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Mangrove response to sea-level rise: paleo-ecological insights from macrotidal systems in northern Australia

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Abstract

Accelerated sea-level rise threatens coastal wetlands; it is unclear whether sediment accretion beneath mangroves will be sufficient to keep pace. A conceptual framework, used to describe response of reefs, can also be applied to mangroves, discriminating drowning or back-stepping with rapid rise from keep-up or catch-up under moderate rates. In macrotidal estuaries of northern Australia, different mangrove species grow across particular elevation ranges, and accretion rates decrease with tidal elevation. Paleo-ecological reconstructions, from drilling, dating and pollen analysis, record mangrove distribution over past millennia. Estuarine plains are underlain by a vertically-continuous stratigraphy of muds implying continuity of widespread 'big swamp' mangrove forests during decelerating stages of postglacial sea-level rise about 7,000 years ago. By contrast, on higher-energy open coasts, mangroves back-stepped, but re-established as the shoreline prograded when the nearshore built to suitable elevation: a catch-up mode. These results demonstrate that mangrove response to sea-level rise has varied, determined by availability of sediment and the oceanographic processes by which it is redistributed. How mangrove forests adjust in future will also vary as a function of local topography and sediment availability. Extensive plains flanking estuarine systems are particularly vulnerable to tidal creek extension and saline incursion under future higher sea levels.

Keywords: Mangrove, Macrotidal estuary, Sea-level rise, Paleo-ecology, northern Australia

Introduction

Concern about the impacts of global warming and related rise in sea level has resulted in considerable speculation as to how intertidal wetlands will respond (Woodroffe, 1990; Lovelock et al., 2015). A rise in sea level will mean that areas that are behind mangrove and saltmarsh will be inundated by the highest tides, and terrestrial ecosystems are likely to be gradually replaced by salt-tolerant plants. In northern Australia, this places extensive freshwater wetlands at risk, and there is an urgent need to develop credible models that can be used to forecast what changes can be expected in future.

There have been many attempts to model intertidal wetland response. The SLAMM model, for example, has been widely applied to temperate saltmarshes (Glick et al., 2007; Craft et al., 2009), and in recent years there have been attempts to apply it to more complex tropical and subtropical mangrove systems (Akumu et al., 2011; Payo et al., 2016). However, the substrate beneath mangrove ecosystems is actively accreting; mangroves promote accretion, enhancing deposition of fine sediment, and incorporate organic matter, primarily root material, into the substrate (Woodroffe et al., 2016). Although there is clear evidence for rapid fine-grained sediment accumulation beneath mangroves (Walsh and Nittrouer, 2009), there is presently inadequate data to incorporate spatial variability in sedimentation rates into models, such as SLAMM. One approach has been to measure surface elevation change and vertical accretion in mangrove forests (Rogers et al., 2012), and preliminary results are providing increasingly useful datasets with which to calibrate models (Oliver et al. 2012; Rogers et al., 2014; Lovelock et al., 2015).

An alternative approach is to examine how mangrove shorelines have changed in the past to inform how they may respond in future. Identification of former mangrove sediments has provided evidence for past positions of sea level and the pattern of postglacial sea-level rise (Scholl and Stuiver, 1967; Hanebuth et al 2000). Sea level has risen rapidly since the peak of the last glaciation 20,000 years ago, causing shorelines to migrate landwards across the inner continental shelf. In geological parlance, this is called a transgression, which is marked stratigraphically by an upwards transition from formerly exposed terrestrial landscapes, through overlying intertidal sediments into a sequence of marine sedimentary environments. When sea level is stable, or if it falls slightly, the term regression is used. If there is a supply of sediment, the shoreline builds seawards, called progradation, and the stratigraphy

transitions upward from nearshore marine sediments through intertidal, to overlying supratidal deposition.

The pattern of sea-level change since the last glaciation around the Australian margin, as for many continental areas remote from former icesheets, comprises a period of transgression when sea level rose rapidly due to ice-melt, followed by a period of regression over the past 7,000 years in which coastal and estuarine plains have formed (Lewis et al., 2013).

Radiocarbon ages on mangrove material have provided much of the evidence for the trajectory and rates of sea-level change during the Holocene, both specifically in the Northern Territory (Woodroffe et al., 1987) and around other parts of Australia (Lewis et al., 2013), as well as elsewhere in the world (Toscano and Macintyre, 2003; Fontes et al., 2017). However, these sedimentary archives also provide insights into the way in which coastal wetlands have responded to sea-level change. In the macrotidal systems of northern Australia the fact that mangroves colonise a broad intertidal accommodation space, ranging from a few tens of centimetres below mean sea level (MSL) to 3 m or more above, makes it possible to look in more detail at paleo-ecological transitions across the upper intertidal.

In this paper, this longer-term perspective is re-examined to demonstrate how deciphering paleo-ecological changes provides insights into the way that wetlands respond to sea-level rise and sediment availability. First, a framework is outlined that has been used to consider coral reef response to postglacial sea-level change, and it is adapted for application to mangrove shorelines. Then, the distribution of mangrove species within the upper intertidal of macrotidal estuaries of northern Australia is described. This provides context for a review of paleo-ecological reconstructions in the Alligator Rivers region fringing van Diemen Gulf, based on drilling, radiocarbon dating and pollen analysis. The large tidal range in this region facilitates differentiation of species associations which are determined primarily by elevation in the tidal frame. The sedimentary record on the coastal plain indicates retreat of mangrove shorelines in response to transgression ~8,000 years ago, and subsequent progradation that has been prevalent for the past 6,000 years. This contrasts with mangrove forests within the estuaries which have been better able to keep up with sea level. Accretion beneath mangroves and successive replacement of mangrove communities is conceptualised under different scenarios of sea-level rise. Some evidence in support of these transitions is apparent in the paleo-ecological reconstructions. Inferring how these systems have altered in the past provides insights into possible future responses to sea-level rise.

A framework for considering sea-level change on tropical coasts

Figure 1 shows a schematic representation of the response of coral reefs to mid-late Holocene sea-level change, introduced by Neumann and Macintyre (1985) and expanded by Hubbard (1997). This framework can be modified to consider likely response of mangrove shorelines to sea-level change (Woodroffe, 2007). It is important to emphasise that the sea-level curve shown in this figure is not the pattern that the sea level followed at any point on the globe, but is schematic. The actual pattern of sea-level change has varied geographically over the past 10,000 years because of global isostatic adjustments to the altered ice and ocean loads on the lithosphere. From the peak of the last glaciation, about 20,000 years ago, when the sea was around 120 m below present, to ~7,000 years ago, the sea rose rapidly as the major northern hemisphere ice sheets melted (Lambeck and Chappell, 2001), with accelerated rise during one or more meltwater pulses. Over the past 7,000 years, the contribution from ice-melt has been much reduced as many of the icesheets have disappeared, and geographical variation in the isostatic response of the earth to the changed ice and ocean-water loads has resulted in different relative sea-level curves around the globe (Lambeck et al., 2010; Murray-Wallace and Woodroffe, 2014). Many areas that are remote from former icesheets, including Australia, have experienced a relative sea-level history in which the sea was slightly higher than present in mid-Holocene (around 5,000 years ago; in radiocarbon chronology referred to as BP, before present, where present is the year 1950), subsequently falling to its present level. This contrasts with areas close to the margins of the icesheets where the sea level has been gradually rising at a decelerating rate over past millennia, as has been observed in the West Indies (Toscano and Macintyre, 2003). Those regions that were covered by ice, such as Scandinavia, have rebounded, but as these high latitude areas do not have mangroves they will not be considered further.

Reef response

Rapid sea-level rise drowned coral reefs as their rate of vertical accretion could not maintain reef growth at or close to sea level. Slower rates of sea-level rise have resulted in reefs backstepping. At still slower rates, vertical accretion of reefs may track the rising sea; these reefs are considered to 'keep up'. When much of the polar ice had melted by around 7,000 years BP, sea level stabilised at a level close to its present, and the deceleration of the sea enabled slower growing reefs to 'catch up' with sea level, as observed for many places on the

Great Barrier Reef (Hopley et al., 2007). During periods of unchanging sea level, reefs cannot accrete vertically above a level at which corals are exposed during the lowest tides; instead reefs may prograde seawards (Montaggioni and Braithwaite, 2009). A gradual fall of relative sea level in the past few thousand years has resulted in emergent fossil corals and reef flat in the Indo-Pacific region (Dickinson, 2004).

Mangrove response

Fossil reefs are better preserved than mangrove sediments, but similar types of response are shown schematically in Figure 1 for the stratigraphy beneath mangrove forests. Mangrove sediments have been recovered in cores from the Sunda and Sahul shelves indicating former shorelines drowned by rapid postglacial sea-level rise (Hanebuth et al., 2000, 2011; Yokoyama et al., 2001). Mangrove forests appear to have back-stepped on the Great Barrier Reef, and the Belize barrier reef in the western Caribbean, where mangrove peats are preserved on the shelf beneath lagoonal sediments (Grindrod et al., 1999). Basal transgressive organic-rich peaty mangrove muds occur at the base of cores through coastal plains in southeast Asia and northern Australia (Woodroffe, 1993), as well as in eastern Brazil (Fontes et al., 2017). It will be shown below that about 8,000 years ago mangrove sedimentation was unable to keep pace with sea-level rise on open coasts, with mangrove forests back-stepping landwards, impinging on the hinterland ecosystems.

The coastline of the Northern Territory

There are extensive low-lying coastal plains on the southern shore of van Diemen Gulf in the Northern Territory (Figure 2). Several major macrotidal estuaries occur within undulating lateritic lowlands, each fed by rivers that rise in this monsoonal region, several on the sandstone plateau of Arnhemland (Woodroffe et al., 1993). Mangrove forests fringe the southern shore of the gulf, in which the tidal range is around 5 m, and extend up to 100 km upstream along the banks of the tidal river estuaries. Behind the littoral mangroves are broad estuarine and coastal plains that have formed over the past 7,000 years as the pre-Holocene topography has been infilled with fine sediments (Lucas et al., 2017). The plains are seasonally flooded in the monsoonal wet season (December-April), and support a freshwater grass and sedge vegetation and backwater paperbark (*Melaleuca* spp.). Runoff is negligible in the dry season and many rivers stop flowing. The tidal reaches of the rivers become

progressively more saline; riverine mangroves, such as *Sonneratia lanceolata* flank the channels at the upstream limit to tide influence. By contrast, the broad open embayments of Darwin and Bynoe Harbours have been incompletely filled with sediments. The tide is amplified hydrodynamically in these embayments (Williams et al., 2006), which have some of the most extensive stands of mangroves in northern Australia (~20,000 ha in Darwin Harbour, ~24,000 ha in Bynoe Harbour, Brocklehurst and Edmeades, 2003).

Mangrove occurrence in the intertidal zone in northern Australia

Mangroves grow in the upper intertidal. The seawardmost mangroves appear able to survive close to mean sea level, but are replaced by species apparently less tolerant of inundation higher in the tidal frame (Woodroffe, 1995; Crase et al., 2013). Tidal amplitude varies along the coast. At the Darwin tide gauge, the maximum recorded tide reached 4.09 m above Australian Height Datum [AHD which approximates mean sea level]. Figure 3 shows a simplified distribution of mangroves in terms of elevation in the tidal frame (where 0 = MSL = AHD) based on extensive surveys through Creek H in East Arm of the harbour (Woodroffe, 1995). *Sonneratia alba* grows rooted below MSL. Creek bank communities are dominated by *Rhizophora stylosa*, often with *Camptostemon schultzei*, both of which occur at elevations up to 2.5 m above MSL. *Ceriops tagal* is prominent to landward of *Rhizophora* and is abundant above an elevation of 2 m above MSL. Two species of *Bruguiera* occur within these Rhizophoraceous forests; they overlap, with *B. parviflora* occupying a lower range in the tidal frame than *B. exaristata*. *Avicennia marina* grows across the broadest elevational range but typically occurs as emergent individuals within other communities. *Excoecaria ovalis* and *Lumnitzera racemosa* are only found at the uppermost part of the tidal frame, generally at elevations >3 m above MSL. This broad patterning is typical of mangroves throughout both Darwin Harbour (Brocklehurst and Edmeades, 1996), and also adjacent Bynoe Harbour (Brocklehurst and Edmeades, 2003).

Along the tidal rivers, mangroves generally occupy a narrow fringe along the river banks. This littoral fringe may be several hundred metres wide near the mouth but decreases to a discontinuous band, typically less than 50 m wide upstream. *Sonneratia alba*, often with *Avicennia marina*, and sometimes with *Camptostemon*, dominates the most seaward communities at the river mouths. Distribution is affected by elevation, but also varies with distance along the estuary (Wells, 1995; Duke, 2006). A detailed surveying program on the

plains of the South Alligator River provided data on the absolute elevation at which mangrove species occur at points along the river (Woodroffe et al., 1986). The bars in Figure 3 span the observational data and broad patterns of distribution of *Rhizophora*, showing its more restricted elevational range with distance upstream; it does not occur more than 70 km upstream from the mouth. As in Darwin Harbour, *Rhizophora* rarely occurs above 2.5 m above MSL. Towards the tidal limit, *Sonneratia lanceolata* occurs on the steep river banks, in many cases together with *Avicennia*. The landwardmost mangroves throughout the length of the tidal river are *Avicennia marina*, often with *Lumnitzera* or samphire.

Figure 3 illustrates that the elevation of the landwardmost mangroves varies along the river and appears to coincide with the highest tides. Mangroves occur at elevations up to 3.7 m above MSL, reflecting an amplification of the tide in mid-estuary. This compares with a relatively consistent upper elevation to mangroves around Darwin Harbour of 3.6 m above MSL. However, in both circumstances it appears that the tidal range has been amplified hydrodynamically, and elsewhere the elevation of the back of the mangroves is considerably lower, for example on the open coast north of Darwin, and along the coastal plain at the mouths of the West and South Alligator Rivers, elevation of the landwardmost mangrove is around 2.8 m above MSL. The availability of LiDAR for several parts of the region permits a broader representation of these upper elevations, also indicating variation in tidal amplitude across the region, which further complicates both the unravelling of how sea level has varied in the past and the likely response of mangroves in the future. The plains are usually considerably lower away from the subtle levees that flank the channels; many paleochannels across the plains, as well as backwater paperbark swamp areas, are below the elevation that high tides reach at the river mouth (Woodroffe et al., 1986; Woodroffe and Mulrennan, 1993). These plains are not flooded tidally because of the topography of riverbank levees, but they may be prone to rapid tidal creek extension and subsequent saline incursion, as has occurred on the Mary River system.

Stratigraphy of Holocene plains of the South Alligator River

Estuarine plains

The stratigraphy, from numerous boreholes, and chronology, based on radiocarbon dating, of plains flanking the South Alligator River have been described in detail (Woodroffe et al., 1986, 1989, 1993), and is summarised in Figure 3. The Holocene muds are underlain by a pre-

Holocene surface that occurs at an average depth of about 12-14 m below the plains. This surface was rapidly inundated as the sea rose in the final stages of the postglacial marine transgression. Blue-grey muds, with abundant woody and fibrous organic remains, sometimes with intertidal infauna, were deposited. Radiocarbon ages on these remains have been used to derive a relative sea-level curve for the region (Woodroffe et al., 1987); ages have been calibrated to sidereal years and are shown in Figure 3 as years BP (before 1950). *In situ* stumps of mangroves, exposed by riverbank erosion, mark the upper units of these muds, and indicate that 7,000 to 5,000 years ago mangrove forests extended through many of these northern Australian estuaries. This phase has been called the 'big swamp' (Woodroffe et al., 1985), and it is inferred that mangrove forests covered most of what are now estuarine plains, although the full extent of the mangrove mud facies has been reduced by more recent meandering of the river channel. The large tidal range in northern Australia makes it difficult to differentiate whether there has been a slight fall of sea level in the past few thousand years; clearer evidence for such a fall is seen elsewhere in Australia (Lewis et al., 2013) and in southeast Asia, where, highly-oxidised mangrove muds have been left emergent (Geyh et al., 1979). However, for the purposes of this discussion, a pattern of sea-level change comprising rapid rise (transgression) until about 7,000 years BP and stability at present level since then will be adopted (see Figure 8, following Woodroffe et al., 1987; Lewis et al., 2013). Continuity of mangrove facies within the 12-14 m thick sediment wedge, from a fibrous transgressive lower unit about 8,000 years ago, to the upper big-swamp unit, implies that mangrove forests have promoted sedimentation following a 'keep-up' mode within this estuary (Woodroffe et al., 1986, 1989).

Coastal plains

The modern coastal plains, by contrast, have built out by progradation from a back-stepped shoreline position. Drillholes through the coastal plain encounter a similar basal transgressive mangrove mud overlying the pre-Holocene basement, recording a retreating shoreline 7,500 – 7,100 years ago. These are overlain by an intermediate shelly marine sand and mud unit (gradual aggradation of which is shown by isochrons based on radiocarbon ages on shell in Figure 3, transect A - A'), and an upper regressive mangrove unit. The upper 1-2 m also contains mangrove fragments, and pollen, recording at least part of the regressive progradation of the plain (Grindrod, 1988), but is less apparent in some cores as a result of oxidation of the upper metre due to the fluctuating water table. The stratigraphy indicates a

‘catch up’ mode, with intertidal wetlands re-establishing as the shoreline has prograded seaward.

The peak of the transgression is marked by a prominent chenier or beach ridge that can be identified at the landward margin of the plains along most of southern van Diemen Gulf. This paleo-shoreline separates estuarine plains from coastal plain, and importantly in the context of this review, the region in which mangrove sediment appears to have ‘kept-up’ with sea level, from the coastal plain which has caught up as the shoreline has prograded. Progradation of the coastal plain has been interrupted by the formation of one or more subsequent ridges. A second ridge is apparent on the plains east of the mouth of the South Alligator River (Figure 4), but several ridges are preserved on the broader plains associated with the Mary and Adelaide Rivers to the west.

What this dichotomy between the coastal plain and the estuarine plain implies is that it is not only the rate of sea-level rise that determines the vertical accretion within wetlands, but the availability of sediment to fill the potential accommodation space (that is the intertidal elevation range within which mangroves grow) that becomes available. The strong tidal currents have served to pump sediment into the estuary. However, the open coast, exposed to moderate wave energy, has not been suitable for mangrove forests to persist, but instead there has been a gradual retreat landwards of the mangrove fringe. Mangroves have re-established after the accretion of nearshore sediments, adopting the ‘catch-up’ mode illustrated in Figure 1, and have then in turn been replaced as the shoreline has prograded laterally.

Stratigraphy of Holocene plains of the Mary River

The situation portrayed in Figure 4, representing the South Alligator River, is replicated in the case of other estuaries along this coast (Woodroffe et al., 1993). Three phases of estuarine evolution have been recognised for the South Alligator River: a transgressive phase as sea level rose, a big swamp phase as sea level stabilised, and a subsequence phase when mangroves were replaced by plains covered with freshwater wetlands. These phases occurred on the Mary River system, and evidence from both the Adelaide River (Woodroffe et al., 1993), and Magela Creek in the upstream region of the East Alligator River (Wasson, 1992) indicates that transitions occurred in a similar progression on these systems also.

The geomorphology of Mary River system has been described by Woodroffe and Mulrennan (1993), and its surface geomorphology is summarised in Figure 5 (the radiocarbon ages on mangrove remains have also been calibrated to years BP). The Mary River drains a slightly smaller catchment than the South Alligator River (~8,000 km² compared to nearly 12,000 km²) and the main river channel bifurcated into several intermittent channels. In the mid 20th century, these channels did not reach the sea, although paleo-channels apparent on the plains indicate that there had been previous phases when the Mary River also had a broad tapering estuary similar to those on other macrotidal rivers in northern Australia (Woodroffe and Mulrennan, 1993). Two tidal creek systems, Sampan and Tommycut Creeks, have incised through the coastal plain over the past 7 decades to re-connect with the main river channel at Shady Camp (Knighton et al., 1991). Tidal creek extension has promoted rapid expansion of mangrove forests along their banks, with saltwater intrusion resulting in the death of extensive areas of paperbark (Miloshis and Fairfield, 2015).

The landward limit of the coastal plain is marked in a similar way by a prominent beach ridge that has been shown to have been deposited when sea level stabilised around 7,000 years ago (Figure 5). An estuarine plain occurs south of this ridge, and it has accreted vertically through a 'big swamp' phase. The pre-Holocene basement at which drilling terminated consists of oxidised sands, gravels, or a stiff mottled clay palaeosol. This is overlain by blue-grey fine sandy or silty clay with organic fragments. The basal muds are often highly organic with the remains of compacted wood, much of which appears to be derived from *Rhizophora*. The mangrove origin has been further demonstrated by pollen analysis. This organic-rich mud transitions upwards into freshwater clays deposited beneath the grass and sedge vegetation that presently flourishes over the plains. Intense oxidation characterises the uppermost 0.5-2.0 m of these alluvial muds, and organic remains, including pollen, have been lost. Stratigraphy and chronology based on cores from throughout both estuarine and coastal plains indicate that transgression over the pre-Holocene basement occurred about 8,000 years ago at depths of 6-9 m below the surface, somewhat shallower than in the South Alligator River. Whereas vertical accretion beneath mangroves is inferred for the estuarine plain at rates of up to 10 mm/yr, the basal transgressive mangrove muds beneath the coastal plain are overlain by shelly nearshore sediments; *Anadara granosa* and a species of *Cerithidea* are common, but shell hash derived from molluscs in the families Trochidae, Turitellidae, Mactridae and Cardiidae is also encountered.

Pollen analysis and former mangrove communities

The mangrove origin of sediments has also been substantiated by pollen analysis, recording the proportion of mangrove genera at depths through several cores. Mangrove pollen is subject to redistribution by tides and bioturbation in sediments. It has been shown that pollen signatures from modern surface sediment samples reflect the adjacent mangrove vegetation in preference to pollen rain assessment using pollen traps, which are used to collect regional vegetation signatures in terrestrial applications of pollen analysis (Chappell and Grindrod, 1985; Grindrod, 1988). Regional and long distance pollen grains typical of sclerophyll vegetation are rare in intertidal or subtidal muds, but are represented in the alluvial sediments of the floodplains. It has been possible to recognise some mangroves to genus level, whereas others could only be discriminated to family level. The pollen of *Rhizophora* is generally larger than that of *Ceriops* and *Bruguiera* in the same family, but where size was not sufficiently distinct to assign a grain it was labelled as Rhizophoraceae id (Grindrod, 1988).

An upward progression in the abundance of taxa through cores collected in big-swamp mangrove muds has been described comprising 6 zones (Woodroffe et al., 1985). The lowermost zone comprises marine or estuarine sediments in which *Rhizophora* pollen occurs; zone 2 contains abundant *Rhizophora* and *Ceriops/Bruguiera* pollen; *Rhizophora* dominates zones 3 and 4, but *Sonneratia* is present in zone 3; in zone 5 the total mangrove component declines and *Avicennia* is dominant; zone 6 is dominated by grass and sedge pollen characteristic of the modern plains. Since the initial description of the sequence (Woodroffe et al., 1985; Russell-Smith, 1985; Chappell and Grindrod, 1985), this big swamp transition has been widely reported from the Alligator Rivers region (Clark and Guppy, 1988) and elsewhere in northern Australia (Grindrod, 1985, 1988; Crowley, 1996). Rhizophoraceous pollen dominates the big-swamp, partly because *Rhizophora* is a prolific pollen producer and its pollen is likely to be tidally transported. However, the vertical sequence corresponds with the relative position in the tidal frame and records the replacement of mangroves as sediment has accreted. *Avicennia* becomes more apparent in the upper mangrove facies and is then replaced by grasses and sedges (Poaceae and Cyperaceae). A small peak in *Sonneratia* pollen is noted in several pollen diagrams, prior to the transition through *Avicennia* to freshwater wetlands.

Pollen analysis of several cores from the Mary River plains is shown in Figure 6 (synthesising details in Woodroffe and Mulrennan, 1993). Pollen spectra indicate the transition from Rhizophoraceae through *Avicennia* into grasses and sedges that dominate the modern freshwater wetland vegetation in the upper part of many cores. Pollen can also be used to reinforce the interpretation that shelly coastal plain facies were deposited in an environment adjacent to, but seaward of, mangroves. Modern pollen signature studies have shown that *Rhizophora* pollen often exceeds 70% of total pollen beneath stands of *Rhizophora* (Grindrod, 1988). Where *Rhizophora* pollen accounts for 50-60% of the ~200 grains counted on slides, it is inferred that a relatively well-flushed Rhizophoraceous forest dominated. *Rhizophora* was prominent throughout most cores in the estuarine plain, but low pollen counts were obtained in the nearshore sediments. Figure 6 shows several cores (MRH 51, 52 and 56) from the estuarine plain; Rhizophoraceous pollen dominates with transition, through *Sonneratia* and *Avicennia*, in the upper core to the freshwater vegetation (Poaceae and Cyperaceae, as well as Myrtaceae; reflecting the big-swamp transition referred to above).

For the coastal plain, the history of its progradation following sea-level stabilisation is recorded seaward of the ridge that marks the 6,000-7,000 year-old shoreline and which is up to 15 km landward of the modern shoreline. Several more seaward ridges mark subsequent shorelines occupied successively during this build out. Sandy lenses of shell hash within the cores differentiate this from the vertically-accumulated mangrove facies found within the estuarine embayment further south. Although mangrove is the principal pollen type, total pollen counts are low. The pollen of *Rhizophora* can float, as can woody debris, so it is not surprising that mangrove pollen and organic fragments characterise even these facies. However, the contrast in the representation of mangrove pollen has been interpreted as differentiating these cores from those of the estuarine plain. Transgressive mangrove facies, however, does occur at the base of coastal plain cores, overlying the pre-Holocene. Organic and woody fragments, many recognisably of *Rhizophora* with its characteristic reddish and fibrous nature, are much more abundant but highly compressed. The proportional count of pollen also supports deposition beneath mangrove forests, but the compressed nature of this unit, and poor recovery from such depth, makes it impossible to infer the nature of transitions within the mangrove forests during this period of transgression.

Discussion

Paleo-ecological studies such as those in the Alligator Rivers region provide a longer-term perspective on the response of mangroves to sea-level rise. The macrotidal range enables greater differentiation of the elevational tolerances of mangrove species in the tidal frame and allows discrimination of past changes in mangrove dominance, partially supported by pollen analysis. In this section, the way in which sea-level changes are recorded in the stratigraphy of sedimentary units is re-examined in relation to the relative patterning of mangrove communities, expanding on the generalisations in Figure 1. A conceptual framework is described for sedimentation beneath mangroves in the upper intertidal, and its response to sea-level rise. The stratigraphic record in northern Australia is then reconsidered and the extent to which it supports these ideas is assessed, providing insights into types of response that could be anticipated as sea level rises in the future.

Sedimentation and sea-level rise on mangrove shorelines

Figure 7 explores the concept of elevation change of the mangrove substrate as a result of sedimentation when compared with rates of sea-level rise. It expands on the continuum from transgression (back-stepping) to regression (progradation) by examining likely sequences of mangrove vegetation adjustment predicated on the relative balance of surface elevation change (accretion) and sea-level rise. The simulation builds on initial concepts presented by J.R.L. Allen for saltmarshes (Allen, 2000). As with Figure 1, this figure is highly schematic; it provides a visualisation of what could be expected if the rate of sea-level rise was constant and sediment supply unlimited over a long period of time, neither of which have occurred in the past or are likely to in future.

In Figure 7, Mean Sea Level (MSL) is regarded as the lower bound at which mangrove establishes. Accretion, primarily through vertical mud aggradation, but also through addition of mangrove material into and onto the substrate, builds surface elevation in the upper tidal frame (Woodroffe et al., 2016), until it no longer receives tidal inundation, for convenience considered to be Highest Astronomical Tide (HAT). Details of mangrove distribution within these vertical range limits in Darwin Harbour and along the South Alligator River can be seen in Figure 3.

Stable sea level

There is considerable evidence indicating that the rate of vertical accretion is greatest lower in the tidal frame, at which there is a greater frequency and duration of inundation (Swales et al., 2015). In the absence of observational data on accretion, the morphology of the mangrove zone provides further evidence to indicate a more rapid rate of accretion lower in the tidal frame (as initially observed in temperate mangroves by Bird and Barson, 1975). Surveys in Darwin Harbour and east of the South Alligator River, augmented by digital terrain models derived from airborne LiDAR indicate that the ground is steeper in the *Rhizophora* zone, compared with a more gradual gradient above, indicating more rapid accretion.

In Figure 7a sea level remains unchanged over time, and substrate builds beneath the mangroves, with an exponential decrease in sedimentation as anticipated by Allen (2000). In the case of the complex mangrove communities of northern Australia, this would also entail a transition through several floristic assemblages of mangroves. In Figure 7, these are represented as lower, mid and upper communities, but in simplified terms could be represented by the *Sonneratia* – *Rhizophora* – *Avicennia*, the zones seen in modern mangroves and the vertical transition observed in pollen diagrams from the big-swamp. Under stable sea level, pioneer mangrove communities establish around MSL and rapidly build substrate; slower accretion occurs beneath mid communities, with still slower accretion beneath landwardmost mangroves which are only inundated intermittently. Eventually they are so infrequently inundated that mangroves are replaced.

Sea-level rise

If sea level rises at a moderate rate, replacement of lower mangrove communities by mid, and eventually upper communities takes longer and timing of transitions depends on sedimentation rate compared to rates of sea-level rise. In Figure 7b, it is assumed that accretion beneath lower mangrove communities is faster than sea-level rise, which is in turn faster than accretion beneath upper communities. This condition was illustrated by Allen (2000), who showed asymptotically decreasing sedimentation rates beneath saltmarshes reducing until equal to the rate of sea-level rise. Under these circumstances, mangroves could still prograde, establishing at MSL and building vertically, if nearshore sediments aggrade fast enough to provide suitable substrate. However, if HAT also rises, as it will in most circumstances, further expansion of mangrove forests can occur landwards. A landward (upper community) species of mangrove would replace the hinterland ecosystem (assuming

that there is suitable space and not a hard structure, as occurs with what is called coastal squeeze). If vertical accretion beneath those landwardmost mangroves is slower than the rate of sea-level rise then they will become inundated more frequently on the highest tides, which would enable the rate of accretion to increase. Replacement of the upper community by the mid community would eventually occur, constrained by population dynamics, propagule dispersal and establishment capabilities.

If sedimentation rate is directly related to elevation in the tidal frame, from faster at MSL to negligible at HAT, then an equilibrium accretion rate equivalent to the rate of sea-level rise will eventuate over time at any point. At the lowest points in the tidal frame where accretion exceeds the rate of sea-level rise, the substrate will gradually build up towards the critical elevation at which the accretion rate equals the rate of sea-level rise. At the landwardmost sites, at or close to HAT, sedimentation will be negligible until sea-level rise results in more frequent inundation, increasing the potential for accretion. Theoretically there is an elevation in the tidal frame at which accretion rate is equal to sea-level rise, which can be regarded as a stable equilibrium (Woodroffe, 2003). Any deviation caused by a change of sea level would alter sedimentation rate; if sea level rises, accretion rate rises (because the site is now lower in the tidal frame), whereas if the surface builds beyond this critical balance, accretion rate would decrease due to less frequent inundation. These negative feedbacks would maintain the accretion rate equalling rate of sea-level rise in a stable equilibrium. Moreover, if vegetation were also directly a function of position in the tidal frame, the equilibrium situation would not only comprise a vertical accretion rate equivalent to the sea-level rise rate, but would also mean that the appropriate community (in this case, upper, mid or lower mangrove) would continue unchanging through time. An increasingly larger proportion of the wetland would be dominated by this 'equilibrium' community, with only marginal zones colonised by other mangrove communities. Establishment of mangroves to seaward of their initial extent would be much more problematic as the sea rises more rapidly.

A faster rate of sea level rise, results in convergence on communities lower in the tidal frame, as long as it does not exceed the rate at which mangrove substrate can build. More important in this case, tidal inundation reaches further into the hinterland, but landward mangrove communities are much sooner replaced by mid, and ultimately lower communities, which then become widespread. Figure 7d shows the most rapid rate of sea-level rise, one that exceeds sediment accretion beneath any mangroves. In this case, mangroves established in the

hinterland at highest tides are soon inundated too frequently as conditions become typical of those lower in the tidal frame. Mangroves are drowned at these fastest rates of sea-level rise; the progression of mangrove communities would be upper-mid-lower before their total demise. Recovery of mangrove sediments in cores from the inner continental shelf and barrier-reef lagoons is evidence that the drowning and back-stepping scenarios of Figure 1 occurred during rapid post-glacial sea-level rise.

Sediment availability

The schematised scenarios in Figure 7 are over-simplified. Nevertheless, they demonstrate broad responses that it can be shown have occurred in northern Australia in the past 10,000 years. Sea level does not change at a uniform rate over time; sedimentation is not as linearly related to position in the tidal frame as inferred, and the complex inter-relationships between surface elevation change and accretion demonstrated from SET studies (see, for example, Rogers et al., 2014) have not been taken into consideration. Most importantly, there has been assumed to be limitless sediment available to build substrate in this simulation.

The stratigraphy from the southern van Diemen Gulf coastline indicates that mangrove forests have accreted vertically (keep-up mode) in the estuaries, as the sea has risen in the final stages of postglacial sea-level rise, whereas those on the coastal plain continued to backstep until after sea level stabilised, and subsequently prograded over nearshore sediments (catch-up mode). It appears that when sea level rises rapidly there is unlikely to be sufficient sediment to fill all the accommodation space that becomes available, and spatial variations in mangrove response should be anticipated. Strong tidal currents, which can exceed 2 m/s on incoming spring tides, serve to pump sediments upstream into these macrotidal estuaries, whereas wave and cyclone activity promotes retreat on the open coast, except on those sections where nearshore sedimentation is particularly rapid.

A range of sedimentation rates has been measured from mangroves around the world, with average rates observed over a decade or more rarely exceeding 8-10 mm/yr (Krauss et al., 2014), although faster rates have been recorded at some sediment-rich locations over short periods of monitoring (Lovelock et al., 2015). The sea-level rise scenarios in Figure 7 are broadly indicative. No specific rates are adopted, and precise rates of change in the Alligator Rivers region cannot yet be deciphered from the paleo-ecological data, primarily because of the large tidal range over which mangroves grow. Scenarios a, b, c and d could perhaps be

taken to indicate 0, ~3, ~6 and ~10 mm/yr respectively. Similarly the timescale on the x axis cannot be specified. Transition to a stable equilibrium could be expected in most instances to require hundreds of years to eventuate, depending both on accretion rates and tidal range at a site (requiring much longer where tidal range is large as in northern Australia). It is premature to attempt to define threshold rates of sedimentation, for example rates of sea-level rise beyond which mangrove accretion cannot keep up, because the paleo-ecological interpretation from northern Australia demonstrates that mangroves in one location may have kept pace while others did not. This indicates that there are more complex issues, including the availability of sediment and the oceanographic processes operating (tides, waves and storms).

Mangrove succession

If surface elevation increases more rapidly in the tidal frame than the rate at which the sea rises, then conditions will preferentially favour alternative mangrove species. In Figure 7 idealised lower, mid and upper mangrove communities are shown. Successive replacement of mangrove communities seems inevitable over timescales of decades to centuries. Under stable sea-level conditions, vertical accretion at a site would lead to a succession of communities (lower-mid-upper, Figure 7a). Pollen reconstructions imply that this occurred in the big swamp phase, and it must also characterise the regressive sequence as the coast progrades. By contrast, the succession of communities with rapid sea-level rise is the reverse (upper-mid-lower), with mangroves being lost after a period of time, to be replaced by lower intertidal mudflat and ultimately open water. This is the transition that is captured in a transgressive sedimentary sequence.

Estuarine stratigraphy reconsidered

The stratigraphic and geochronological evidence from the Alligator Rivers region, and from adjacent systems in northern Australia, indicates a contrast between what has happened within the major estuaries, and progradation that has dominated the open coast of van Diemen Gulf. Figure 8a summaries mangrove evidence from the region with a schematic longitudinal cross-section of a macrotidal system based on the Mary River system. It shows estuarine plains in which mangrove muds underlie most of the plains recording transgression at the base of cores but with sedimentation vertically transitioning into big-swamp mangrove forests throughout most of the estuary. Continued vertical accretion resulted in a transition, partially recorded by

pollen spectra, from regularly inundated Rhizophoraceous forests, through *Avicennia*, replaced in the past few thousand years by freshwater grass-sedgelands (Woodroffe et al., 1993).

Figure 8b shows the broad pattern of sea-level change (compiled from radiocarbon ages from the South Alligator system, Woodroffe et al., 1987), and the likely vertical mangrove accommodation range (yellow). The probable trajectory of sedimentation is shown for several sites, recording accretion and successive mangrove communities following the lower, mid, upper schematisation proposed in Figure 7. As sea level rose from the last glacial maximum, mangrove forests would have been rapidly drowned on the inner continental shelf (Woodroffe, 2000). Cores from the Sahul shelf record brief periods when mangrove flourished during this rapidly rising phase (Yokoyama et al., 2001), representing drowned and back-stepped modes as shown in Figure 1. Mangrove forests progressively back-stepped and the shoreline was displaced landwards until the culmination of the transgression. The succession of communities can be inferred to have been upper-mid-lower, but pollen data from the base of cores, in which this transgressive unit has been compacted, do not have the resolution to discriminate this sequence. As the estuary (at that stage a river valley) was inundated, strong tidal currents transported muds landwards to provide sufficient sediment for estuarine mangroves to persist. As can be seen in Figure 7, the faster the rate of sea-level rise, the more likely it will be that a mangrove community characteristic of lower in the tidal frame will persist. *Rhizophora* forests appear to have been prominent both during transgression and during vertical accretion transitioning into big-swamp.

At locations A and B, mangroves established around 8,000 years ago as the sea inundated the prior valley. It can be inferred that the more landward, upper species, including *Avicennia*, were the first species to establish in the terrestrial landscape that was being tidally inundated. As the sea rose, landward mangrove communities would have been replaced by mangroves lower in the tidal frame, which is consistent with abundant *Rhizophora* remains. Mangrove forests persisted in the estuary (keep-up mode), but were drowned on the coastal plain, where they are likely to have been more exposed to wave and storm activity. Pollen analysis provides support for the later stages of demise of mangrove forests on the estuarine plain, with reduction of Rhizophoraceous pollen and increase in *Avicennia* prior to transition to grass-sedgelands. Progradation of the coastal plain appears to have occurred at a decelerating

rate. Availability of sediment was an important control on mangrove shoreline response with mud being preferentially carried into, and deposited in, more sheltered forests in the estuary.

The broad pattern of paleo-environmental change in this region provides insights into the response of mangrove shorelines to sea-level change. It demonstrates several of the modes of response shown in Figure 1. However, it also reinforces the importance of availability of sediment. There are enormous volumes of mud sequestered in the plains along the southern shore of van Diemen Gulf. The catchments produce little sediment through erosion, and it seems likely that much of this mud has been reworked from offshore by strong tidal currents, transported landwards and pumped into the macrotidal estuaries. In contrast to these largely infilled systems, Darwin and Bynoe Harbours remain only partially filled with sediment over the same period, and do not have the large volumes of mud or the extensive low-lying plains that occur to landward of mangroves flanking the rivers to the east (Siwabessy et al., 2017). This has important implications for response to future sea-level rise, discussed briefly below.

Despite the very different time scales, the paleo-ecological reconstruction of the behaviour of past mangrove shorelines provides insights into potential future changes (Wolanski, 2006; Woodroffe, 2017). It demonstrates the contrast between transgressive conditions, in which the sea is rising, and stable conditions in which a regressive sequence of sedimentary environments has eventuated. Different modes of response can be anticipated, and have occurred under a range of sea-level change conditions in the past (Figure 1). Mangroves have an ability to establish propagules in shallow water, meaning that they can assist in shoreline progradation. Accretion will be most rapid lower in the tidal frame, and as substrate rises it will be progressively less frequently flooded in future. This is in contrast to what can be inferred to have occurred under rapid sea-level rise in the past. A schematisation is proposed in Figure 7 that implies a capacity for mangrove systems to keep up with a constant sea-level rise (provided there is sufficient sediment available), as long as the rate of rise does not exceed the fastest accretion rate. Some evidence is provided in Figure 8 to support the application of this to the sedimentary record of macrotidal estuaries in northern Australia. However, there needs to be sufficient sediment available to fill the accommodation space that becomes available when the sea rises. Organic mangrove-derived material makes an autochthonous contribution, and there are locations where mangrove peats appear to have kept pace with gradual sea-level rise (McKee et al., 2007), but in northern Australia the substrate is primarily mud.

Implications

Sea-level rise is occurring associated with global warming; rates of global mean- sea-level rise of around 3 mm/yr are being observed. Considerably faster rates have been observed at the Darwin high-precision Seaframe tide gauge in the past couple of decades (White et al., 2014). For the broad plains of the Alligator Rivers region, and similar adjacent tidal rivers, the change from a predominantly stable sea level to one that is rising at such rates represents a transition from the situation schematised in Figure 7a to that in 7b, or even 7c. There are some places, for example west of the mouth of the West Alligator, where sedimentation in the nearshore is still continuing and there is seaward extension of mangroves (Asbridge and Lucas, 2016). However, far more widespread is the circumstance where the highest tides are inundating parts of the low-lying plains and mangroves are expanding to landwards. If sea-level rise persists and the extensive plains become inundated, then widespread mangrove, as occurred during the big-swamp, may result (Wolanski and Chappell, 1996).

A return to transgressive conditions would ultimately see mangrove expand landwards in those locations where this can occur, and where there are not hard engineering structures that prevent such migration, leading to coastal squeeze (Phan et al., 2015). Initially, such a pattern of transgression may be difficult to discriminate because mangrove systems are subject to a series of perturbations, for example by tropical cyclones, lightning strikes, and the widespread dieback observed across much of northern Australia in 2015-6 (Duke et al., 2017; Lucas et al., 2017). Transgression in the future will not always resemble that which can be reconstructed from paleo-ecological records. For much of the postglacial marine transgression, mangrove systems would have been encroaching on low gradient hillslopes and inundating former valleys. However, anticipated sea-level rise over coming decades will result in mangroves intruding across broad horizontal plains that have accumulated over the past few millennia.

The prognosis is different for Darwin/Bynoe Harbours from that for the broad plains flanking the tidal river estuaries. Little change in the distribution of mangrove vegetation appears to have occurred in Darwin Harbour over past decades from several decades of Landsat imagery (Rogers et al., 2017). The landwardmost mangroves in these harbours abut terrestrial vegetation on gentle hillslopes. There is an abrupt transition, in many places at an elevation of 3.6 m above MSL. As sea level rises, the slopes are steep enough that only gradual

incremental incursion will occur; saltwater will affect the eucalypt forest and grass understorey of hinterland ecosystems. However, this contrasts with the extensive grass and sedge-covered plains that have formed behind mangroves on both estuarine and coastal plains flanking the macrotidal systems to the east, such as the biodiverse wetlands of Kakadu National Park (Finlayson and Woodroffe, 1996). Already, incursion of tidal creeks into these plains and the establishment of mangroves is being observed, most spectacularly on the Mary River system, which has experienced remarkable extension of tidal creeks over past decades (Mulrennan and Woodroffe, 1998). Efforts to stop tidal incursion have been largely unsuccessful and mangroves have extended particularly along low-lying paleo-channels that were once formerly tidal (Miloshis and Fairfield, 2015). Similar saltwater incursion has occurred on the Alligator rivers (Woodroffe et al., 1986; Winn et al., 2001; Cobb et al., 2007). Iconic freshwater wetlands occupy these low-lying plains, and there is unlikely to be sufficient sediment deposition over most of the plains to offset the rapid salinization that can be anticipated.

Conclusions

Concepts of ‘keep up’ and ‘catch up’, which have provided a useful framework for considering response of coral reefs to sea-level changes, have broad application to mangrove shorelines. Rapid rates of postglacial sea-level rise drowned former mangrove ecosystems on the continental shelves of northern Australia. Mangrove muds beneath the coastal plain indicate that forests backstepped along the southern shore of van Diemen Gulf, with subsequent catch-up as the shoreline prograded following nearshore sediment accretion. By contrast, tidal pumping of mud into the macrotidal estuaries enabled them to accrete sediment at a sufficiently rapid rate to keep up with the final stages of the postglacial transgression. Mangroves in these more sheltered conditions were able to maintain vertical accretion and transitioned into extensive big-swamp forests as sea level stabilised.

Over most of these plains, mangroves have been replaced by freshwater wetlands as accretion has filled the intertidal accommodation space which they occupy. Rapid rates of sea-level rise will lead to a succession of mangrove communities that broadly follows a transition through upper-mid-lower within the tidal frame. Pollen evidence supports the proposition that under stable sea-level conditions the transition is lower-mid-upper, with replacement by hinterland ecosystems. Future sea-level rise will incrementally inundate the hinterland vegetation around

Darwin and Bynoe Harbours, but the low-lying plains flanking the macrotidal river estuaries are very vulnerable to rapid tidal creek extension and saline intrusion, and with prolonged sea-level rise will progressively revert to mangrove wetlands.

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References

- Akumu, C.E., Pathirana, S., Baban, S. and Bucher, D. (2011). Examining the potential impacts of sea level rise on coastal wetlands in north-eastern NSW, Australia. *Journal of Coastal Conservation Planning and Management* **15**, 15-22.
- Allen, J.R.L. (2000). Morphodynamics of Holocene salt marshes: a review sketch from the Atlantic and Southern North Sea coasts of Europe. *Quaternary Science Reviews* **19**, 1155-1231.
- Asbridge, E. and Lucas, R.M. (2016). Mangrove response to environmental change in Kakadu National Park, Australia. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* **9**, 5612-5620.
- Bird, E.C.F. and Barson, M.M. (1975). Shoreline changes in Westernport Bay. *Proceedings of the Royal Society of Victoria* **87**, 15-28.
- Brocklehurst, P.S. and Edmeades, B.F. (1996). Mangrove Survey of Darwin Harbour, Northern Territory, Australia, Technical Report. Department of Lands, Planning and Environment, 206pp.
- Brocklehurst, P. and Edmeades, B. (2003). Mangrove Survey of Bynoe Harbour Northern Territory. Department of Infrastructure Planning and Environment, Palmerston, Northern Territory. 109pp.
- Chappell, J. and Grindrod, J. (1985). Pollen analysis: key to past mangrove communities and successional changes in North Australian coastal environments, In 'Coastal and tidal wetlands of the Australian monsoon region' (Eds. K.N. Bardsley, J.D.S. Davie and C.D. Woodroffe) pp. 225-236. ANU press.
- Clark, R.L. and Guppy, J.C. (1988). A transition from mangrove forest to freshwater wetland in the monsoon tropics of Australia. *Journal of Biogeography* **15**, 665-684.
- Cobb, S.M., Saynor, M.J., Eliot, M., Eliot, I. and Hall, R. (2007). Saltwater intrusion and mangrove encroachment of coastal wetlands in the Alligator Rivers Region, Northern Territory, Australia, Supervising Scientist Report. Supervising Scientist, Darwin NT.
- Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., Guo, H. and Machmuller, M. (2009). Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. *Frontiers in Ecology and the Environment* **7**, 73-78.
- Crase, B., Liedloff, A., Vesk, P.A., Burgman, M.A. and Wintle, B.A. (2013). Hydroperiod is the main driver of the spatial pattern of dominance in mangrove communities. *Global Ecology and Biogeography* **22**, 806-817.
- Crowley, G.M. (1996). Late Quaternary mangrove distribution in Northern Australia. *Australian Systematic Botany* **9**, 219-225.
- Dickinson, W.R. (2004). Impacts of eustasy and hydro-isostasy on the evolution and landforms of Pacific atolls. *Palaeogeography, Palaeoclimatology, Palaeoecology* **213**, 251-269.
- Duke, N.C. (2006). 'Australia's Mangroves: the authoritative guide to Australia's mangrove plants'. University of Queensland Press.
- Duke, N.C., Kovacs, J.M., Griffiths, A.D., Preece, L., Hill, D.J.E., van Oosterzee, P., Mackenzie, J., Morning, H.S. and Burrows, D. (2017). Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: a severe ecosystem response, coincidental with an unusually extreme weather event. *Marine and Freshwater Research* **68**, 1816-1829.
- Finlayson, C.M. and Woodroffe, C.D. (1996). Wetland vegetation of the Alligator Rivers region, In 'Landscape and Vegetation Ecology of the Kakadu Region, Northern Australia' (Eds. C.M. Finlayson and I. von Oertzen), pp. 81-112. Kluwer, Dordrecht.

- Fontes, N.A., Moraes, C.A., Cohen, M.C.L., Alves, I.C.C., França, M.C., Pessenda, L.C.R., Francisquini, M.I., Bendassolli, J.A., Macario, K. and Mayle, F. (2017). The impacts of the middle Holocene high sea-level stand and climatic changes on mangroves of the Jucuruçu River, southern Bahia – northeastern Brazil. *Radiocarbon* **59**, 215-230.
- Geyh, M.A., Kudrass, H.-R. and Streif, H. (1979). Sea-level changes during the late Pleistocene and Holocene in the Strait of Malacca. *Nature* **278**, 441-443.
- Glick, P., Clough, J. and Nunley, B. (2007). Sea-level Rise and Coastal Habitats in the Pacific Northwest An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon. National Wildlife Federation.
- Grindrod, J. (1985). The palynology of mangroves on a prograded shore, Princess Charlotte Bay, North Queensland, Australia. *Journal of Biogeography* **12**, 323-348.
- Grindrod, J. (1988). The palynology of Holocene mangrove and saltmarsh sediments, particularly in northern Australia. *Review of Palaeobotany and Palynology* **55**, 229-245.
- Grindrod, J., Moss, P. and van der Kaars, S. (1999). Late Quaternary cycles of mangrove development and decline on the north Australian continental shelf. *Journal of Quaternary Science* **14**, 465-470.
- Hanebuth, T., Stattegger, K. and Grootes, P.M. (2000). Rapid flooding of the Sunda Shelf: a late-glacial sea-level record. *Science* **288**, 1033-1035.
- Hanebuth, T., Voris, H.K., Yokoyama, Y., Saito, Y. and Okuno, J. (2011). Formation and fate of sedimentary depocentres on Southeast Asia's Sunda Shelf over the past sea-level cycle and biogeographic implications. *Earth-Science Reviews* **104**, 92-110.
- Hopley, D., Smithers, S.G. and Parnell, K. (2007). 'Geomorphology of the Great Barrier Reef: development, diversity and change'. Cambridge University Press.
- Hubbard, D.K. (1997) Reefs as dynamic systems, In 'Life and death of coral reefs' (Ed. C. Birkeland) pp. 43-67. Chapman & Hall, New York.
- Knighton, A.D., Mills, K. and Woodroffe, C.D. (1991). Tidal creek extension and saltwater intrusion in northern Australia. *Geology* **19**, 831-834.
- Krauss, K.W., McKee, K.L., Lovelock, C.E., Cahoon, D.R., Saintilan, N., Reef, R. and Chen, L. (2014). How mangrove forests adjust to rising sea level. *New Phytologist* **202**, 19-34.
- Lambeck, K. and Chappell, J. (2001). Sea level change through the last glacial cycle. *Science* **292**, 679-686.
- Lambeck, K., Woodroffe, C.D., Antonioli, F., Anzidei, M., Gehrels, W.R., Laborel, J. and Wright, A.J., (2010). Paleoenvironmental records, geophysical modeling, and reconstruction of sea-level trends and variability on centennial and longer timescales, In: 'Understanding sea-level rise and variability' (Eds. J Church, P.L. Woodworth, T. Aarup and W.S. Wilson) pp. 61-121. Wiley Interscience.
- Lewis, S.E., Sloss, C.R., Murray-Wallace, C.V., Woodroffe, C.D. and Smithers, S.G. (2013). Post-glacial sea-level changes around the Australian margin: a review. *Quaternary Science Reviews* **75**, 1-24.
- Lovelock, C.E., Cahoon, D.R., Friess, D.A., Guntenspergen, G.R., Kruass, K.W., Reef, R., Rogers, K., Saunders, M.L., Sidik, F., Swales, A., Saintilan, N., Thuyen, L.X. and Triet, T. (2015). The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature* **526**, 559-563.
- Lucas, R., Finlayson, C.M., Bartolo, R., Rogers, K., Mitchell, A., Woodroffe, C.D., Asbridge, E and Ens, E. (2017). Historical perspectives on the mangroves of Kakadu National Park. *Marine and Freshwater Research* (in review).
- McKee, K.L., Cahoon, D.R. and Feller, I.C. (2007). Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. *Global Ecology and Biogeography* **16**, 545-556.

- Miloshis, M. and Fairfield, C.A. (2015). Coastal wetland management: A rating system for potential engineering interventions. *Ecological Engineering* **75**, 195-198.
- Montaggioni, L.F. and Braithwaite, C.J.R. (2009). 'Quaternary Coral Reef Systems: history, development processes and controlling factors'. Elsevier, Amsterdam.
- Mulrennan, M.E. and Woodroffe, C.D. (1998). Saltwater intrusion into coastal plains of the Lower Mary River, Northern Territory, Australia. *Journal of Environmental Management* **54**, 169-188.
- Murray-Wallace, C.V. and Woodroffe, C.D. (2014). 'Quaternary Sea-Level Changes: a global perspective'. Cambridge University Press, Cambridge.
- Neumann, A.C. and Macintyre, I. (1985). Reef response to sea level rise: keep-up, catch-up or give-up. *Proceedings of the 5th International Coral Reef Congress* **3**, 105-110.
- Oliver, T., Rogers, K. and Woodroffe, C.D. (2012). Measuring, mapping and modelling: an integrated approach to the management of mangrove and saltmarsh in the Minnamurra River estuary, southeast Australia. *Wetland Ecology and Management* **20**, 353-371.
- Payo, A., Mukhopadhyay, A., Hazra, S., Ghosh, T., Ghosh, S., Brown, S., Nicholls, R.J., Brichenno, L., Wolf, J., Kay, S., Lazar, A.N. and Haque, A. (2016). Projected changes in area of the Sundarban mangrove forest in Bangladesh. *Climatic Change* **139**, 279-291.
- Phan, L.K., van Thiel de Vries, J.S.M. and Stive, M.J.F. (2015). Coastal mangrove squeeze in the Mekong Delta. *Journal of Coastal Research* **31**, 233-243.
- Rogers, K., Saintilan, N. and Copeland, C. (2012). Modelling wetland surface elevation dynamics and its application to forecasting the effects of sea-level rise on estuarine wetlands. *Ecological Modelling* **244**, 148-157.
- Rogers, K., Saintilan, N. and Woodroffe, C.D. (2014). Surface elevation change and vegetation distribution dynamics in a subtropical coastal wetland: Implications for coastal wetland response to climate change. *Estuarine Coastal and Shelf Science* **149**, 46-56.
- Rogers, K., Lymburner, L., Salum, R., Brooke, B.P. and Woodroffe, C.D. (2017). Mapping of mangrove extent and zonation using high and low tide composites of Landsat data. *Hydrobiologia*.
- Russell-Smith, J.J. (1985). A record of change: studies of Holocene vegetation history in the South Alligator River region, Northern Territory. *Proceedings of the Ecological Society of Australia* **13**, 191-202.
- Scholl, D.W. and Stuiver, M. (1967). Recent submergence of southern Florida: a comparison with adjacent coasts and other eustatic data. *Geological Society of America Bulletin* **78**, 437-454.
- Siwabessy, P.J.W., Tran, M., Picard, K., Brooke, B.P., Huang, Z., Smit, N., Williams, D.K., Nicholas, W.A., Nichol, S.L. and Atkinson, I. (2017). Modelling the distribution of hard seabed using calibrated multibeam acoustic backscatter data in a tropical, macrotidal embayment: Darwin Harbour, Australia. *Marine Geophysical Research*. In press.
- Swales, A., Bentley, S.J. and Lovelock, C.E. (2015). Mangrove-forest evolution in a sediment-rich estuarine system: opportunists or agents of geomorphic change? *Earth Surface Process and Landforms* **40**, 1672-1687.
- Toscano, M.A. and Macintyre, I.G. (2003). Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ¹⁴C dates from *Acropora palmata* framework and intertidal mangrove peat. *Coral Reefs* **22**, 257-270.
- Walsh, J.P. and Nittrouer, C.A. (2004). Mangrove-bank sedimentation in a mesotidal environment with large sediment supply, Gulf of Papua. *Marine Geology* **208**, 225-248.
- Wasson, R.J. (1992). Modern sedimentation and late Quaternary evolution of the Magela Creek Plain, Research Report 6. Australian Government Publishing Service, Canberra, p. 322.

- Wells, A.G. (1995). Groupings of tidal river systems in northern Australia based on mangrove species. *Proceedings of the Linnean Society of New South Wales* **115**, 135-148.
- White, N.J., Haigh, I.D., Church, J.A., Koen, T., Watson, C.S., Pritchard, T.S., Watson, P.J., Burgette, R.J., McInnes, K.L., You, Z.-J., Zhang, X. and Tregoning, P. (2014). Australian sea levels—Trends, regional variability and influencing factors. *Earth-Science Reviews* **136**, 155-174.
- Williams, D., Wolanski, E. and Spagnol, S. (2006). Hydrodynamics of Darwin Harbour, In 'The Environment in Asia Pacific Harbours' (Ed. E. Wolanski) pp. 461-476. Elsevier, Dordrecht.
- Winn, K.O. (2001). Saltwater intrusion and morphological change at Point Farewell, Alligator Rivers Region. Supervising Scientist Internal Report 387.
- Wolanski, E. (2006). The evolution time scale of macro-tidal estuaries: Examples from the Pacific Rim. *Estuarine, Coastal and Shelf Science* **66**, 544-549.
- Wolanski, E. and Chappell, J. (1996). The response of tropical Australian estuaries to a sea level rise. *Journal of Marine Systems* **7**, 267-279.
- Woodroffe, C.D. (1990). The impact of sea-level rise on mangrove shorelines. *Progress in Physical Geography* **14**, 483-520.
- Woodroffe, C.D. (1993). Late Quaternary evolution of coastal and lowland riverine plains of Southeast Asia and northern Australia: an overview. *Sedimentary Geology* **83**, 163-173.
- Woodroffe, C.D. (1995). Response of tide-dominated mangrove shorelines in northern Australia to anticipated sea-level rise. *Earth Surface Processes and Landforms* **20**, 65-85.
- Woodroffe, C.D. (2000). Deltaic and estuarine environments and their Late Quaternary dynamics on the Sunda and Sahul shelves. *Journal of Asian Earth Sciences* **18**, 393-413.
- Woodroffe, C.D. (2003). Coasts: form, process and evolution. Cambridge University Press.
- Woodroffe, C.D. (2007). Critical thresholds and the vulnerability of Australian tropical coastal ecosystems to the impacts of climate change. *Journal of Coastal Research, Special Issue* **50**, 469-473.
- Woodroffe, C.D., Chappell, J., Thom, B.G. and Wallensky, E. (1986) Geomorphological dynamics and evolution of the South Alligator River and plains, N.T. ANU Press.
- Woodroffe, C.D., Chappell, J., Thom, B.G. and Wallensky, E. (1989). Depositional model of a macrotidal estuary and floodplain, South Alligator River, Northern Australia. *Sedimentology* **36**, 737-756.
- Woodroffe, C.D. and Mulrennan, M.E. (1993). Geomorphology of the lower Mary River plains, Northern Territory. North Australia Research Unit and Conservation Commission of the Northern Territory, Darwin.
- Woodroffe, C.D., Mulrennan, M.E. and Chappell, J. (1993). Estuarine infill and coastal progradation, southern van Diemen Gulf, northern Australia. *Sedimentary Geology* **83**, 257-275.
- Woodroffe, C.D., Rogers, K., McKee, K.L., Lovelock, C.E., Mendelssohn, I.A. and Saintilan, N. (2016). Mangrove sedimentation and response to relative sea-level rise. *Annual Review of Marine Science* **8**, 243-266.
- Woodroffe, C.D., Thom, B.G. and Chappell, J. (1985). Development of widespread mangrove swamps in mid-Holocene times in northern Australia. *Nature* **317**, 711-713.
- Woodroffe, C.D., Thom, B.G., Chappell, J., Wallensky, E., Grindrod, J. and Head, J. (1987). Relative sea level in the South Alligator River region, North Australia, during the Holocene. *Search* **18**, 198-200.

Yokoyama, Y., Purcell, A., Lambeck, K. and Johnston, P. (2001). Shore-line reconstruction around Australia during the Last Glacial Maximum and Late Glacial Stage. *Quaternary International* **83**, 9-18.

List of Figures

Figure 1. The response of mangrove shorelines to general trajectories of sea-level change. A schematic sea-level curve is shown with rapid sea-level rise, decelerating, then stabilising before a gradual fall to present. The typical response for coral reefs is shown based on the concepts outlined by Neumann and Macintyre (1985) and Hubbard (1997). Inferred responses for mangrove shorelines, as indicated by the stratigraphy of mangrove sediments (brown represents t_1 , orange t_2), are indicated on the right (after Woodroffe, 2007).

Figure 2. The Top End of the Northern Territory from Darwin to Arnhemland, showing the principal macrotidal estuarine systems of van Diemen Gulf, the distribution of mangroves, and estuarine and coastal plains, and the location of drillholes that encountered big-swamp mangrove sediments.

Figure 3. The distribution of mangroves in relation to tidal conditions: (a), the vertical range of mangroves in Darwin Harbour (generalised from Woodroffe 1995); (b) the vertical range of several of the key mangroves occurring along the South Alligator River (based on Woodroffe et al., 1986).

Figure 4. The South Alligator River coastal and estuarine plains showing locations at which big-swamp sediments have been encountered in drillholes and calibrated radiocarbon ages on mangrove remains (from Woodroffe et al, 1993). An inset of the coastal plain is shown on which probable isochrons are drawn to indicate the likely history of buildout.

Figure 5. The Mary River coastal and estuarine plain with calibrated radiocarbon ages on mangrove sediments (after Woodroffe et al., 1993).

(a) Coastal Plain

(b) Estuarine Plain

Figure 6. Pollen diagrams from cores through (a) the coastal plains, and (b) the estuarine plains of the Mary River system (see Figure 5 for location; data from Woodroffe and Mulrennan, 1993).

Figure 7. Schematised response of mangrove substrate elevation under four protracted sea-level scenarios: (a) stable sea level, under which once mangroves establish close to mean sea level (MSL), sediments accrete at a decelerating rate until the substrate is no longer inundated at a level represented by highest astronomical tide (HAT), after which mangroves are replaced by a hinterland ecosystem; (b) gradually rising sea level, whereby some mangroves may be able to establish to seaward and accrete sediments at a decelerating rate (bold line), and those establishing to landward, experience accretion that increases from slow at first (thin line), until a stable equilibrium is reached whereby accretion rate equals rate of sea-level rise. Points within the mangrove stand, for example that are already a mid community, follow a trajectory between these two lines; (c) under a faster rate of sea-level rise, a similar response occurs except that establishment of mangroves to seaward is less likely (thin line), compared with the new accommodation space generated to landward (bold line), and equilibrium involves a faster rate of accretion which is experienced at a lower position in the tidal frame;

consequently mangroves that tolerate more frequent inundation (and occur at a lower elevation in the tidal frame) persist; (d) the rate of sea-level rise is faster than accretion can occur within the mangroves and those mangroves that establish are drowned, and replaced by a shallow water ecosystem; in this case, which involves seawater intrusion into terrestrial habitats, conditions initially favour landward mangroves which are likely to be replaced by increasingly inundation-tolerant species until even these can no longer survive the repeated and persistent inundation.

Figure 8. (a) A schematic longitudinal profile through the plains flanking tidal rivers (this example is based on the Mary River system shown in Figure 6), distinguishing the estuarine plain underlain by mangrove muds most of which accreted during the 'big swamp', and the coastal plain which has prograded since sea-level stabilisation. (b) the broad pattern of sea-level change over the past 9000 years (based on calibrated radiocarbon ages; the original conventional ages are reported in Woodroffe et al., 1987). The trajectory of change in

substrate elevation, and particularly that beneath mangrove forests following the schema shown in Figure 7, is shown. The inferred pattern is shown for locations A-E, whereby mangroves initially established during the transgressive phase (as sea level was rising in the closing stages of rapid postglacial ice-melt). Within the estuary, locations A and B received sufficient sediment to be able to 'keep up' with sea level resulting in widespread mangrove in these estuaries when sea level stabilised, replaced by freshwater wetlands ~5,000 years ago. Locations C and D were inundated around 8,000 years ago, but mangrove forests back-stepped; progradation of the coast over the past 6,000 years has seen these locations 'catch up'. Location E represents the modern mangrove fringe. The inferred succession of mangroves typical of lower (green), mid (red) and upper (blue) positions within the tidal frame follows the colour scheme in Figure 7.