Mangrove Sedimentation and Response to Relative Sea-Level Rise

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*A visual abstract of this article is also available online at **http://prezi.com/dtfasu6khdti** and as **Supplemental Material.**

Abstract

Mangroves occur on upper intertidal shorelines in the tropics and subtropics. Complex hydrodynamic and salinity conditions, related primarily to elevation and hydroperiod, influence mangrove distributions; this review considers how these distributions change over time. Accumulation rates of allochthonous and autochthonous sediment, both inorganic and organic, vary between and within different settings. Abundant terrigenous sediment can form dynamic mudbanks, and tides redistribute sediment, contrasting with mangrove peat in sediment-starved carbonate settings. Sediments underlying mangroves sequester carbon but also contain paleoenvironmental records of adjustments to past sea-level changes. Radiometric dating indicates long-term sedimentation, whereas measurements made using surface elevation tables and marker horizons provide shorter perspectives, indicating shallow subsurface processes of root growth and substrate autocompaction. Many tropical deltas also experience deep subsidence, which augments relative sea-level rise. The persistence of mangroves implies an ability to cope with moderately high rates of relative sea-level rise. However, many human pressures threaten mangroves, resulting in a continuing decline in their extent throughout the tropics.*

▶ Supplemental Material

INTRODUCTION

Halophyte: a plant that is able to tolerate salinity; all mangrove species are halophytes

Tidal frame: the vertical range over which the tide varies at a site, generally between the lowest and highest astronomical tide

Accommodation space: the space within which mangrove sediments may accumulate (see **Figure 2**, below)

Accretion: short-term vertical aggradation of sediment; where surface elevation table–marker horizon instruments are deployed, accretion is measured relative to the marker horizon

Subsidence: the net movement of a land surface; deep subsidence includes tectonic, hydro-isostatic, and flexural geological processes, often exacerbated by groundwater extraction, and shallow subsidence includes subsurface autocompaction (see also Subsidence and Relative Sea-Level Rise sidebar, below)

Coastal squeeze: a loss of intertidal habitat arising when biota encounter solid structures as they attempt to extend landward following an increase in sea level

Mangroves comprise trees and shrubs that colonize upper intertidal shorelines along tropical and subtropical coasts. These halophytes have morphological, physiological, and reproductive adaptations in common that enable growth in saline and anoxic conditions. Worldwide, mangroves occupy $\sim 1.5 \times 10^5$ km^2, with several species extending into temperate latitudes (Spalding et al. 2010, Giri et al. 2011). Some mangroves grow along open coasts subject to moderate wave processes; however, most occur in more sheltered, muddy locations that are either frequently or occasionally inundated by tides.

Many mangrove forests fringe coastal plains, comprising estuarine, deltaic, and other depositional landforms. Mangroves are generally limited to a narrow elevation range within the tidal frame (McKee et al. 2012). The extent of such suitable intertidal habitats, referred to as accommodation space, is a function of the stage, or maturity and geomorphological complexity, of these larger depositional systems. The distribution of mangroves on a shoreline changes with time, involving subtle balances between accretion and subsidence, erosion and vegetative stabilization, productivity and decomposition, and tidal flushing and drainage efficiency (FitzGerald et al. 2008).

Dense mangrove forests contain substantial aboveground biomass, and belowground stores of organic matter are often even more substantial (Twilley et al. 1992, Donato et al. 2011, McLeod et al. 2011, Lovelock et al. 2014). Carbon that is sequestered by mangroves, known as blue carbon, has become a focus of attention because of its potential for climate-change mitigation (Breithaupt et al. 2012, Pendleton et al. 2012, Siikamaki et al. 2012, Duarte et al. 2013, Alongi 2014). Donato et al. (2011) measured above- and belowground carbon stores in tropical mangroves across the Indo-Pacific region and found that belowground carbon accounted on average for 1,074 ($\pm$171) Mg C ha^{-1} of carbon storage in estuarine settings and 990 ($\pm$96) Mg C ha^{-1} in oceanic-island settings.

Observed and anticipated future rates of sea-level rise (SLR) are likely to have far-reaching impacts on mangrove forests, raising concerns that such wetlands are vulnerable to drowning and coastal squeeze (Phan et al. 2015). However, measured sediment accumulation rates beneath subtropical mangrove forests have shown rapid accretion, in many cases more rapid than the rate of SLR (Krauss et al. 2014). It has become apparent, particularly through use of surface elevation-change methodologies developed in herbaceous wetlands, that subsurface processes play a much more important role than was hitherto realized. This role includes subsurface movements (e.g., subsidence caused by autocompaction, or expansion caused by root growth) that combine with sediment accretion on the surface to drive elevation change. At broader regional scales, many low-lying delta environments are subsiding through geological processes, exacerbated by anthropogenic activities such as groundwater extraction (Syvitski et al. 2009, Erban et al. 2014), which augment the relative rate of SLR. Land movement in combination with the increase in ocean height, termed relative SLR (Cahoon 2014), creates accommodation space for future deposition of sediment and organic matter beneath mangroves.

This review focuses on sediment accumulation rates beneath mangrove forests and the hydrodynamic conditions that affect them. It concludes that there is insufficient understanding of nonlinear feedbacks to realistically forecast or model the future behavior of most mangrove shorelines.

ENVIRONMENTAL SETTINGS

Investigations of mangrove habitat and ecosystem functioning need to discriminate among the different environmental settings in which mangrove stands can occur. For instance, on relatively sheltered open coasts, some locations may have a narrow mangrove fringe, often comprising several species of mangroves growing in shore-parallel zones. This pattern contrasts with locations

where mangrove forests form complex mosaics, such as sediment-rich deltas, along the flanks of estuarine channels within embayments, or behind spits and other sandy barriers (Thom 1982, Woodroffe 1992). A particular geomorphological setting may contain a range of hydrodynamic conditions, sediment fluxes, and organic and geochemical characteristics of the substrate, all of which influence the growth of mangroves. Sediments that have accumulated also record aspects of geomorphological history and longer-term dynamics.

An early attempt at ecological classification of mangroves, developed in the Caribbean, differentiated fringe, basin, overwash, scrub, and riverine mangroves (Lugo & Snedaker 1974). This hydrogeomorphic scheme, also called ecomorphodynamics, combines aspects of mangrove growth forms and hydrodynamics (Twilley & Rivera-Monroy 2005, 2009). It was developed to address functional differences between stands of *Rhizophora mangle* that are regularly and effectively flushed by tides and basin mangroves that are flooded seasonally or by only the highest tides, favoring accumulation of mangrove-derived organic carbon (Twilley 1985).

Figure 1 illustrates several geomorphological settings in which mangrove forests occur and summarizes schematically some gross stratigraphic relationships from which long-term sedimentation patterns can be reconstructed. The four examples—delta, estuary, lagoon, and carbonate reef environments—do not represent all settings within which mangroves are found, but serve to focus on several contrasting aspects.

Autocompaction: shallow subsidence of sediments under their own weight; this process includes consolidation, compression, and loss of organic matter

Progradation: lateral extension of the shoreline, characterized by mangrove establishment as a consequence of sediment accretion in the lower intertidal zone
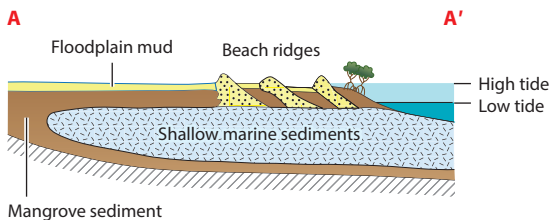
Deltas

Figure 1a shows a schematic representation of the Mekong River Delta, one of several Asian megadeltas fed by large rivers draining from the monsoonal Himalayan massif. The Mekong River, which has peak flows of ~50,000 m³ s⁻¹ and an estimated annual sediment load of 160 million tonnes, discharges sediment via many distributaries into the South China Sea. During periods of particularly rapid postglacial SLR, mangrove forests were drowned or displaced landward, as shown by peats recovered from cores on the Sunda Shelf (Hanebuth et al. 2011). The final stages are recorded in the Mekong River Delta by basal transgressive sediments overlying Pleistocene basement, culminating in a period of abrupt SLR approximately 8,200 years ago. At the apex of the modern delta, a vertical sequence of mangrove sediments in southern Cambodia indicates the persistence of mangrove forests during this period (Tamura et al. 2009, Li et al. 2012). Since then, the delta has gradually built more than 200 km southward to form the modern coast. Mangrove organic matter in cores extracted from across the deltaic plain indicates the persistence of mangrove ecosystems as the shoreline prograded (Ta et al. 2002, Proske et al. 2010).

The interaction of tidal, wave, and riverine hydrodynamic processes is apparent in the Mekong River Delta and is also typical of other large deltas. The effects on sedimentation and on the distribution of mangroves around the delta are also clear, although there has been severe degradation associated with human impacts such as reclamation and defoliation (Phan & Hoang 1993). Tides are semidiurnal along the southeastern margin of the delta, with a range of >3 m, reaching a maximum of 4 m near Ho Chi Minh City, where there are extensive tide-dominated mangrove forests. Mangroves on the adjacent open coast are exposed to wave energy (Bao 2011), which has periodically built sandy beach ridges. A sequence of stranded ridges across the southern delta indicates that this section of the delta has been wave dominated for at least the past 3,000 years (Tamura et al. 2012). Sediment from the river mouth is carried southwestward along the coast, with rapid progradation of the Ca Mau Peninsula and establishment of mangrove forests over the accreting mudbanks. Tides are diurnal in the Gulf of Thailand, with a range of 1–1.5 m, and this coast receives much less sediment.
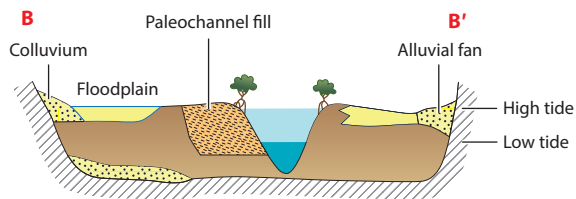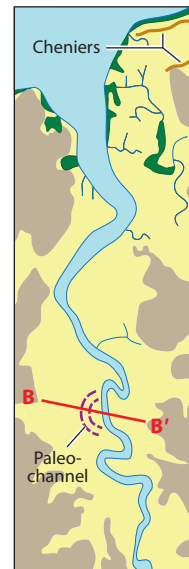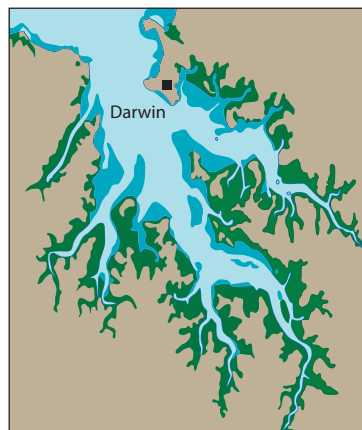
a River delta

A — Floodplain mud — Beach ridges — High tide / Low tide
Shallow marine sediments
Mangrove sediment — A′

b Tidal estuary

Cheniers

Paleo-channel

B — Colluvium — Paleochannel fill — Alluvial fan — B′
Floodplain — High tide / Low tide

c Lagoon

Abandoned distributaries
Mangroves
Lagoon
Tidal inlet
Beach ridge coastal sand

C — Levee — Floodplain mud — Lagoon — C′
High tide / Low tide
Mangrove mud

d Carbonate reef

Sand cay
Reef crest

D — Sand cay — Calcareous sediments — D′
High tide / Low tide
Mangrove peat — Pleistocene limestone
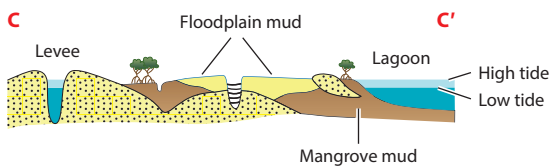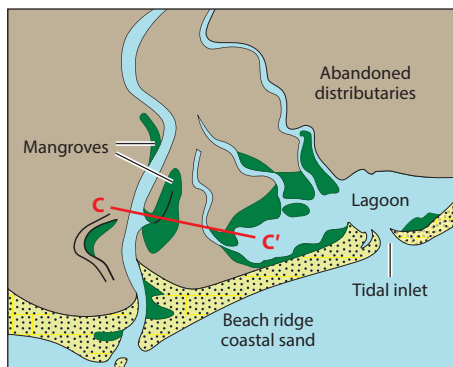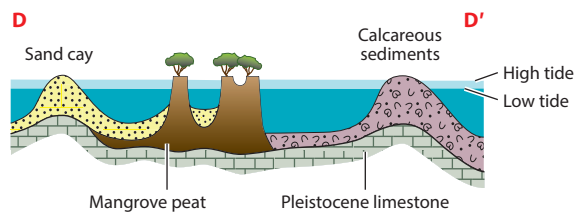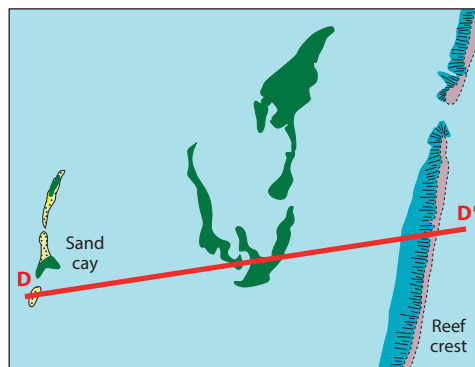
Estuaries

Northern Australia has a series of macrotidal estuaries along its northern and northwestern coasts (**Figure 1b**). The stratigraphy of the underlying sediments is broadly similar to that beneath southeast Asian deltas, comprising transgressive, basal, organic-rich mangrove muds overlain by more marine muddy sands, which record the landward retreat of mangroves during the final stages of postglacial SLR. Extensive mangrove forest development took place after the sea level stabilized at its modern level approximately 7,000 years ago, a period described as the "big swamp" phase (Woodroffe et al. 1993). Sediment accretion led to the demise and gradual replacement of these mangrove forests by alluvial floodplains. Pollen analysis during this regressive phase indicates that *Sonneratia* was replaced by *Rhizophora* and then by *Avicennia*, culminating in grass and sedgeland, which characterizes modern plains flanking these estuaries. This vertical core sequence mirrors the horizontal plant zonation from midtide to the highest tidal level on the modern shore and in larger embayments such as Darwin Harbor.

Whereas this sequence is typical of the open coast, the largely infilled estuaries have a series of mangrove environments upstream, several of which are illustrated schematically in **Figure 2**. Backwater swamps lie below the elevation reached by high tides at the coast (Wolanski & Chappell 1996), and saline intrusion and tidal creek extension have been observed on many estuarine plains with landward extension of mangroves (Mulrennan & Woodroffe 1998, Winn et al. 2006, Cobb et al. 2007, Eliot & Eliot 2012).

Lagoonal Environments

Figure 1c represents a sandy barrier on a wave-exposed coast with mangroves established in a sheltered back-barrier lagoon. This example is based on the Grijalva River Delta in Tabasco, Mexico, where delta distributary channels have undergone periodic switching and have built levees. Sedimentation and subsidence determine suitable environments for mangrove growth. Mangrove forests flourish in several geomorphological environments; there are tidally flushed mangroves on accreting mudflats, which contrast with interdistributary basins that receive little inorganic sediment and have accumulated thicknesses of mangrove peat (Thom 1967). Mangroves occur in back-barrier settings like this on many other sandy, wave-dominated coasts (López-Medellin et al. 2011).

Sediment-Starved Reef Environments

In carbonate settings, mangroves have accumulated peat in the absence of a supply of terrestrial sediment. The example in **Figure 1d** schematically represents overwash mangrove islands, locally termed mangrove ranges, on the Belize Barrier Reef. Peat thicknesses of 10 m or more indicate that mangroves have persisted on these islands as sea level rose at a decelerating rate over the past 8,000 years (Toscano & Macintyre 2003, Macintyre et al. 2004, McKee et al. 2007). Mangrove peats are buried beneath calcareous sands in the lagoons on the Belize Barrier Reef, indicating that not all mangroves kept pace with the rising sea (Macintyre et al. 2004) and that the present

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Figure 1

Examples of mangrove settings, showing the distribution of modern mangroves and schematic stratigraphy indicating past changes in mangrove distribution. (*a*) A river delta, based on the Mekong River Delta. (*b*) Two types of tidal estuary, based on Darwin Harbor and the Alligator Rivers region in northern Australia. (*c*) A lagoon, based on Grijalva River Delta in Tabasco, Mexico. (*d*) A carbonate reef, based on the Belize Barrier Reef.

Upstream riverbank **Paleochannel** **Back basin** **Downstream riverbank** **Open coast**

Mudflat

Highest astronomical tide

Mean sea level

Accommodation space

Potential accommodation space
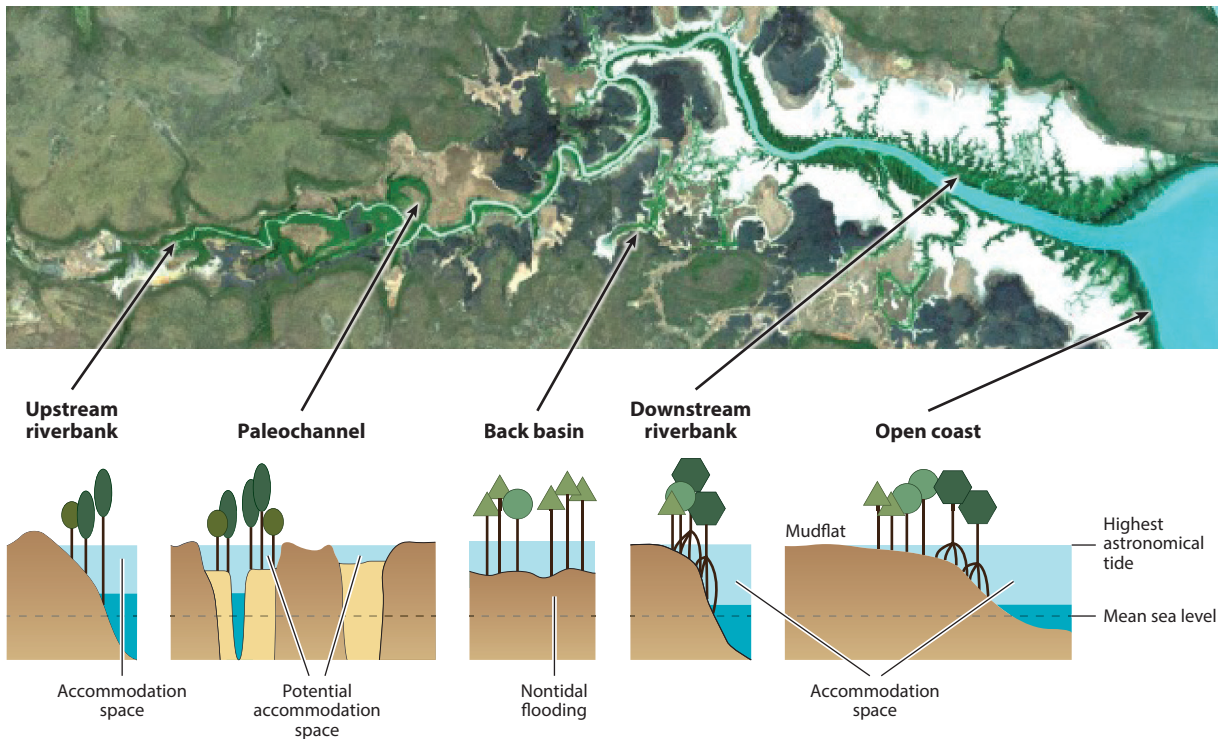
Nontidal flooding

Accommodation space

Figure 2

Hydrodynamics and accommodation space. On the open coast, mangrove forests often show a zonation of species, with a few pioneer species able to establish on sediments that have accreted to an elevation close to mean sea level, and species less tolerant of inundation occurring landward and higher in the tidal frame. More complex hydrodynamic settings occur farther upstream in deltaic-estuarine systems, illustrated schematically in this example from the Alligator Rivers in northern Australia. *Rhizophora* species (appearing as *dark green*) are flooded by most tides but are replaced by other species up to the highest astronomical tide level, beyond which are saline mudflats. Tidal flows become increasingly distorted upstream along the estuarine funnel, and other mangroves occupy a contracted accommodation space on the riverbanks near the tidal limit. Mangroves also occur away from the tidal river estuary itself within seasonally flooded basins. Low-lying areas within the extensive adjacent floodplains, particularly incompletely infilled paleochannels, lie below the highest elevation at which mangroves can grow and represent potential accommodation space. This area can be colonized by mangroves if a tidal connection is reestablished, as in the case of the abandoned paleochannel meander in this example. Landsat image © 2009 Commonwealth of Australia (Geoscience Australia).

islands are erosional remnants. Even within these relatively simple mangrove environments, there are geographical variations in mangrove composition and structure in island interiors. Variations also occur in rates of elevation change and surface accretion observed in different habitats (McKee 2011). Similar peats underlie wetlands in other microtidal reef settings and in southwestern Florida, where mangroves have gradually extended landward into the freshwater Everglades as the sea level has risen (Woodroffe et al. 2014).

MORPHODYNAMICS AND SCALE

Figure 3 provides a framework, across several scales, within which to consider mangrove ecosystems. At the broadest geomorphological macroscale, involving entire deltas or estuaries, climate and relative sea-level change influence the system. Climate determines the intertidal

floristic composition (mangrove, salt marsh, or algal mat), influences the delivery of sediment to the coast, and dictates the nature of adjacent terrestrial ecosystems, which are likely to replace mangrove vegetation over time. Intertidal wetlands are flanked by saline mudflats in arid and semiarid locations, seasonally flooded freshwater wetlands in monsoonal tropics, and peat-swamp forests underlain by domed woody peat in perennially wet equatorial regions of Southeast Asia. Periodic climate influences, such as hurricanes (referred to as tropical cyclones in Australia and typhoons in Asia) and El Niño–Southern Oscillation phenomena, can also be a significant influence on inundation and recruitment dynamics.

Also important is relative sea-level change, which is the combination of local changes in sea level and the net movement of the land surface. Where the land is lowered, by various physical and biological processes broadly termed subsidence, the coast experiences relative SLR (see sidebar, Subsidence and Relative Sea-Level Rise). These phenomena can influence vegetation productivity and the transition of one vegetation type into another and are examined in greater detail below.

At the mesoscale, there are likely to be distinctive mangrove habitats, often associated with different landforms or microtopography. **Figure 3** uses the functional classification introduced by Lugo & Snedaker (1974) as an illustration. Hydrodynamics, particularly the hydroperiod, influence how a particular stand of mangroves functions. The position within the tidal frame, which is partly mediated by the elevation of the ground surface beneath mangroves, is particularly important in determining frequency, duration, and interflood periodicity. The hydroperiod influences the

Hydroperiod: the flooding characteristics of an area, such as frequency, depth, and duration of inundation; for mangroves, this is driven primarily by tidal hydrodynamics
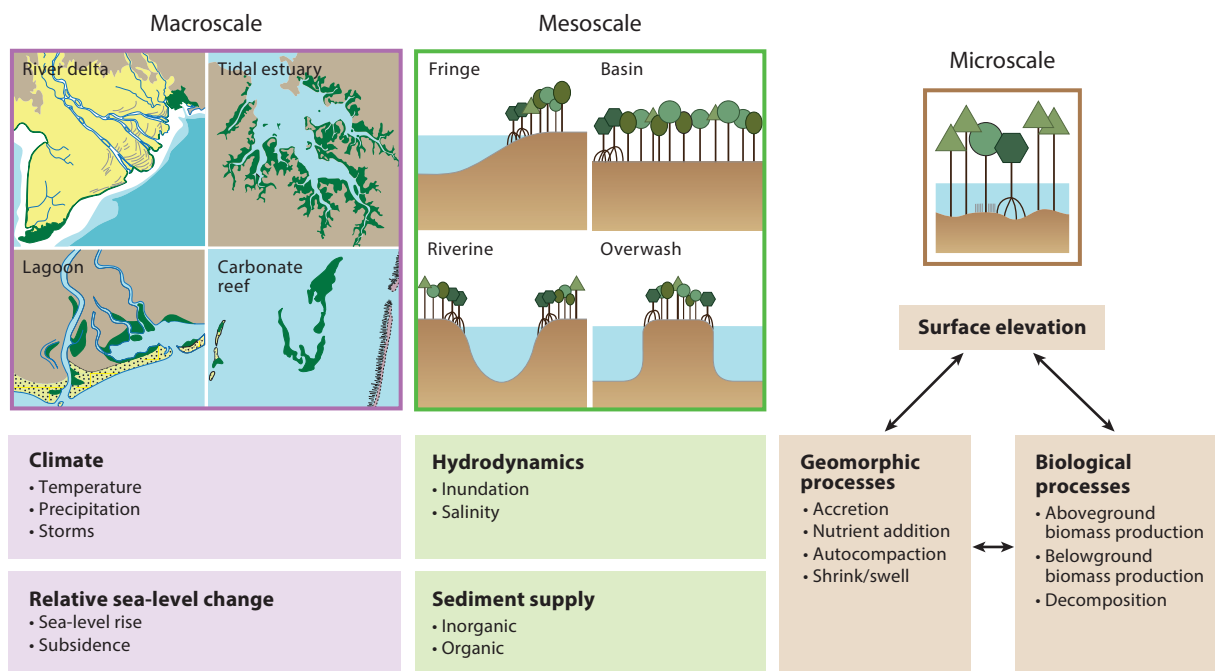

Figure 3

A scale-based framework within which to view mangrove systems, comprising macroscale regional boundary conditions (climate and relative sea-level change, which includes both subsidence and sea-level rise); mesoscale processes, in which hydrodynamics and sediment supply are important influences on mangrove systems; and microscale at-a-site interactions within a mangrove stand, including surface and subsurface processes.

SUBSIDENCE AND RELATIVE SEA-LEVEL RISE

Relative sea-level rise on a particular shoreline refers to the net change caused by adjustments of the sea surface and those of the land. The latter are captured by the term subsidence, but this incorporates a range of processes operating at different timescales, divided into deep and shallow subsidence. Many large deltas of the world are subsiding at rates up to an order of magnitude greater than the global rate of sea-level rise (Syvitski et al. 2009, Hanebuth et al. 2013, Auerbach et al. 2015). Geophysical processes of deep subsidence include tectonic movements, hydro-isostatic adjustments to the mass of water accumulated in ocean basins following postglacial ice melt, and flexure in response to sediment loading of the lithosphere. These natural processes can be further exacerbated by several anthropogenic factors, primarily groundwater or hydrocarbon extraction, with alarmingly rapid rates of subsidence beneath megacities, such as Bangkok (where the rate in the 1980s was up to 120 mm year^{-1}; Phien-wej et al. 2006).

The term shallow subsidence describes a suite of processes that are presently inadequately differentiated. Surface elevation table measurements in combination with marker horizons (SET-MH), which record accretion, allow calculation of shallow subsidence rates over short timescales. This approach measures changes in the thickness of sediments between the base of a benchmark pole or bedrock and the marker horizon (see **Figure 4b**) but does not indicate the causes of these changes. Bulk density and organic content provide some indication of compressibility over several years, and correlations with rainfall or groundwater levels enable inferences about likely shorter-term variations in water content (Whelan et al. 2005, Rogers & Saintilan 2008, McIvor et al. 2013, Rogers et al. 2013a).

In large deltas, such as the Mississippi River Delta, the principal component is compaction of sediments (Törnqvist et al. 2008). Rates of inferred subsidence are alarmingly high, but paleoenvironmental evidence implies that they must be nonlinear, because if observed rates had been occurring over centuries, fossil mangrove material would not have been preserved at elevations similar to those of its modern counterpart.

environmental factors that determine which mangrove species are able to establish, persist, and be productive (Crase et al. 2013).

The functional forest types described by Lugo & Snedaker (1974) are less easily discriminated in the more structurally complex mangrove forests of the Indo-West Pacific. Mangroves are extensive along estuaries, and hydrodynamics become increasingly complex owing to frictional distortions along channels and to flows across low-gradient vegetated wetlands (**Figure 2**). Despite attempts at classifying settings, there is still no adequate conceptual morphodynamic framework within which to view the mutual coadjustment between the topography of landforms and the associated hydrodynamic processes that control sediment movement over time (Cowell & Thom 1994). Climate and sea level may be important long-term drivers of change in these systems, but mangrove systems are subject to significant shorter-term internal morphodynamic adjustments, mediated by sediment supply, that may be harder to explain or predict (Chappell & Thom 1986).

At the microscale, involving an individual site, a range of geomorphological and biological surface and subsurface processes operate (**Figure 3**). The hydroperiod influences the rate of sediment accretion and root production, with negative feedback decreasing the flooding depth and accretion rate as surface elevation builds (Adame et al. 2009). As sediment accretes, the hydroperiod changes and the accommodation space is reduced. Negative feedbacks promote recurring, self-regulating forms that imply equilibrium (Woodroffe 1995). Because processes operate in nonlinear ways, complex systems must be studied at appropriate timescales. Rates of surface elevation change measured over decades are extremely variable and often independent of the rate of SLR. However, because the upper limit to mangrove growth is constrained by the highest tides, accumulation rates measured over longer timescales appear to track SLR. At century to millennial scales,

the stratigraphy of coastal plains indicates that accumulation beneath mangroves has culminated in a threshold beyond which mangroves have been replaced by adjacent terrestrial ecosystems. Forest structure responds to elevation changes, although response times may be slow because once mangroves are established, mature trees cannot be replaced quickly. Although zonation has been interpreted as evidence of plant succession in the past (e.g., Davis 1946), there have been few observations of replacement of mangrove species over time (Lucas et al. 2007). Antecedent conditions can influence observed vegetation change (e.g., mangrove reoccupation of paleochannels; see **Figure 2**). Such factors will complicate forecasts and simulation modeling of future mangrove forest behavior in response to changing sea level.

ACCOMMODATION SPACE AND HYDRODYNAMICS

The distribution of mangrove species coincides with the intertidal accommodation space, which progressively fills through sediment accumulation. Emergent properties and biocomplexity are a function of hydroperiod and are related to salinity and flooding tolerance, the latter of which is related to root morphologies, physiology, and reproductive traits such as vivipary (Feller et al. 2010).

Accommodation Space

The term accommodation space has been adopted from sequence stratigraphy, where it was defined by Jervey (1988, p. 47) as "the space available for potential sediment accumulation." Sediment accretion progressively fills the space unless countered by erosion. Tide-borne sediment can be deposited up to the highest tide level, which can change as a result of SLR or land movements (such as subsidence). Effective, or available, accommodation space generally refers to the one vertical dimension, depicting the relationship between sediment surface and the upper limiting tidal level. Within a mangrove forest, the accommodation space is usually greatest at the seaward edge, where mangroves may be rooted at elevations close to mean sea level (MSL) (**Figure 4a**). At the landward edge, where only the highest spring tides reach, the accommodation space is smallest. However, there may be more complex patterns; in basin forests, remote from tidal inundation, flooding may be sporadic or seasonal, and elsewhere, episodic increases in accommodation space occur during storms or flood events.

There may also be areas of potential accommodation space (see **Figure 2**), which could be inundated if they are tidally reconnected or the highest tide level increases slightly. Vegetation is not an intrinsic component of the sedimentological definition of accommodation space, and from a geological perspective, mangroves only fleetingly occupy part of the tidal frame. However, it is useful to consider ecological accommodation (broadly defined for organisms in carbonate stratigraphy by Pomar & Kendall 2008). For mangroves, this accommodation lies between the upper and lower bounds within which mangroves can establish, and these bounds are spatially variable. This concept is particularly important because mangroves and associated organisms (such as molluscs, foraminifera, and algae) produce and accumulate organic matter that contributes to filling accommodation space.

Tidal Hydrodynamics and Hydroperiod

Both mineral accretion and biological accretion are affected by the hydroperiod, which is related to elevation and reflects a combination of frequency, depth, and duration of tidal inundation (Krauss et al. 2006). Each of these factors will vary at individual sites as a function of distortion of the tidal
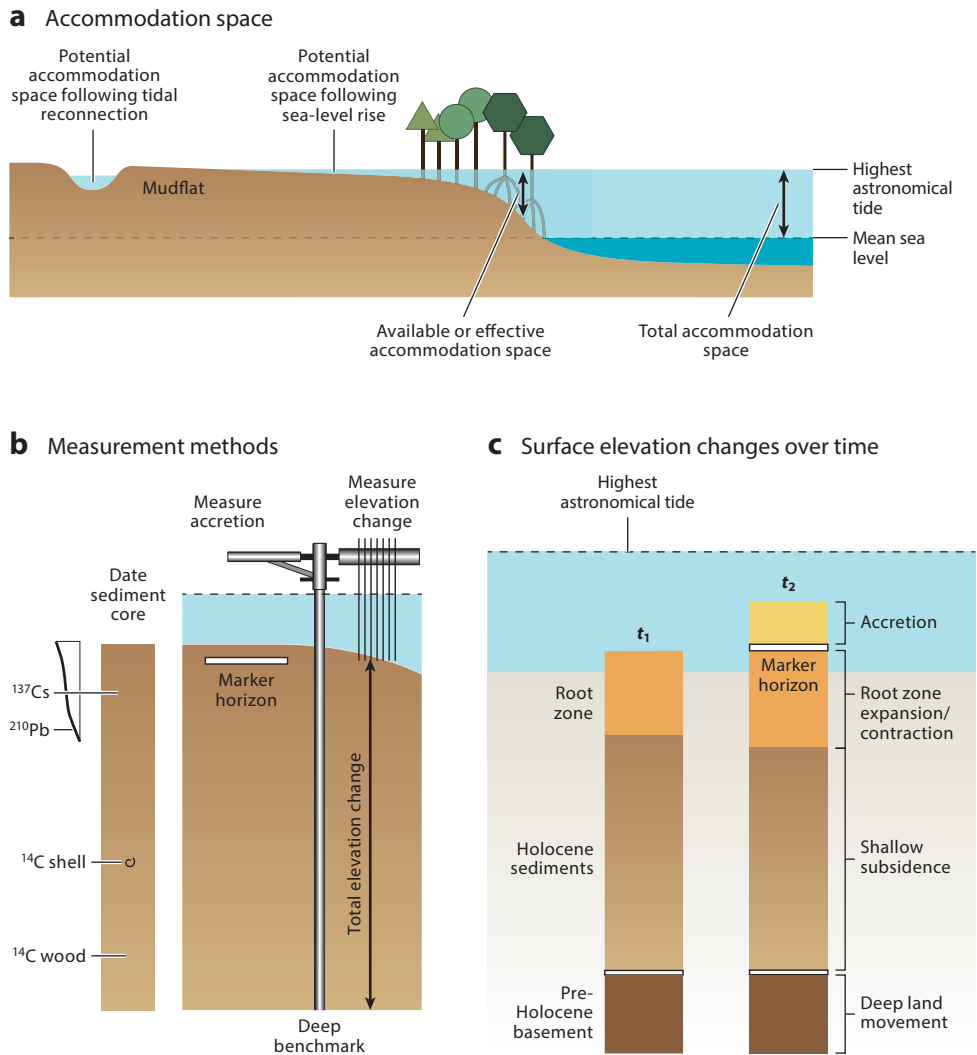
Ecological accommodation: vertical and horizontal adjustments by mangrove forests as the sea level changes, involving accumulation of both organic and mineral sediments

Figure 4

(*a*) Schematic cross section of substrate beneath mangroves, showing variations in accommodation space.
(*b*) Measurement methods adopted to assess sedimentary processes beneath mangroves. (*c*) Surface elevation
changes that occur over time.

curve as well as additional parameters, such as distance to a creek (Janssen-Stelder et al. 2002). On
open coasts, the lower bound to mangrove ecological accommodation space is set by the lowest
elevation at which seedlings can persist and grow to become trees (Balke et al. 2013). The upper
bound is the highest level to which tides or storms rise, although bounding water levels differ in
mangrove forests that are located well inland and infrequently flooded (see **Figure 2**).

Watson (1928) described the relationship of mangrove zones to tidal inundation, indicating
that the lowermost mangroves are flooded on average by 45 tides a month, the middle section by
20–45 tides a month, and the uppermost by <20 tides a month. However, site-specific assessments
of hydroperiod are needed. In Can Gio, east of the Mekong River Delta, elevation classes have

been independently determined: Medium-high tides reach up to 0.9 m above MSL, inundating *Avicennia* and *Sonneratia*; Rhizophoraceae dominate up to 1.5 m above MSL; and above that, *Lumnitzera*, along with *Bruguiera* and *Ceriops*, is flooded less frequently (van Loon et al. 2007). This pattern contrasts markedly with that of the Ca Mau Peninsula in the southwest of the delta, where tides are diurnal and the tidal range is approximately 1 m; here, mangroves are restricted to a much narrower accommodation space, reaching elevations of no more than 0.6 m above MSL. The actual area available for mangrove establishment is a function not only of this vertical accommodation space but also of the gradient of the substrate and the pattern of sedimentation. Mangroves are rapidly prograding across the actively building Ca Mau Peninsula, where there are particularly unusual tidal conditions as a consequence of the differing tidal regimes in the two seas (Phan & Hoang 1993). Despite the profuse supply of sediment, mangroves contribute a substantial organic component, even in this environment, with recent measurements indicating that mangroves in Ca Mau have sequestered more than 600 tonnes per hectare in belowground organic carbon (Tue et al. 2014).

In Darwin Harbor, where there is a larger tidal range, *Rhizophora* is replaced at an elevation of 2.0–2.5 m above MSL by *Ceriops*, and more landward mangroves, such as *Excoecaria*, are present at elevations up to 3.6 m above MSL (Woodroffe 1995). Mangrove species distribution appears to be related to hydroperiod (Crase et al. 2013), but broad characterizations of hydroperiod are only very approximate estimates and require assessment for individual sites (Clarke 2014). Mangrove distribution patterns change substantially in response to tidal distortions upstream in estuaries (Duke 2006) (see **Figure 2**). The tide becomes increasingly asymmetric upstream along tidal channels, with the flood tide of shorter duration but greater velocity than the ebb (Davies & Woodroffe 2010). Tidal range is amplified in systems that taper abruptly (e.g., Capo et al. 2006, Pethick & Orford 2013) but is attenuated in broader waterways (e.g., Knight et al. 2008). Lateral trapping of mud occurs because tidal waters flowing into mangroves can carry abundant sediment, but a large proportion is deposited as flow decelerates. The velocity in the main channel, typically >1 m s^{-1}, contrasts with the much slower flows, generally <0.08 m s^{-1}, within mangrove forests (Wolanski et al. 1992, Mazda et al. 1995, Quartel et al. 2007).

By contrast, where small tidal creeks flood extensive intertidal mangrove wetlands, inflowing tides tend to have a constant velocity as the tide rises; however, the velocity increases as water spills overbank into mangroves. After slack high water, the ebb tide is characterized by flows that accelerate to a peak velocity. Ebb dominance maintains channel depth by scouring the creeks (Wolanski et al. 1992), assisting outwelling of organic carbon from these wetlands (Hemminga et al. 1994, Lee 1995). The morphology of the mangrove system (i.e., both the forests and the associated channels) influences hydrodynamics and, consequently, sedimentation patterns through complex morphodynamic feedbacks.

SEDIMENTS AND SEDIMENT SUPPLY

The substrate beneath mangroves is composed of both inorganic mineral sediments and organic components derived from mangroves and other organisms. Where large rivers supply abundant terrigenous sediment, these allochthonous mineral sediments can accumulate rapidly in mudbanks, which provide habitats for opportunistic colonization by mangroves (Proisy et al. 2009, Lovelock et al. 2010, Swales et al. 2015). In more complex systems, sediments are redistributed by tides. In sediment-poor settings, mangroves themselves contribute to accumulation of autochthonous material; these often form peats composed predominantly of root matter incorporated into the substrate, but with some accumulation of leaf litter and other aboveground biomass, as well as algal mats (McKee & Faulkner 2000, Alongi et al. 2004, McKee 2011, Saintilan et al. 2013).

Allochthonous sediments: sediments produced from outside a site; these can include terrigenous sediment from rivers, tidally resuspended muds, or biogenic calcareous reef sediments

Autochthonous sediments: sediments produced in situ by living organisms such as mangroves or calcareous organisms

Rates of mangrove leaf production and turnover may be high (Komiyama et al. 2008), but a large proportion of litterfall is labile and tidally exported or is processed by crabs (Lee 1995). This contrasts with the fate of more refractory root material (Krauss et al. 2014). Stable-isotope analysis of carbon in temperate mangrove substrates indicates that mangrove roots dominate belowground carbon accumulation (Saintilan et al. 2013), although allochthonous carbon from adjacent sources dominates some sections of coastal wetland (Yang et al. 2013, 2014).

Rivers supply large volumes of sediment to the oceans, much of which accumulates in deltas. Extensive mangrove forests are associated with the megadeltas of Asia; for example, the enormous delivery of sediment from the Ganges and Brahmaputra Rivers has enabled vertical accretion that has maintained the shoreline at close to its present position during rapid postglacial SLR (Wilson & Goodbred 2015). The morphology of individual deltas varies according to the relative balance of river, tide, and wave processes, and the locus of mud deposition also varies. Mud is retained in some estuarine channels, whereas in others it is dispersed to delta-front and deep-water fans or moved along the delta front by longshore transport (Walsh & Nittrouer 2009, Woodroffe & Saito 2011). For example, because of mud deposition at the mouth of the Amazon, mangroves have increased by >700 km^2 in 12 years (Nascimento et al. 2013). Highly mobile mud-banks extend for more than 1,500 km along the northeast coast of South America between the mouths of the Amazon and Orinoco Rivers. The mudbanks migrate alongshore, protected from wave attack by the dampening effect of mud, and are colonized by mangroves, which are subsequently overwhelmed by a further phase of mudbank instability (Fromard et al. 2004, Anthony et al. 2010). In some locations, the dynamics of the mangrove fringe appear to be related to the 18.6-year cycle of highest tides (Gratiot et al. 2008). Similarly rapid mudbank accretion and mangrove colonization occur in the sediment-rich Gulf of Papua, with vertical accumulation rates of several centimeters per year prior to mangrove establishment (Walsh & Nittrouer 2004, Shearman 2010). In these cases, mangrove ecological accommodation is controlled by dynamic topographic changes following mud redistribution.

Mud, comprising silt and clay particles, is deposited only when there is minimal velocity of flow; however, once deposited, it is cohesive and requires much more rapid flows for resuspension. Muds are also prone to flocculation; when suspended sediments reach saline waters, they form a turbidity maximum. Tidal pumping occurs when flood tides carry sediment upstream farther than ebb flows carry it downstream, and such mechanisms can trap sediments in the turbid estuary. In tidal rivers in northern Australia, such as the Daly River, import of sediment by tidal pumping occurs in the dry season, and sediment export occurs in the wet season (Wolanski 2006).

Mangroves growing in sediment-deficient locations represent the other extreme of this continuum. Substrate is built by the plants, and organic input into the substrate contributes to increases in surface elevation (McKee 2011). For example, within predominantly carbonate islands in Belize, peat accumulation has tracked sea level as it has risen at a decelerating rate over the past few millennia (McKee et al. 2007). Mangrove islands have persisted amid the biogenic calcareous sediment that dominates these reef environments, but they now appear to be threatened by a combination of human pressures, including accelerated SLR (McKee & Vervaeke 2009).

Accumulation of organic and inorganic material is not continuous in time, but can undergo perturbations as a result of disturbance (**Figure 4b**). For example, storms can have profound effects on carbon retention and surface elevation within mangrove forests. Hurricanes can devastate mangroves, causing windthrow and defoliation, which interrupt forest growth. These hurricanes can also erode the substrate and deposit unusually thick layers of sediment that result in forest mortality (Ellison 1999, McCloskey & Liu 2013). Subsurface processes identified following a storm include accretion or erosion that causes elevation change, shrinkage, root decomposition, root growth, and other changes of volume (Cahoon 2006, Smith et al. 2009, Lovelock et al. 2011b,

SEDIMENT ACCUMULATION AND RELATIVE SEA-LEVEL RISE

Measuring Sedimentation and Elevation Change

Figure 4c shows a schematic cross section of mangrove substrate down to the pre-Holocene basement. The sediments have accumulated over the past few thousand years, often beneath earlier generations of mangroves. The upper section is the root zone. The surface of the substrate can change over time, generally increasing in elevation, as a result of several surface and subsurface processes (Gilman et al. 2008, Soares 2009, McIvor et al. 2013, Krauss et al. 2014). The most obvious is sediment accretion on the surface, primarily of fine-grained mud but also potentially of some organic matter, such as leaf (and other plant) litter and perhaps algal-mat development (Cahoon et al. 2006, McKee 2011, Krauss et al. 2014). Organic subsurface processes are also very important, particularly root growth. Other subsurface processes include decomposition of root material (Middleton & McKee 2001) and bioturbation by burrowing animals (Kristensen et al. 2008). Autocompaction occurs gradually and includes several poorly differentiated processes, collectively termed shallow subsidence (Whelan et al. 2005). These processes include consolidation as sediment grains readjust; compression, particularly of organic material such as roots; and changes in water content.

Figure 4b shows a series of methods that have been used to determine sediment accumulation. Several radiometric dating techniques provide age control on the stratigraphy beneath mangrove forests. Sediment cores can be dated using radiocarbon analyses on either the organic remains of plants or fossil molluscs. The decay of ^{14}C enables an estimate of the time at which an organism died, but it is necessary to know how the dated material related to both the sediment surface and the tidal frame in order to determine the sea level at that time. Although most mangrove roots are concentrated in the top 10–20 cm, some can penetrate as much as 1 m into the substrate, meaning that the age of the root does not necessarily represent the former sediment surface. Fossil molluscs are easily moved and may not be found now in the location at which they lived. Radiocarbon ages require calibration, and carbonate samples require an environmental correction before they can be compared with ages of plant matter. As a consequence, radiocarbon chronologies have provided age control over past millennia but are not as effective in the past century or two; ^{14}C in the atmosphere increased considerably following atomic bomb testing in the 1950s (Nolte et al. 2013).

Whereas the "bomb spike" confounds radiocarbon dating since 1950, this period of atomic bomb testing has left other markers that can be used to provide estimates of sediment accumulation in the past 60–70 years. One widely used isotope is ^{137}Cs, which first appeared in the early 1950s and reached a peak around 1963. Cesium has a relatively short half-life (~30 years), and most of it has decayed; however, it may be possible to identify a bomb spike using plutonium, which has a substantially longer half-life. Also based on the decay chain of uranium is ^{210}Pb; excess ^{210}Pb is also supplied from the atmosphere and delivered by river and ocean waters, such that the profile of this unsupported lead provides a down-core indication of time (Van Santen et al. 2007, Sanders et al. 2008, Comeaux et al. 2012).

A still shorter-term technique for determining sediment dynamics is direct observation with surface elevation tables (SETs). This is a precise, nondestructive method for measuring relative changes in substrate elevation, adapted for mangroves from its use in salt marshes (Cahoon et al. 2000). It consists of a rod or pole driven to refusal on hard underlying basement. A portable

Surface elevation table (SET): an elevation-change apparatus comprising a rod driven to the basement with a portable horizontal arm from which pins are lowered to the ground surface

Marker horizon (MH): a distinctive layer, generally of feldspar, that is placed on the substrate surface and resampled over time to measure sediment accretion

horizontal arm is positioned on top of the rod, and pins are lowered until they touch the ground surface. The length of the pins extending above the measuring arm is remeasured at successive points in time to record changes in the relative elevation of the surface. The most recent version of this approach, rod SET, has allowed placement of benchmarks at greater depths because the rods have less frictional resistance than the aluminum pipes used in the original SET technique (Cahoon et al. 2002).

Vertical accretion of sediment is usually determined at the same time as SET measurements. Marker horizons (MHs) of feldspar or sand are established near the SET, and the thickness of the sediment deposited above these is measured in short cores. Marker layers have proved difficult to relocate in mangroves owing to the effects of tidal resuspension and bioturbation, particularly those lower in the tidal frame. If cumulative vertical accretion over a period of several years substantially exceeds net surface elevation change over that period, then shallow subsidence is inferred (Rogers et al. 2005, 2006). In some locations, however, elevation change may exceed accretion, which indicates subsurface expansion, typically caused by root matter accumulation (McKee et al. 2007).

SET-MH measurements of surface elevation change allow users to distinguish between surface processes of accretion and subsurface processes. Results have shown that subsurface processes beneath mangroves can lead to considerable variation in surface elevation, in both sites with highly organic sediments and those with mineral sediments (Webb et al. 2013). These subsurface processes include autocompaction and hydrologically driven processes of shrink and swell that are not necessarily unidirectional (Rogers et al. 2014). They also include organic processes, such as root growth and decomposition. Together, subsurface processes can make a substantial contribution to net change in mangrove substrate elevation. For example, vertical change caused by root volume inputs to the substrate varied across mangrove islands in Belize from 1.2 to 10.8 mm year^{-1} and accounted for 52% of variation in elevation change (McKee et al. 2007); by contrast, subsidence and accretion explained 36% and 2% of variation, respectively. In Micronesia, accretion rates were highly variable (2.9 to 20.8 mm year^{-1}), but 7 out of 13 mangrove sites showed decreases in elevation (-0.6 to -5.8 mm year^{-1}), implying significant shallow subsidence caused by autocompaction and related processes (Krauss et al. 2010). **Table 1** summarizes published observations using SET-MH methods and demonstrates the apparent disparity between measured rates of sediment accretion and surface elevation gain (Alongi 2012, Krauss et al. 2014).

Sedimentation in mangrove habitats can be beneficial and can promote plant growth in several ways. Sedimentation can directly increase wetland elevation and reduce inundation stress. Mangroves quickly generate roots that grow into newly accumulated sediment, promoting soil development and elevation change (Lovelock et al. 2011a). In addition, fine-grained sediments contain active redox metals, moderating redox intensity and root oxygen stress. They may

Table 1 Published ranges of surface elevation change, vertical accretion, and subsurface adjustment for different mangrove hydrogeomorphic settings determined using surface elevation table–marker horizon (SET-MH) methods (for a full list of references, see Krauss et al. 2014)

Hydrogeomorphic setting	Surface elevation change (mm year^{-1})	Vertical accretion (mm year^{-1})	Subsurface change (mm year^{-1})
Fringe	-1.3 to $+5.9$	$+1.6$ to $+8.6$	-9.7 to $+2.4$
Riverine	$+0.9$ to $+6.2$	$+6.5$ to $+13.0$	-11.2 to -0.2
Basin/interior	-3.7 to $+3.9$	$+0.7$ to $+20.8$	-19.9 to $+2.8$
Scrub	-1.1	-2.0	-3.1
Overwash	-0.6 to -2.5	$+4.4$ to $+6.3$	-3.8

provide a nutrient subsidy that stimulates mangrove growth, particularly as soil conditions are often nitrogen or phosphorus limited. Sediments can also indirectly promote uptake of nutrients by limiting sulfide availability; soluble sulfide is a known phytotoxin that impairs salt-marsh vegetation (Mendelssohn & Morris 2000) and may affect mangroves similarly (McKee 1993). Too much sediment can be detrimental to mangrove growth, however, depending on the sediment texture, volume of sediment delivered, and period of accretion. Mangrove breathing roots (pneumatophores and prop roots) can be completely or partially smothered after burial by sediment, resulting in root anoxia that leads to mortality (Ellison 1999).

Relative Sea-Level Rise

There is ample evidence that sea level has risen in the past, and paleoenvironmental studies provide important perspectives on how mangroves and associated wetlands have coped with these changes (Woodroffe 1990, McKee et al. 2007, Ellison 2008, Semeniuk 2013). A key question is whether surface elevation beneath mangroves is able to keep pace with rising sea level. Linear regression of sediment accretion rate against SLR rate indicates that many forests are presently accreting at rates exceeding SLR (Alongi 2015). It is important to link SET-MH measurements with nearby tide-gauge observations (Cahoon 2014); however, presently there are few SET-MH measurements or tide-gauge observations in the most extensive mangrove areas (Webb et al. 2013).

Progressive accretion, slowing through time because of negative feedback, will eventually lead to such infrequent tidal inundation at the rear of the mangrove forest that a threshold is crossed and the mangroves are replaced by terrestrial ecosystems, the nature of which depends on the regional climate. Contrary to concerns expressed about the ability of mangroves to keep up with SLR, accretion rates in many mangrove forests appear to exceed present rates of SLR (**Table 1**). SLR raises that threshold, enabling mangrove ecosystems to expand landward. However, accretion does not necessarily occur at the same rate as sea level rises: In several locations where both have been measured, the rate of elevation gain (accretion plus subsurface movement) is less than the local sea-level trend (measured by tide gauges)—i.e., an elevation deficit exists.

Thus, subsurface movements may play a major role in determining whether a mangrove forest adjusts to SLR. Subsurface movements include deep geophysical processes (such as tectonics, hydro-isostasy, and lithospheric flexure), as well as shallower autocompaction within Holocene sediments (comprising undifferentiated processes such as consolidation, compression, dewatering, and decomposition of organic matter). Until recently, the principal concern was about the capacity of mangroves to accrete sediment at sufficiently rapid rates to track the rate of eustatic SLR, but it is increasingly apparent that accommodation space is also augmented by subsurface processes, including both shallow and deeper subsidence. Filling the accommodation space requires ample sediment, leading to concerns that even large deltas, many of which receive less sediment because of dam construction in their catchments, will no longer receive sufficient sediment to accrete across their entire surface (Ibáñez et al. 2013, Giosan et al. 2014). By contrast, the peat-forming mangroves studied to date appear to be keeping pace with SLR through subsurface expansion driven by mangrove root ingrowth (McKee et al. 2007, McKee 2011).

If there is no change in sea level and no subsidence, then accommodation space (in the vertical plane) will diminish as sediments fill it over time (assuming a sediment supply). Such a succession is evident from the stratigraphy of coastal and deltaic plains, which reveals that considerable horizontal advance (progradation) has occurred (Grindrod 1985). Once the substrate reaches the height of the highest tide, it is no longer inundated, and because the intertidal accommodation space is filled, no further tide-borne sediment accretion occurs except in the event of a storm surge that temporarily raises water level. However, there may be other processes of accumulation, for

Elevation deficit: a condition in which the rate of elevation gain in accommodation space (accretion plus subsurface movement) is less than the local sea-level trend

example, alluvial sediment deposition from river floods. Another source of accumulation is peat, as occurs in the peat-swamp forests in Southeast Asia, but these generally occur at much lower rates than intertidal sedimentation (Woodroffe 1993).

In most settings, mangroves persist because there is a continual increase in accommodation space as ocean height increases and the land subsides. This enables vertical sediment accretion (organic and inorganic). Many studies conclude that mangrove sediment accretion will keep pace with sea level, but more realistic scenarios must incorporate surface and subsurface processes. However, if the rate of vertical land development (through accretion and subsurface root accumulation) is less than relative SLR, mangroves will become progressively drowned (Ellison & Stoddart 1991). In such a scenario, mangroves could potentially expand landward into the hinterland, where they are unimpeded, producing further accommodation, which also requires sediment. Such displacement of mangroves landward has been modeled (e.g., Traill et al. 2011, Di Nitto et al. 2014). This is not possible where rock abuts mangroves or where infrastructure such as embankments and roads limit landward extension, causing coastal squeeze (Phan et al. 2015). If sediment accumulation occurs more rapidly than relative SLR and raises surface elevation to the level of the highest tide, then conditions favoring invasion by hinterland vegetation develop.

Sediment accumulation rates are spatially variable, and therefore models that adopt rates that vary geographically should be more realistic than lumped parameter models. Such modeling, incorporating rates observed at SETs, has been attempted in southeastern Australia; however, the results are highly dependent on the rates used and the underlying model assumptions (Rogers et al. 2012, 2013b; Oliver et al. 2012). Using accretion rates alone to predict the sustainability of mangroves will often overestimate survival, especially in locations with high rates of shallow subsidence, or may underestimate survival in locations where roots make a significant contribution to elevation adjustment.

The stratigraphic record of postglacial SLR provides some indication of how mangroves might respond to renewed marine transgression. In one sense, it can be inferred that the mangrove wetlands have kept pace with sea level. In the Caribbean, continuous sequences of mangrove peat spanning thousands of years illustrate that mangroves persisted during the past 7,000–8,000 years of relative SLR (Macintyre et al. 2004, McKee et al. 2007). Clearly, there is a rate of SLR above which mangrove substrate cannot accumulate fast enough to keep pace with rising sea levels, but this rate remains difficult to determine from paleoenvironmental analyses, although high rates of adjustment have been identified. Peat sequences are interrupted by calcareous layers in other places, indicating periodic disruption by storms or seismic activity (McCloskey & Liu 2013). By contrast, the sea was at or above its present level for much of the past 7,000 years in the Indo-Pacific, and mangroves that occupied many of the coastal and deltaic plains that formed over this period have been replaced, with only a narrow fringe persisting along the modern shoreline. The future of mangroves is thus likely to vary between sites, depending on a range of surface and subsurface processes and on rates of relative SLR.

DISCUSSION AND CONCLUSIONS

Mangroves occur in locations where topography exposes them to suitable tidal or other flooding regimes. Sedimentation within the available accommodation space can be rapid where there is abundant supply of inorganic sediment (Lovelock et al. 2010). Organic matter, particularly root matter, accumulates beneath mangroves and is now recognized as a globally significant repository of blue carbon. In some conditions, organic sediments build substrate even in the absence of terrigenous sediment. Paleoenvironmental studies indicate that mangroves have persisted during SLR, building substrate rapidly enough to keep up with the rise or being displaced landward onto

Marine transgression: a rise in sea level that causes the shoreline to move landward

previous hinterland. Fossil mangrove deposits provide important evidence for reconstruction of past sea level.

Sediment accretion and elevation-change rates are more rapid at lower elevations, decreasing as the substrate builds in the tidal frame, and in the short term they appear to be independent of the rate of SLR (Lovelock et al. 2015). Subsurface processes further decouple surface elevation gains from SLR, augmenting accommodation space because of the larger rate of relative SLR. The view that mangrove sedimentation tracks or keeps up with sea level is therefore misleading. The accommodation space for mangroves is directly constrained by the upper limit of tidal flooding. Mangrove forests that appear to track SLR, either in the past or based on measurements using SETs, have been filling the accommodation space to this limit. Mangroves have been replaced by terrestrial ecosystems once that upper threshold has been exceeded, as is clear from the stratigraphy of broad plains throughout much of the tropics. However, both shallow and deep land movements increase accommodation space, whereas sediment accretion reduces it. When sediment accumulation rates (both organic and inorganic) equal the combined rates of land and sea movements, mangroves maintain their elevation relative to MSL. When there is insufficient elevation change, mangrove forests may be drowned unless they can establish themselves in more landward locations as their existing locations are inundated (Ellison 2008).

Mangrove resilience at a site is largely dependent on the relationship between accretion (both allochthonous and autochthonous) and relative sea-level change. Assessment of resilience needs to incorporate nonlinear feedbacks among hydrodynamic conditions, sediment inputs, plant productivity, and elevation change. Rising sea levels, augmented by subsidence, can be expected to alter the size and characteristics of accommodation space and thus the composition of mangrove forests as inundation conditions come to favor particular species over their competitors. However, a focus on vertical adjustment within a particular mangrove stand risks missing the broader regional picture. Mangrove extent has changed substantially over time, including during the relatively stable sea level of the past few millennia and during the slowly rising sea level of the past century. Mangroves can extend seaward where subtidal accretion makes habitat available, and there may be considerable potential accommodation space on low-lying coastal plains that have not been occupied by people or impacted by land-use change but can be colonized by mangroves when tidally reconnected (Traill et al. 2011, Eliot & Eliot 2012, Rogers et al. 2013a). Such natural expansion of mangroves provides an important opportunity for carbon sequestration, facilitating both climate-change adaptation and mitigation (Rogers et al. 2013a). The topography of the land being inundated is the most significant control on changes in accommodation space resulting from higher water levels, and is therefore the most important factor to quantify when forecasting the future response of mangroves to relative SLR.

Unfortunately, human impacts have too often severely reduced the area occupied by mangrove forests (Giri et al. 2011) or monopolized areas into which they might have expanded. Land-use changes not only directly affect mangrove forests, but also reduce the opportunities for mangroves to extend farther landward as the sea rises, because embankments and infrastructure cause coastal squeeze. Human activities are imposing many additional pressures on mangrove forests, including accelerating rates of subsidence through groundwater extraction. Mangrove clear-cutting eliminates production of organic sediments and increases erosion of accumulated sediments (McKee & Vervaeke 2009).

Programs of restoration, rehabilitation, and planting can reverse declines in mangrove forest areas if appropriate hydrodynamic and sedimentary prerequisites are met, including returning tidal flooding to previously empoldered areas and enabling mangrove reestablishment. Mangroves of the Mekong River Delta have been especially impacted by human activities, including extensive destruction by defoliants during military conflict in the 1960s and 1970s, cutting for timber, and

reclamation for shrimp ponds (Ha et al. 2012). Nevertheless, the 10 million or more inhabitants of the delta have traditionally coped with vagaries of water management (including engineering structures such as dykes and sluice gates), broadening the range of adaptation and policy options available (Smajgl et al. 2015).

Although several simple models have been developed to simulate the response of salt marshes to SLR, it is questionable whether there is sufficient understanding of the ecological dynamics of mangroves, and of the morphodynamic behavior of sedimentary settings in which they grow, to extrapolate such models confidently to mangrove systems. As in the case of salt marshes, process studies of mangrove systems are often too short to understand the timescale at which these systems operate, and few address hydrodynamic processes or their variability in space. The few stratigraphic studies, which have focused on sparse auger or drill-hole evidence, provide a tunneled view through time with insufficient insight into variations in space. There remain sparse data on sediment accumulation and subsurface processes beneath most mangroves. Much more focused research is needed to disentangle interrelationships before modeling will be sufficiently useful for coastal managers to realistically forecast future mangrove extent.

SUMMARY POINTS

1. Mangroves are confined largely to the upper intertidal part of the tidal frame, referred to as the accommodation space, which is a function of hydrodynamics (or hydroperiod).

2. Mangroves can grow on a range of substrate types, from allochthonous terrigenous sediment to autochthonous mangrove-derived peat. Mangrove systems sequester significant volumes of carbon in sediments, termed blue carbon.

3. The paleoenvironmental record indicates that over millennial timescales, mangrove shorelines have been exposed to different sea-level trajectories, which suggests a broad capacity to adjust to sea-level changes.

4. Rates of surface elevation change beneath mangroves vary spatially and temporally and involve sediment accumulation as well as a range of subsurface processes, broadly termed subsidence. To persist, mangrove substrates must build vertically at a rate equal to the combined rates of eustatic sea-level rise and land subsidence.

5. Inorganic sediment supply and sequestration of organic matter endow mangrove forests with considerable natural resilience in response to sea-level rise. However, there are many other anthropogenic pressures that interfere with accretion processes and decrease mangroves' capacity to adjust to sea-level change.

DISCLOSURE STATEMENT

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Contents

Errata

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