to allow for a delay between rain falling and it influencing groundwater levels). Rogers *et al.* (2005) concluded that the reduced rainfall associated with an El Niño event which occurred in the middle of their measurement period had a measurable effect on the rate of surface elevation change seen within the mangrove. (See below for further discussion of the effects of the El Niño Southern Oscillation on mangrove surface elevations.)

In a separate study at the same location, Rogers and Saintilan (2008) measured surface elevation every 2 weeks over a 4 month period in 2004, and found a strong correlation between groundwater depth and surface elevation (where surface elevation was averaged from one SET measurement in the saltmarsh zone, three SETs in the mangrove zone, and one in a mixed zone, all measured at low tide to control for tidal variations in surface elevation). They note that groundwater level reflected monthly rainfall. Mean surface elevation increased by 2.5 mm over the first month (groundwater depth rose by 200 mm during this period and rainfall exceeded 100 mm); surface elevation then fell by 3.5 mm over the next 2 months (groundwater depth fell by approximately 60 mm over this time), and finally increased again by 2 mm over the last month (groundwater depth increased by 100 mm).

Whelan *et al.* (2005) studied the effect of groundwater pressure and river level on mangrove surface elevation along Shark River in the Everglades National Park, Florida. They explored the response of mangrove soils at different depths by measuring surface elevation change in a way that allowed them to separate out soil volume changes in deep, middle and shallow soil layers (using 3 SETs whose benchmarks were buried to depths of 6 m, 4 m and 0.35 m). The SETs were monitored on a monthly basis over 1 year (March 2002 to March 2003), with all measurements taken at low tide; hourly measures of ground water level and river levels were also recorded. Over this time the highest mean elevation above initial surface elevation (15.1 mm) was seen at the end of the wet season (November 2002) and the lowest mean elevation was seen during the dry season (-0.1 mm in January 2003). Changes in groundwater pressure were strongly correlated with changes in soil elevation; the change in thickness of the bottom soil zone (4 m to 6 m) accounted for most of the change in surface elevation. Whelan *et al.* (2005) concluded that hydrology and groundwater pressure have a large influence on mangrove surface elevation, and that it is important to consider the differential effects on different soil zones.

The El Niño Southern Oscillation (ENSO)

Over a three year study period, Rogers and Saintilan (2008) found that surface elevation fell at several sites in southeastern Australia, despite sustained vertical accretion over the same time period. Their study period coincided with the onset of an El Niño drought in 2001-2002. To explore the relationship between the El Niño event and mangrove surface elevation, they plotted surface elevation against the Southern Oscillation Index (SOI; a measure of the changes associated with the El Niño Southern Oscillation). They found that the SOI accounted for 70 to 85% of the variability in surface elevation. However, the two deltaic sites did not fit into this pattern, which they attribute to lower groundwater inputs at these sites.

3.2.3 Compaction, compression and rebound

Compaction of soils usually refers to the consolidation of soils over time, as soil particles are packed closer together and moisture is forced out of the soil. The term “autocompaction” was used by Kaye and Barghoorn (1964) in relation to wetland peats to refer to “the compression of peat beneath its own weight”. Peat is very compressible because of its high porosity and weak skeletal framework of vegetable fibre (Kaye and Barghoorn, 1964). Mangrove peat includes both organic and inorganic material (Cahoon *et al.*, 1995a); as the weight of the sediment above increases due to accretion and growth of mangroves, autocompaction is expected to increase in a similar way to that seen in tidal marshes.

The weight of sea water can also compress peat soils, and this is particularly noticeable after large storm surges where the soil has been under several metres of water (Cahoon, 2006). This compression is assumed to occur through the squeezing out of air from the shallow aerated layer of soil just below the soil surface (Cahoon, 2006). Surface elevation may be able to rebound following this type of short-lived compressive load (Cahoon, 2006), and this may contribute to sub-surface expansion after large storm surges. This rebound may be caused by the regasification of the shallow aerated layer by microbial activity (Cahoon, 2006).

Little is known about the factors affecting the compaction and compression of mangrove soils. The most important factors are likely to be the weight of material or water pressing down on the soil, the relative volumes of particles and pores, the soil composition (and particularly the organic content), and the depth of different soil layers.

3.2.4 Subsurface faunal processes

Many animals live in the mangrove substrate in burrows, such as crabs and bivalves. Their burrowing activity can increase oxygenation of the soil, mix the surface layers (bioturbation), and allow flows of dissolved nutrients into and within the soil (Hogarth, 2007). Mangrove substrates may be underlain by the tunnels these animals create. Many crabs bury organic material, helping incorporate it into the soil. A crab exclusion experiment in Australia found changes in soil chemistry and reduced growth of trees in their absence (Hogarth, 2007). The tunnelling activity and the effects on tree growth could potentially affect soil volume and hence surface elevation change.

4. Magnitude of surface and sub-surface contributions to surface elevation change

Surface elevation change is the result of surface and subsurface processes (Table 5), and also the interactions between them. In this section we will first focus on the contributions from surface and subsurface processes to elevation change, as measured using the SET-MH methodology described in Box 1 in the studies listed in Table 2. We then consider possible interactions between the surface and subsurface processes, and the evidence for the existence of interactions. Finally we briefly explore factors that have been shown to influence surface elevation change rates.

Table 5. The contribution of surface and subsurface processes to surface elevation change, showing the direction of change.

	Contribution to surface elevation change:	
	Surface elevation rises	Surface elevation falls
Surface processes (above ground)	Sedimentation and accretion	Erosion
Sub-surface processes (below ground)	Sub-surface expansion: swelling, root growth, rebound	Shallow subsidence: root decomposition, shrinkage, compaction, compression

4.1 Accretion, shallow subsidence and surface elevation change

The magnitudes of surface and subsurface contributions to elevation change varied considerably in the different locations covered by the studies listed in Table 2, as shown in Figure 10 (data disaggregated within locations where such data are given in the source references; data shown in Appendix A). The magnitude of surface processes was measured as accretion, and rates of accretion in these studies varied from 0.7 to 20.8 mm/year (rates of erosion cannot be distinguished from rates of shallow subsidence using the SET-MH methodology). The term “shallow subsidence” was generally used to describe all sub-surface processes (it is generally not possible to distinguish between the sub-surface processes involved), and shallow subsidence measurements ranged from -19.9 to +2.4 mm/year (positive measurements indicate that sub-surface expansion has occurred).

Accretion rates and surface elevation change rates were not correlated (Figure 11). However there was a strong correlation between accretion rates and shallow subsidence rates (Figure 12), and this is discussed further in the following section.

These data show that sub-surface processes are as important as surface processes in determining the overall rate of surface elevation change in mangroves. Notably, accretion rates are rarely similar to surface elevation change rates (few points fall near the line of equality in Figure 11), and as such, accretion rates are not a good predictor of surface elevation change rates in most locations. In general, accretion rates are higher than surface elevation change rates, the balance being made up by shallow subsidence. In a small number of cases, accretion rates are lower than surface elevation change rates (points above the dashed line in Figure 11), implying that subsurface expansion has taken place.

The relationships between surface elevation change, accretion and shallow subsidence have also been explored at individual locations. Krauss *et al.* (2010) found a significant relationship between surface elevation change and surface accretion in riverine mangrove zones in Micronesia, where the highest rates of surface accretion were consistently recorded (however, these sites still experienced high rates of shallow subsidence). This suggests that in minerogenic settings with high sediment inputs, there may be a stronger correlation between accretion and elevation change rates. In some saltmarshes with high mineral sediment inputs, only low rates of shallow subsidence have been seen, and accretion rates may match elevation change rates more closely (Cahoon *et al.*, 2000a).

In Twin Cays mangroves, McKee *et al.* (2007) found that elevation change was not correlated with surface accretion over a 3 year period; accretion rates varied between 0.71 and 3.5 mm/yr while elevation change rates varied between -3.7 and 4.8 mm/yr, depending on the mangrove zone and on various experimental treatments. It is likely that sub-surface change makes a larger contribution to surface elevation change in carbonate settings with low sediment input**.**

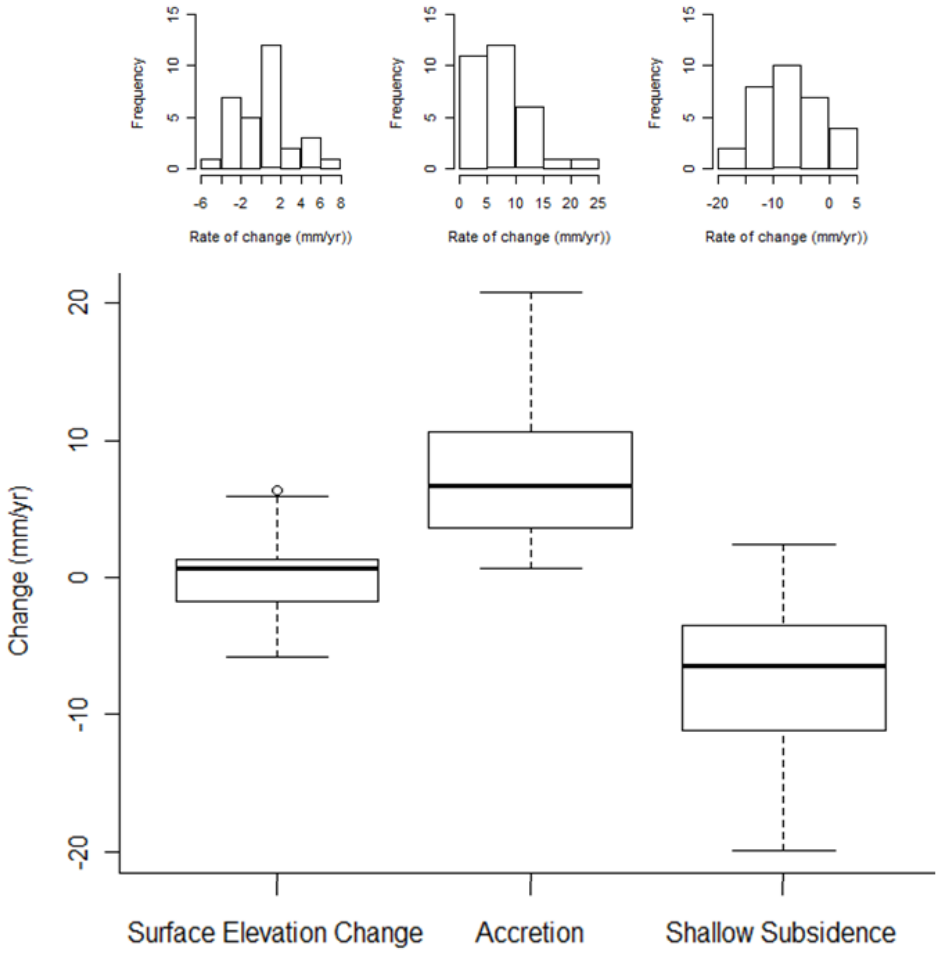


Figure 10. Rates of surface elevation change, accretion and shallow subsidence from the studies included in Table 2, with frequency histograms above the bars. Raw data and sources given in Appendix A; data now disaggregated within locations where these data are given in the source papers (e.g. surface elevation change was measured in 7 sites on Kosrae, Micronesia (Krauss *et al.*, 2010); the mean of these 7 measurements was used in Section 2.2 to allow comparisons with other locations where data had already been averaged in the source papers).

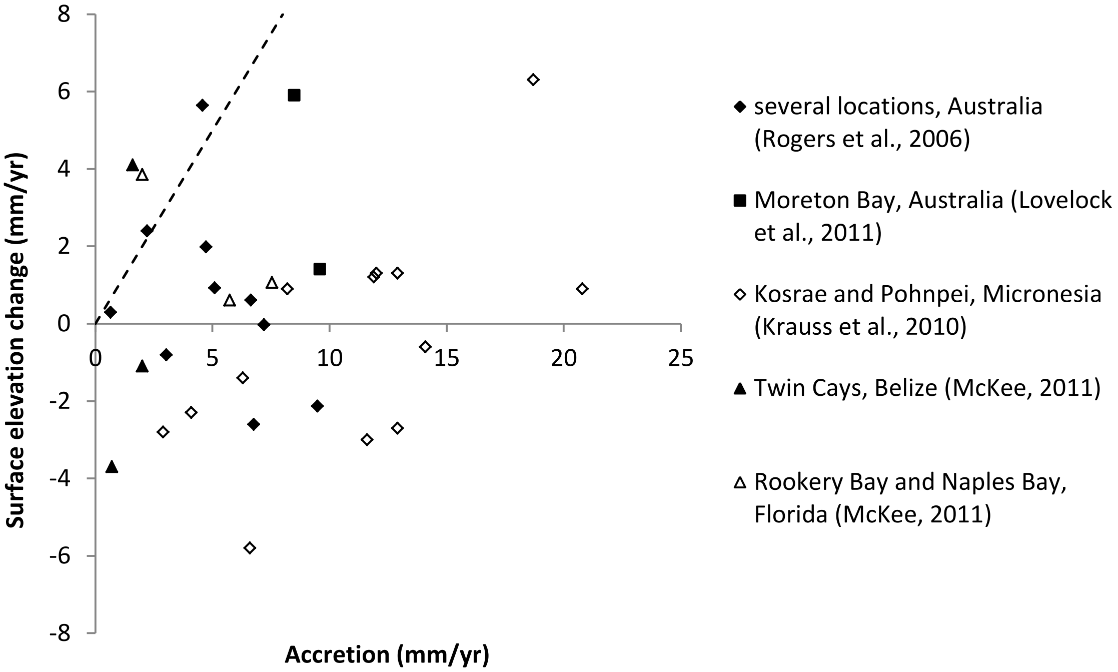


Figure 11. A plot of surface elevation change rates against accretion rates (data in Table 2 and Appendix A). The dashed line indicates the expected relationship if elevation change rates and accretion rates were equal.

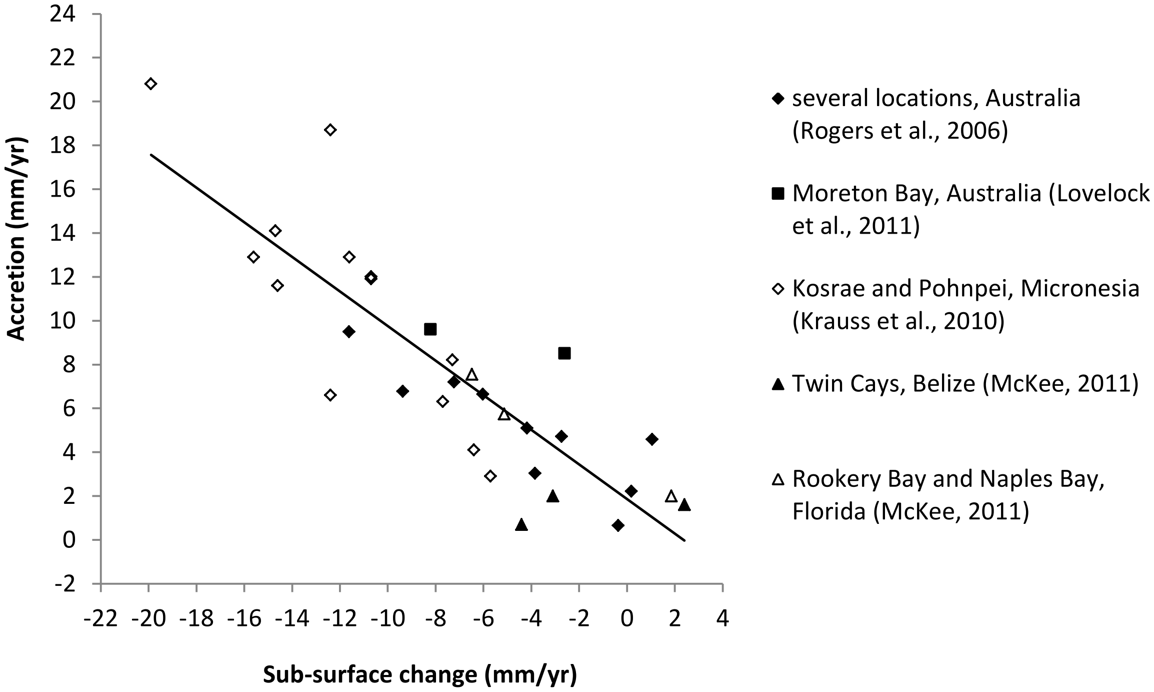


Figure 12. The annual rate of shallow subsidence plotted against annual accretion rate (raw data given in Appendix A). The line shows a linear regression through the data (see text).

4.2 Interactions between surface and subsurface processes

In over half of these measurements (17 out of 31 measurements, i.e. 54%), accretion and shallow subsidence were of approximately equal magnitude, resulting in an overall elevation change between -2 and 2 mm/year (Figure 10). The mean rate of surface elevation change across all these sites was 0.38 mm/yr, and the difference between accretion rate and shallow subsidence rate was not significantly different from zero (paired t-test, $t = 0.7282$, d.f. = 30, p-value = 0.4721, where shallow subsidence was multiplied by -1 so that absolute rates of surface and sub-surface change could be compared).

Figure 12 shows that accretion and shallow subsidence are highly correlated, and a regression analysis of accretion on sub-surface change gave $F_{(1,29)} = 79.4$, $p < 0.0001$. Such a strong relationship between surface and subsurface rates of change implies that the two sets of processes are not independent of each other, but are influencing each other in some way. Little is known about interactions between surface and subsurface processes in mangroves: no studies have been found that investigated how these processes affect each other in mangroves. Some possible ways in which surface and subsurface processes may interact include:

i. the weight of matter accreted at the surface presses down on subsurface material, resulting in the compression of this material and causing shallow subsidence (i.e. autocompaction within the upper layers);
ii. areas with higher subsurface expansion have a higher surface elevation, and therefore a shorter hydroperiod, so that accretion rates are reduced (and vice versa);
iii. newly sedimented material may bring nutrients allowing subsurface roots to grow more vigorously, enhancing sub-surface expansion (Lovelock *et al.*, 2011a); however, this would result in a positive relationship between accretion and subsurface expansion, which is not seen here.

Numbers i and ii are expected to result in a negative correlation between accretion and shallow subsidence, as seen in Figure 12. Interactions between processes are discussed further in Section 5, in relation to positive and negative feedbacks between sea level change and elevation change.

4.3 Factors affecting surface elevation change rates

In Section 3 we explored the factors affecting the different processes contributing to surface elevation change in mangroves. However, as our understanding of many of these processes and factors affecting them is incomplete, we are not yet able to bring together information on factors and processes to predict elevation change (see also Section 6 for models that attempt to do this). Therefore, it is also useful to explore the relationship between environmental factors and surface elevation change itself, as surface elevation change represents the synthesis of the effect of environmental factors on the many processes involved, and also any interactions between these processes (this is shown schematically in Figure 13). A small number of studies have investigated the relationship between various factors and elevation change. In this section we briefly describe these studies, and we speculate about which of the processes explored in Section 3 may be involved in bringing about the observed changes in elevation.

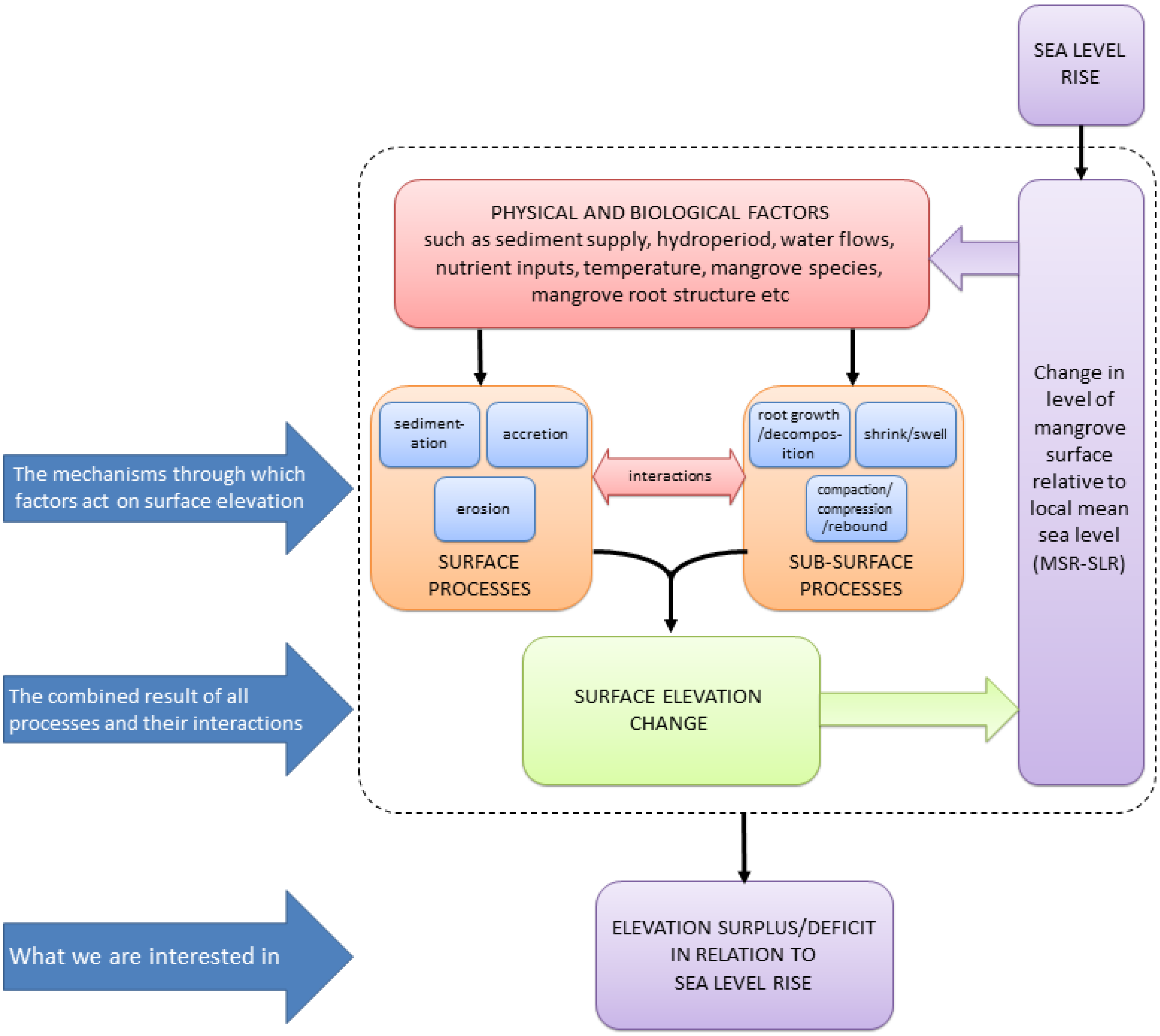


Figure 13. The different levels (blue arrows) at which we can explore the effects of environmental and biological factors (red box) on the response of surface elevation in mangroves to sea level rise.

4.3.1 Forest type

Mangrove forests are highly variable in their physical structure, ranging from tall, closed-canopy forests to open areas with sparsely distributed dwarf trees and shrubs. These different formations are usually related to frequency of tidal flooding and river flooding (Figure 14). The different types of mangrove forest have been associated with different rates of surface elevation change.

Krauss *et al.* (2010) found significant differences in elevation change rates in fringe, riverine and interior mangrove forests in the Pacific High Islands of Micronesia, with the largest increases in elevation being seen in the interior mangroves in three out of four sites (data in Appendix 1).

In a different study of mangroves in carbonate settings in Belize and Florida, McKee *et al.* (2011) observed a lowering of surface elevation in dwarf and scrub forest types, while surface elevation increased in fringe and basin mangroves (data in Appendix 1). They attributed this to high root contributions to sub-surface change and/or rapid growth of living benthic mats which contributed to surface accretion.

No clear pattern has yet emerged linking mangrove forest type to elevation change rates. It is likely that the type of forest combines with other factors (e.g. geomorphic setting or carbonate/minerogenic setting) to influence the rate of surface elevation change. More research is needed to understand how these factors interact.

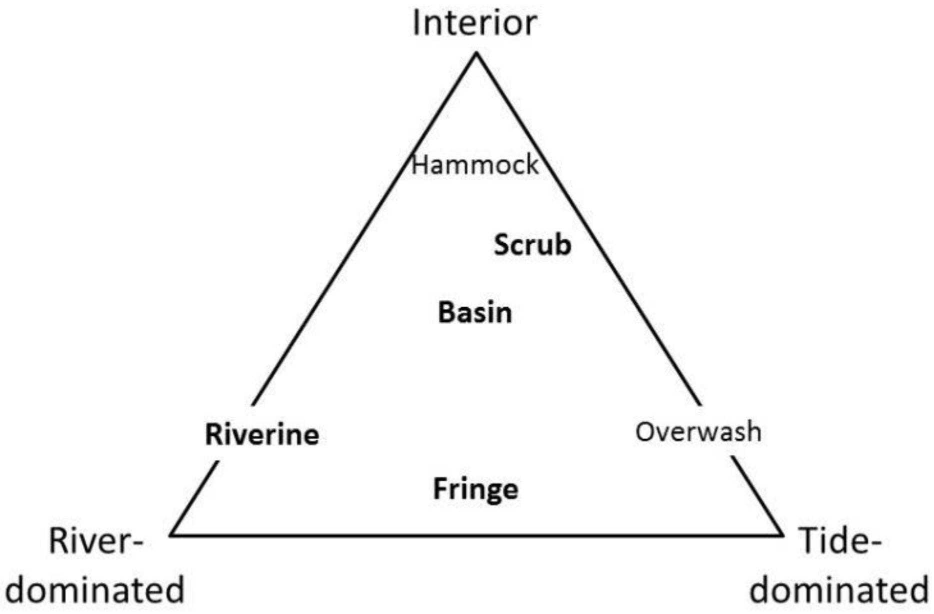


Figure 14. Mangrove settings, showing the types of forest most commonly referred to in studies on elevation change (i.e. fringe, basin, scrub and riverine forests). Adapted from Woodroffe (2002).

4.3.2 Tidal range

Cahoon *et al.* (2006) in their review of SET-MH mangrove datasets found that elevation change in embayments increased with increasing tidal range; however no relationship was found between elevation change and tidal range in other geomorphic settings.

4.3.3 Tree density

The density of mangrove seedlings was found to influence surface elevation change rates and accretion rates in an experiment in Palakuda, Sri Lanka (Table 3 in Section 3.1.2; Huxham *et al.*, 2010; Kumara *et al.*, 2010). *Rhizophora mucronata* seedlings were planted at different densities, and elevation change rates were highest among the highest densities of mangrove seedlings over a period of 3 years. The increase in surface elevation could be related either to an increase in sedimentation and accretion caused by slower flows through the higher density of vegetation, or by increased sub-surface root growth in the higher density areas.

4.3.4 Nutrient availability

McKee *et al.* (2007) showed that addition of nutrients influenced surface elevation change through its effect on sub-surface root growth and decomposition in Twin Cays, Belize (Section 3.2.1). The effect depended on both the type of nutrient (nitrate or phosphate) and the mangrove zone (interior, transition, fringing mangrove), and it was not possible to generalise the effect of nutrient addition on surface elevation change.

4.3.5 Mean sea level and hydrological factors

Lovelock *et al.* (2011a) found a significant relationship between mangrove surface elevation change and mean sea level measured over the same period in the western part of Moreton Bay (but not in the eastern part of the bay). This was based on surface elevation measurements at approximately 6 monthly intervals compared to mean sea level over the same intervals. This implies that mangrove surface elevations may respond rapidly to changes in sea level in some areas.

The effects of various hydrological factors on surface elevation change, acting via subsurface processes, have already been described in Section 3.2 and were summarized in Table 4. These studies showed that tidal levels (over periods of hours), river levels (with a 15 to 30 day time lag), rainfall (with a 3 month time lag), groundwater depth, groundwater pressure and the El Niño Southern Oscillation (measured using the Southern Oscillation Index) strongly influence surface elevation change through their effects on sub-surface processes, primarily the swelling and shrinkage of soils. These factors are expected to change surface elevation over the short term (hours to years).

4.3.6 Storms and hurricanes

The effects of storms and hurricanes on processes contributing to mangrove surface elevation change have been discussed in the sections on sediment deposition (Section 3.1.1), erosion (3.1.3), root decomposition resulting from tree death (Section 3.2.1), and compaction and compression of mangroves soils (Section 3.2.3). Cahoon (2006) reviewed the effects of storms on wetland surface elevations. While large pulses of sediment can result in raised surface elevations (e.g. a 48 mm increase in mangrove surface elevation along Shark River following Hurricane Wilma in 2005), tree death and subsequent decomposition of subsurface roots can result in lowering of surface elevations (e.g. mangroves in southwest Florida and Guanaja, Honduras, experienced a reduction in surface elevation of -20 mm/yr and -9 mm/yr respectively, following Hurricane Andrew (1992) and Hurricane Mitch (1998) (Wanless, unpublished data, in Cahoon, 2006; Cahoon *et al.*, 2003b)).

5. The effect of sea level rise rates on elevation change rates

Section 3 explored the various processes that govern elevation change in mangroves, and the factors which are known to affect those processes. Section 4 then examined the contribution of surface and subsurface processes to surface elevation change, and summarised factors likely to influence elevation change rates. One important factor that was not explored in either Sections 3 or 4 was the rate of sea level rise; we have chosen to explore this factor separately here, because of its central place in understanding mangrove responses to sea level rise.

Sea level rise is expected to affect several of the processes contributing to mangrove surface elevation change:

- a rise in sea level will result in an increased hydroperiod, during which time allochthonous sedimentation can occur, possibly resulting in increased accretion; accreted sediments may bring in nutrients which may affect mangrove sub-surface root growth and decomposition (McKee *et al.*, 2007; Lovelock *et al.*, 2011b)
- a rise in sea level will increase water depth, allowing waves to penetrate further into mangrove areas, and possibly resulting in increased resuspension and erosion of both autochthonous and allochthonous sediments, or alternatively in increased delivery of allochthonous sediment into mangroves;

- a rise in sea level will increase water logging in some mangrove areas, resulting in increased anoxia and possibly affecting root growth of some mangrove species and autochthonous sediment inputs (McKee, 1996); and
- a rise in sea level is expected to result in a rise in groundwater levels, and possibly saline intrusion, affecting plant growth, including sub-surface root growth.

While few studies have investigated these hypothetical interactions between local sea level rise and surface elevation change processes, it is clear that sea level rise could influence surface elevation change rates in multiple ways.

In this section we first explore some of the factors that are likely to influence the response of mangrove surface elevation to sea level rise. We then consider some potential feedbacks between sea level and mangrove surface elevation, which might result in mangrove surface elevation tracking changes in sea level under some circumstances. Finally, we consider possible thresholds affecting these feedbacks, above or below which mangrove surface elevation might no longer be able to track sea level. Due to the paucity of data, much of this section is speculative; where data are available to support possible mechanisms, these are highlighted.

5.1 Factors affecting surface elevation change in the face of SLR

Several factors may affect whether mangrove surface elevation keeps pace with sea level rise, the most important of which are likely to be sediment inputs, tidal range and geomorphological setting (note that these factors are not independent of one another).

5.1.1 Sediment inputs

The delivery of allochthonous sediment is often cited as one of the most important factors contributing to the ability of mangroves to maintain their extent, location and zonal organization during sea level rise (Ellison and Stoddart 1991; Woodroffe 1995; Soares, 2009). Mangroves in large river deltas and other areas with high sediment inputs are expected to increase in elevation in pace with sea level rise, as sufficient sediment is available to fill the increase in accommodation space created by sea level rise.

In support of an increase in sedimentation with sea level rise, Cahoon *et al.* (2006) found that accretion rates increased with sea level rise rates, based on a linear regression using data from 41 sites ($p < 0.0001$). When they separated out the data by geomorphological setting, they found that estuarine settings showed the strongest linear relationship between accretion and relative sea level rise (20 sites, $p < 0.001$); there was a weaker relationship between accretion and relative sea level rise in embayments (8 sites, only significant at $p = 0.08$).

Lovelock *et al.* (2011a) also found a correlation between accretion rates and sea level at two sites in Moreton Bay, Australia, where accretion was measured approximately every 6 months over a 3 year period; accretion rates were then correlated with mean sea level over the same time interval (sea level fluctuated over a 200 mm range during this 3 year period).

However, both Cahoon *et al.* (2006) and Lovelock *et al.* (2011a) found that elevation change rates did not show the same relationship as accretion with sea level rise in some areas. Lovelock *et al.* (2011a) found that elevation change increased with mean sea level on the sandy western side of Morton Bay, but not on the muddy eastern side. Cahoon *et al.* (2006) found some evidence for increasing elevation change rates with rates of sea level rise in embayments but not in other geomorphological settings (data described in Section 2.2). These results suggest that in most sites, shallow subsidence played an important role in determining elevation change, overwhelming the effects of sea level rise on sedimentation and accretion.

Therefore, while it is anticipated that areas with high sediment inputs should be better able to keep pace with sea level rise, high sediment inputs are not sufficient to ensure this, because other processes, such as shallow subsidence, also influence mangrove elevation change. The strength of the relationships between accretion, elevation change and relative sea level rise rate are likely to depend on geomorphological setting (as found by Cahoon and Hensel, 2006) and also on sediment type.

5.1.2 Tidal range

Wetlands along macro-tidal coastlines (with tidal ranges greater than 4 m) have been considered less vulnerable to the impact of sea level rise (Alongi, 2008; Day *et al.*, 2008), following early observations that accretion deficits (defined as sea level rise minus accretion rate) decreased with increasing tidal range (Harrison and Bloom, 1977). However, data are lacking to confirm this relationship, and recent studies have not found any relationship between tidal range and elevation change in mangroves (Rogers *et al.*, 2006), except in embayments (Cahoon *et al.*, 2006).

5.2 Feedbacks

Feller *et al.* (2010) proposes that the persistence of mangroves on Belizean islands (McKee *et al.*, 2007; Toscano and Macintyre, 2003), and the close similarity between current surface elevation change rates and sea level rise rates in some mangrove areas, suggests the existence of a feedback mechanism that allows mangrove surface elevation to adjust to changing sea levels. Gilman *et al.* (2008) also propose the existence of feedback mechanisms “where processes that control the mangrove sediment elevation interact with changes in sea-level” (Gilman *et al.*, 2008, p. 240). The feedback mechanisms put forward by Gilman *et al.* (2008) and Feller *et al.* (2010) are shown in Figure 15; they are based on the processes and factors already described in Sections 3 and 4 of this report.

Gilman *et al.* (2008) focus on feedbacks between accretion, surface elevation and tidal inundation, which they propose may operate as follows: an increased hydroperiod (i.e. increased duration, frequency and depth of inundation, as would occur with a rise in sea level), may result in increased sedimentation and accretion; as sedimentation can stimulate plant growth through increased nutrient inputs (Lovelock *et al.*, 2011b), this could possibly result in more organic debris such as leaves contributing to a further increase in sedimentation (i.e. a positive feedback, where sedimentation may set into a motion a chain of processes that result in more sedimentation). Additionally, Gilman *et al.* (2008) suggest that increased plant growth might result in the growth of more aerial roots, which would further slow the flow of water through the mangroves, and thus further increase sedimentation (a second positive feedback). However, as sedimentation increases (and provided that it results in an increase in surface elevation, i.e. that subsurface processes do not result in an equal or greater loss in elevation), then the hydroperiod will be reduced, resulting in reduced sedimentation, i.e. a negative feedback loop, which could maintain the mangrove surface elevation within a particular part of the tidal range. Feller *et al.* (2010) also note the likely feedback between sedimentation, hydroperiod and position of the mangrove surface relative to sea level.

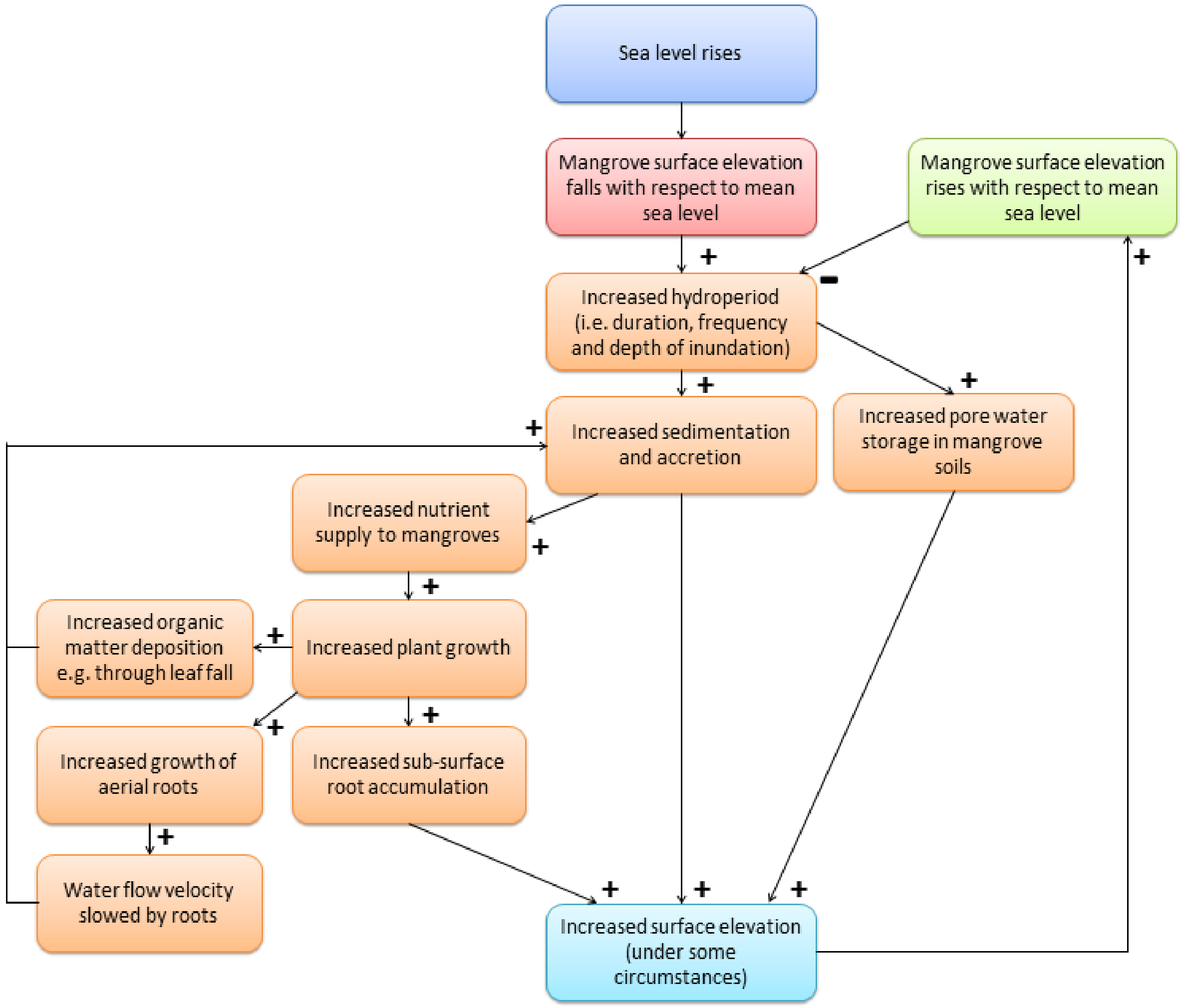


Figure 15 Feedback mechanisms proposed by Gilman *et al.* (2008) and Feller *et al.* (2010) that may govern the response of mangrove surface elevation to changes in sea level.

This feedback mechanism is likely to be most important in areas with high external sediment inputs. In salt marshes, numerical models suggest this feedback operates in areas that are dominated by external inputs of sediments (Allen, 1990; French, 1993).

A further potential negative feedback suggested by Gilman *et al.* (2008) is that the increased hydroperiod could increase the soil pore water storage, potentially resulting in an increase in surface elevation, which would then result in a decreased hydroperiod.

Feller *et al.* (2010) propose another negative feedback mechanism related to subsurface root growth and peat formation, which may be dependent on flooding conditions (i.e. hydroperiod): with moderate flooding, sub-surface root production is high, and root decomposition is slow, resulting in peat formation. This then results in a rise in surface elevation, resulting in reduced flooding and reduced peat formation.

These feedback mechanisms remain putative. They are likely to operate only under some circumstances, such as within certain geomorphological settings (Gilman *et al.*, 2008). Despite uncertainty over when and where they may operate, they are included here because of their potential importance in governing the behaviour of mangrove surfaces in response to sea level rise.

Certainly they do not always operate, as evidenced by mangrove areas that have either been drowned by sea level rise (e.g. fringing mangroves in Bermuda; Ellison, 1993), or that have gained elevation faster than sea level rise and have become new terrestrial environments (e.g. some mangrove areas in the Sundarbans increased in elevation until they were rarely flooded by the tides, and were invaded by non-mangrove tree species; Saenger and Siddiqi, 1993).

To better understand the role played by such feedbacks, observations are needed that span much longer time scales (decades or longer) and that come from numerous sites from a range of settings that experience variations in sea level (rises, falls and periods of stability) (Gilman *et al.*, 2008).

5.3 Thresholds

These negative feedbacks may allow mangrove surface elevations to track changes in sea level under certain conditions. These conditions are likely to be bounded, i.e. to have thresholds, beyond which the feedbacks no longer function. One threshold which has been discussed extensively in the literature is the critical rate of sea level rise that mangrove surfaces can keep up with. While mangrove surfaces may be able to keep up with low rates of sea level rise, beyond a certain critical threshold they may no longer able to keep pace (Ellison and Stoddart, 1991; Ellison 1993; McKee *et al.*, 2007).

Some attempts have been made to estimate critical rates of sea level rise and to understand what factors affect these critical thresholds. Ellison and Stoddart (1991) suggested that rates of sea level rise above 12 cm/100 years (1.2 mm/year) would cause the collapse of mangrove ecosystems in locations that did not receive significant allochthonous sediment input. However the mangroves at Key West in Florida have experienced relative sea level rise rates of 19 cm/100 years (based on data showing a mean sea level rise rate of 1.94 mm/yr between 1846 and 1992; Maul and Martin, 1993; some mangrove areas may have been lost, but mangroves are still present here). Rise rates of 26cm/100 years have also been calculated for this area in the early Holocene (Parkinson, 1989). McKee *et al.* (2011) have also recorded surface elevation rise rates of greater than 3 mm/year in carbonate settings in Florida and Belize, suggesting that the critical sea level rise threshold is likely to be greater than this rate.

Where there is a large supply of externally derived sediment, mangroves may be able to keep pace with higher rates of sea level rise: mangroves in the South Alligator tidal river in Australia have kept pace with sea level rise rates between 0.2 and 6 mm/year (Woodroffe 1990) and mangroves in northern Australian estuaries tolerated rise rates of 8-10 mm/year in the early Holocene (Woodroffe 1995).

It is likely that the combination of sediment input and sea level rise rates, as well as location-specific above and below-ground productivity and the frequency of events (e.g. storms) that remove or resuspend deposited materials, ultimately determine the ability of mangroves to keep pace with sea level rise in different locations.

6. Predicting surface elevation change with future sea level rise

As our understanding of the different processes and feedbacks increases, so the ability to predict how mangroves respond will improve; this may also increase our ability to manage mangrove areas in ways that will enhance their ability to keep pace with sea level rise.

Numerical models can be used to help us understand how the processes work together to bring about elevation change, and to predict likely changes in the future with different rates of sea level rise. A number of such models have been developed for coastal wetlands (reviewed in Rybzyk and Callaway, 2009). However the majority of these models deal with salt marshes (e.g. Allen, 1990; French, 1993, 2006; Temmerman *et al.*, 2004; Kirwan and Temmerman, 2009). Only one model has been found that attempts to model surface elevation change in mangroves. This model is described below.

6.1 A mangrove sediment development model for mangroves in Honduras

Cahoon *et al.* (2003a&b) developed a sediment development model to predict surface elevation change in mangroves in Honduras following the passage of Hurricane Mitch. Their model was based on a similar model developed by Rybczyk *et al.* (1998) to predict surface elevation change in a subsiding coastal forested wetland in Louisiana, USA, and used a similar basis to other sediment development models used in marshes (Morris and Bowden, 1986; Callaway *et al.*, 1996; Day *et al.*, 1999; Rybczyk and Cahoon, 2002).

Cahoon *et al.* (2003a&b) used the wetland sediment development model to predict the long-term effects of tree death on surface elevation in a basin mangrove forest on Guanaja, Bay Islands, Honduras, following the passage of Hurricane Mitch. The model used a cohort approach, tracking discrete packages of sediment through depth and time to simulate organic and mineral matter accretion, decomposition, compaction and below-ground productivity (Cahoon *et al.*, 2003a). It used the following initialization parameters: sea-level rise, deep subsidence rate, initial wetland elevation, mineral input, root standing crop, above ground standing crop, sediment bulk density at surface, per cent organic matter at surface, labile fraction of above-ground biomass and the decomposition rates of: deep refractory organic matter, labile organic matter, surface labile organic matter and refractory organic matter.

Cahoon *et al.* (2003a) found that the simulated sediment columns from the model were in general agreement with observed soil characteristics; Figure 16 shows simulated and observed soil organic matter with depth. In this case, the model predicts the decrease in per cent organic matter with depth, but does not predict the sudden drop in organic matter content at 40cm depth seen in soil samples.

The model predicted a rapid sediment collapse of 37 mm/yr in the first 2 years after the hurricane, followed by a decrease of 7.4 mm/yr over the next 8 years. Cahoon *et al.* (2003a) recorded a loss in elevation of 11 mm/yr between 18 months and 33 months after the storm. This is not directly comparable to the outputs from the model because of the different time frames, but it is similar in value to the 7.4 mm/yr loss in elevation predicted by the model between 2 and 10 years after the passage of the hurricane.

Therefore Cahoon *et al.* (2003a) conclude that the model is able to make general predictions about the evolution of soil characteristics and surface elevation in mangroves soils after the passage of the hurricane. However detailed local measurements are required to calibrate the model, and the model needs to be tested at other sites. The model was not used to predict the response of mangrove surface elevation to the effects of sea level rise.

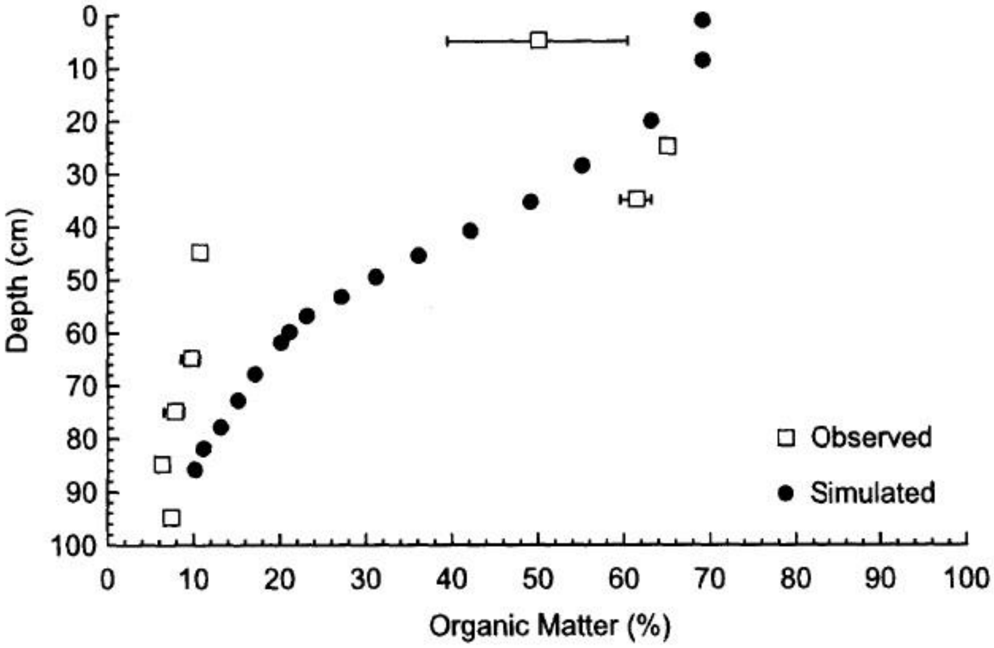


Figure 16. The results of the model used by Cahoon *et al.* (2003a) compared with observed changes in soil organic matter with soil depth (from Cahoon *et al.*, 2003a).

7. Conclusions

Historical evidence based on the dating of mangrove peats demonstrates that mangrove surface elevations have kept pace with sea level rise over thousands of years in some locations. Rates of rise that mangroves kept pace with ranged between 1 mm/yr and 10 mm/yr in different locations and settings (Table 1). While the reasons for this variation are poorly understood, it is likely that rates of delivery of allochthonous sediments and rates of sub-surface root growth are the major controlling factors in minerogenic and carbonate settings respectively.

Recent evidence using the Surface Elevation Table – Marker Horizon methodology (from studies published between 2006 and 2011) suggests that mangrove surfaces are rising at similar rates to local sea level rise in a number of locations; however this is in contrast to the conclusions of Cahoon *et al.* (2006) based on studies before 2006, where surface elevations were lagging behind sea level rise rates. However, surface elevation change measurements are available for a relatively small number of sites, and most records span short time periods (Table 2) relative to the longer time scales over which sea level rise has generally been measured. Therefore, currently available surface elevation data are insufficient to draw conclusions about the long term capacity of mangrove soil surfaces to keep pace with sea level rise. Longer term mangrove surface elevation datasets are needed, and these need to be analysed relative to sea level changes over the same periods of measurement. Additionally these need to cover a greater variety of locations, including different geomorphological settings.

Understanding the processes that govern mangrove surface elevation change can help us understand how mangrove soils respond to sea level rise. A multitude of processes contribute to surface elevation change in mangroves. While understanding of these processes and the factors affecting them is increasing, many of these processes are currently poorly understood. Whereas surface processes have been studied for many decades, the importance of subsurface processes has only been recognized in the last two decades, after the Surface Elevation Table – Marker Horizon made it possible to measure the relative contributions of accretion and sub-surface change to surface elevation change. Consequently, relatively few studies have explored the role of subsurface processes in mangrove surface elevation change. Nevertheless, it is now clear that at least six sets of processes influence surface elevation change in mangroves: sedimentation/resuspension; accretion/erosion; faunal processes; growth/decomposition of roots; shrinkage/swelling of soils in the presence/absence of water; and compaction/compression/rebound of soils over time and under the weight of soil/water above. These processes act at the local scale, and some of them vary even over a few centimetres of substrate; however, they are driven by larger scale processes such as wave climate and sediment supply, which vary along much longer stretches of coast (100s of metres to 100s of kilometres).

Recent measurements using the SET-MH methodology have demonstrated that sub-surface change is often similar but opposite in magnitude to surface change: measurements of surface change and sub-surface change show a strong negative correlation. Clearly sub-surface processes are as important as surface processes in determining elevation change in mangroves. In this respect, mangroves may differ from salt marshes, where accretion rates and elevation change rates are often more similar, particularly in minerogenic settings. The close correlation between accretion and sub-surface change suggests that surface and sub-surface processes interact with each other, although the nature of these interactions is currently unknown.

The deep layers of peat lying beneath some mangroves in the Caribbean suggest that under some circumstances, mangrove soil surfaces are able to track sea level rise over extended periods and variable rates of sea level rise. This points to the possible existence of negative feedbacks between sea level change and surface elevation change. The most likely feedback relates to the change in hydroperiod and sedimentation that is expected to occur as local sea level rises: rising sea levels result in mangrove surfaces being under water for longer, allowing increased allochthonous sedimentation, which may then result in an increase in surface elevation (depending on subsurface change). It is also possible that there may be time lags in the operation of these feedbacks; however these are likely to be relatively short (days or months) based on Lovelock *et al.*'s (2011a) observation that surface elevation change measured over 3 to 6 month periods was correlated with the mean sea level over the same period.

Such feedbacks are routinely included in numerical models of wetland soil development. While several such models have been developed for salt marshes, only one model has been found that aims to predict surface elevation change in mangroves, and this model was used to understand surface elevation change after a hurricane, rather than as a result of sea level rise. There remains a major gap in our ability to predict surface elevation change rates in mangroves in response to sea level rise. However, the lack of understanding of several of the processes affecting surface elevation in mangroves, and how these processes are affected by local environmental factors, remains an obstacle to developing such models. Such models also need validating with long term datasets, and few such datasets are available for mangrove surface elevation.

Monitoring of mangrove surface elevations and relative sea level change near mangrove areas needs to be extended into areas where such data are currently lacking and into the future, so that, in time, much needed longer term records become available, allowing a clearer understanding of the processes influencing mangrove surface elevation change, and the responses of mangrove surface elevation to local sea level rise.

Despite evidence suggesting that some sites are experiencing an elevation deficit with respect to sea level rise, there are few published records of mangroves being drowned by sea level rise (e.g. Ellison, 1993). This may be because there will be a time lag between the recent increases in sea level rise rates and their effects on mangroves, or because such observations have not been made or published, or because the discrepancy in the time scales of measurement of surface elevation change and sea level rise do not allow for accurate calculation of elevation deficits. While some loss of mangrove areas may be expected as sea levels rise, current rates of loss due to anthropogenic habitat conversion and other threats are very high, and these losses probably represent a greater threat to mangroves and to the continued provision of coastal defence services than sea level rise.

To support mangrove soils in maintaining their surface elevation in the face of sea level rise, sediment inputs need to be maintained, e.g. by ensuring that local rivers continue to bring down sediments or that long-shore transport of sediments remains possible. River flows and groundwater levels also need to be protected, as reduced flows and lowering of groundwater levels has been shown to result in lowered mangrove surface elevations; if these combine with rises in sea level, loss of mangroves in lower areas becomes more likely. Related to this, mangroves in areas that are predicted to suffer droughts under climate change scenarios are likely to be at greater risk from sea level rise because of the effect of reduced rainfall and groundwater levels on surface elevations. Efforts should also be made to ensure that mangrove trees remain healthy by protecting freshwater inputs and reducing eutrophication or other forms of pollution; healthy trees are expected to be better able to generate sub-surface roots that can also contribute to increasing surface elevation.

Where possible, space should be allowed behind mangroves for their landward migration in the face of sea level rise. This will hopefully ensure that mangroves can continue to exist along a stretch of coast, even if they are not able to remain in their current location. For as long as some mangrove areas remain intact, they can be expected to continue to provide coastal defence services, such as wave reduction, and other ecosystem services, such as supporting fisheries.

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Appendix A: Data used to create figures of surface elevation change throughout this report, with sources of information.

			Rate of change (mm/yr)								
Location	Site/area	Measurement length (years)	Surface elevation change	Standard error of SEC	Accretion	Standard error of Accretion	Sub-surface change	Standard error of SSC	Relative sea level rise	Elevation surplus / deficit	Source
Rookery Bay and Naples Bay, Florida, US	Basin 1	>3	3.85	0.9	2	0.35	1.85	0.58	2.08	1.77	McKee, 2011
Rookery Bay and Naples Bay, Florida, US	Basin 3	>3	1.06	0.88	7.55	0.94	-6.48	-6.48	2.08	-1.02	McKee, 2011
Rookery Bay and Naples Bay, Florida, US	Fringe 3	>3	0.61	1.84	5.74	0.78	-5.13	-5.13	2.08	-1.47	McKee, 2011
Twin Cays, Belize	Fringe	3.5	4.1	2.2	1.6	0.7	2.4	2.9	2	2.1	McKee *et al*., 2007; McKee, 2011
Twin Cays, Belize	Transition	3.5	-1.1	1.5	2	1.3	-3.1	2.6	2	-3.1	McKee *et al*., 2007; McKee, 2011
Twin Cays, Belize	Interior	3.5	-3.7	1	0.7	0.3	-4.4	1.1	2	-5.7	McKee *et al*., 2007; McKee, 2011
Yela River, Kosrae, Micronesia	Fringe	3	-3	0.8	11.6	1.3	-14.6	1.5	1.8	-4.8	Krauss *et al.,* 2010
Yela River, Kosrae, Micronesia	Riverine	3	-2.7	0.6	12.9	2.1	-15.6	1.1	1.8	-4.5	Krauss *et al.,* 2010
Yela River, Kosrae, Micronesia	Interior	3	1.3	0.7	12	1.2	-10.7	1	1.8	-0.5	Krauss *et al.,* 2010
Utwe River, Kosrae, Micronesia	Fringe	3	1.2	0.3	11.9	1.7	-10.7	0.7	1.8	-0.6	Krauss *et al.,* 2010
Utwe River, Kosrae, Micronesia	Riverine	3	6.3	0.5	18.7	2.2	-12.4	0.7	1.8	4.5	Krauss *et al.,* 2010
Utwe River, Kosrae, Micronesia	Interior	3	1.3	0.2	12.9	4.3	-11.6	1.9	1.8	-0.5	Krauss *et al.,* 2010
Enipoas River, Pohnpei, Micronesia	Fringe	1.4	-5.8	0.9	6.6	3.1	-12.4	2.3	1.8	-7.6	Krauss *et al.,* 2010
Enipoas River, Pohnpei, Micronesia	Riverine	1.4	-1.4	2.2	6.3	0.9	-7.7	1.2	1.8	-3.2	Krauss *et al.,* 2010
Enipoas River, Pohnpei, Micronesia	Interior	1.4	-2.8	0.4	2.9	1.4	-5.7	0.1	1.8	-4.6	Krauss *et al.,* 2010
Sapwalap River, Pohnpei, Micronesia	Fringe	1.4	-2.3	0.6	4.1	1.5	-6.4	1.3	1.8	-4.1	Krauss *et al.,* 2010
Sapwalap River, Pohnpei, Micronesia	Riverine	1.4	-0.6	0.8	14.1	1.7	-14.7	0.9	1.8	-2.4	Krauss *et al.,* 2010
Sapwalap River, Pohnpei, Micronesia	Interior	1.4	0.9	0.5	8.2	1.2	-7.3	0.7	1.8	-0.9	Krauss *et al.,* 2010
Pukusruk, Kosrae, Micronesia	Backswamp	1.4	0.9	0.4	20.8	2.4	-19.9	1.8	1.8	-0.9	Krauss *et al.,* 2010
Moreton Bay, Australia	West, muddy	3	1.4		9.6		-8.2		2.358	-0.958	Lovelock *et al*., 2011
Moreton Bay, Australia	East, sandy	3	5.9		8.5		-2.6		2.358	3.542	Lovelock *et al*., 2011
Ukerebagh Island, Australia		3	2.4	1.39	2.21	0.3	0.19		-0.4	2.8	Rogers *et al*., 2006
Kooragang Island, Australia		3	1.98	0.54	4.72	0.05	-2.74		0.33	1.65	Rogers *et al*., 2006
Homebush Bay, Australia		3	5.64	2.15	4.58	0.28	1.06		0.91	4.73	Rogers *et al*., 2006
Minnamurra River, Australia		3	0.61	0.44	6.64	0.52	-6.03		-0.47	1.08	Rogers *et al*., 2006
Cararma Inlet, Australia		3	-0.81	1	3.03	0.41	-3.84		4.12	-4.93	Rogers *et al*., 2006
Currambene Creek, Australia		3	0.29	2.02	0.65	0.34	-0.36		4.12	-3.83	Rogers *et al*., 2006
French Island, Australia		3	-2.13	1.66	9.49	2.69	-11.62		2.66	-4.79	Rogers *et al*., 2006
Kooweerup, Australia		3	-0.03	2.23	7.2	0.85	-7.23		2.66	-2.69	Rogers *et al*., 2006
Quail Island, Australia		3	-2.6	2.07	6.77	0.79	-9.37		2.66	-5.26	Rogers *et al*., 2006
Rhyll, Australia		3	0.92	1.87	5.1	0.72	-4.18		2.66	-1.74	Rogers *et al*., 2006

Appendix B. Location of tide gauges, approximate distances between SET-MH measurement station and tide gauges, tide gauge measurement period and relative sea level rise measured there.

Surface elevation measurement location	Tide gauge location	Linear distance to tide gauge (km)	Measurement period length (years)	RSLR (mm/yr)	Source
Rookery Bay, Florida	Naples, Florida (NOAA, guage #8725110)	13	35	2.08	McKee, 2011
Naples Bay, Florida	Naples, Florida (NOAA, guage #8725110)	2	35	2.08	McKee, 2011
Twin Cays, Belize	Key West, Florida (NOAA, gauge #8724580)	1075	87	2	McKee *et al*., 2007; McKee, 2011 (RSLR from 2011)
Homebush Bay, Australia	Fort Denison tide gauge, Sidney (60370, GLOSS no. 57)	14	90	0.91	Rogers *et al*., 2006
Ukerebagh Island, Australia	Tweed River at Letitia Spit (ARWC 201429)	1	16	-0.4	Rogers *et al*., 2006
Kooragang Island, Australia	Hunter River at Hexham Bridge (ARWC 210448)	16	19	0.33	Rogers *et al*., 2006
Minnamurra River, Australia	Macquarie Rivulet at Princes Highway (ARWC 214402)	14	19	-0.47	Rogers *et al*., 2006
Cararma Inlet, Australia	Jervis Bay at HMAS Cresswell (ARWC 216470)	15	10	4.12	Rogers *et al*., 2006
Currambene Creek, Australia	Jervis Bay at HMAS Cresswell (ARWC 216470)	8	10	4.12	Rogers *et al*., 2006
French Island, Australia	Stony Point (Westernport) (BoM 586268)	16	10	2.66	Rogers *et al*., 2006
Kooweerup, Australia	Stony Point (Westernport) (BoM 586268)	22	10	2.66	Rogers *et al*., 2006
Quail Island, Australia	Stony Point (Westernport) (BoM 586268)	17	10	2.66	Rogers *et al*., 2006
Rhyll, Australia	Stony Point (Westernport) (BoM 586268)	12	10	2.66	Rogers *et al*., 2006
Moreton Bay, Australia	Bishop Island (PSM 21764)	5 to 30 (6 sites)	10	2.36	Lovelock *et al.,* 2011a
Kosrae, Micronesia	a combination of satellite altimetry and tide gauge measurements	549 to 556 (3 sites)	26	1.8	Krauss *et al*., 2010; Church *et al*., 2006
Pohnpei, Micronesia	a combination of satellite altimetry and tide gauge measurements	18 to 20 (2 sites)	26	1.8	Krauss *et al*., 2010; Church *et al*., 2006