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State Changes in Tropical Intertidal Systems: A Palaeo-Ecological Approach

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ABSTRACT

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The aim was to review ecosystem state changes and the role of palaeo-ecological tools with application to intertidal subtropical and tropical intertidal wetlands. These systems are especially vulnerable to stress from sea-level change, climate change, and development activities. Responses to stress can lead to significant state changes with the system passing thresholds, potentially beyond recovery. Indicators of state changes and approaching tipping points include a critical slowing down following perturbation signalled by, for example, slowing recovery rates, increased attribute variance, and changed skewness. To identify such changes, data are needed for the relevant variables such as vegetation, sea level, and sediment processes so as to observe the indicative changes and their timing. Because changes may be relatively slow in ecological terms, very long-term data are needed to inform management about future likely states or thresholds so that mitigation or adaptation can be planned. One approach is to use palaeo-ecological data. These data are relatively scarce in tropical intertidal systems. This paper reviews a range of palaeo-indicators. These include state indicators (pollen, foraminifera, and diatoms), stable isotope analysis, and stratigraphy and temporal indicators involving sediment dating. Each is potentially useful, although there are uncertainties related to, for example, the redistribution organic matter in sediment cores. In conclusion, it is recommended that integrating or combining several indicators can assist in triangulating results, thereby increasing confidence in their interpretation. It is also suggested that data, if available, can be retrofitted to assess at least some of the state change indicators, such as data variance and skewness.

ADDITIONAL INDEX WORDS: Mangrove, salt marsh, stable state, pollen, foraminifera, diatom, stable isotope analysis, sediment dating, stratigraphy.

INTRODUCTION

Tropical and subtropical intertidal estuarine systems, subsequently referred to simply as tropical, at the interface between land and sea, are particularly vulnerable to sea-level changes, whether related to climate change or other causes (Millennium Ecosystem Assessment Staff, 2005). As part of estuarine systems, mangroves are major contributors to global carbon sequestration and are important for mitigating climate change, as well as being threatened by it and by other anthropogenic factors, such as coastal land development (refer to discussion in the review by Dale, Knight, and Dwyer, 2014). The state changes may be difficult or impossible to reverse, such as when an ecological threshold is passed. Once this has occurred, the system, or its function (Lindig-Cisneros *et al.*, 2003), may transition to unforeseen and unwelcome alternative states (Bestelmeyer, Goolsby, and Archer, 2011; Laurance *et al.*, 2011).

To understand and manage ecosystem change, it is necessary to identify the attributes that characterise it. This requires identifying state changes and temporal variability so as to understand the development of modern ecosystems. This has the potential to facilitate understanding of possible future shifts in ecosystem states (Barnosky *et al.*, 2012) and management to mitigate or adapt.

Long-term observation data have the potential to address this issue, but they are not available in ecologically relevant time frames using traditional field-based research. To remedy this, palaeo-ecology can provide data over very long periods that can be used for retrospective research in intertidal wetlands. This was reviewed by Dahdouh-Guebas and Koedam (2008). See also Saunders and Taffs (2009) for discussion of the role of palaeo-ecological techniques in estuarine management, including technical and institutional issues, and Tibby and Taffs (2011) specifically for palaeolimnology (with a focus on Australian estuaries and a case study of a subtropical site).

An approach is suggested here to identify alternative states, especially in tropical intertidal systems, and state changes over long time frames using palaeo-ecological tools

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Table 1. Examples of information on palaeo-ecological methods provided in the references cited.

Attribute/Variable	Reference	Comment
Biota		
Pollen	Guimarães <i>et al.</i> , 2012	Outline of method and excellent references to standard techniques and handbooks of pollen and spore morphology
Foraminifera	Anorov, 2004 Berkeley <i>et al.</i> , 2009	Details of methods in an appendix Detailed methods provided pages 65–68
Diatoms	Taylor, Harding, and Archibald, 2007	Comprehensive methods manual for collection, preparation, and analysis of diatom samples
Stable Isotope Analysis $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^{18}\text{O}$ and C:N ratio	Guimarães <i>et al.</i> , 2012	Details of method included in the text; analysis done at a laboratory using a continuous flow isotopic ratio mass spectrometer
Sediment Analysis		
Facies analysis (<i>e.g.</i> , colour, lithology, texture, and structure loss)	Hassan, 1978 Guimarães <i>et al.</i> , 2012	Clear description of variables and guide to methods Examples of facies descriptions near the mouth of the Amazon
LOI	Santisteban <i>et al.</i> , 2004	Detailed methods
MS	Marcon and Ostanina, 2012	Review of methods
Dry bulk density	Schindler <i>et al.</i> , 2014	Description of method (though not tropical)
Radioactive Sediment Dating		
^{14}C	Guimarães <i>et al.</i> , 2012	See Pollen attribute
^{210}Pb	Smoak <i>et al.</i> , 2013 Hancock <i>et al.</i> , 2011	Basic description of ^{210}Pb process Used gamma spectrometry to determine ^{210}Pb
^{137}Cs	Williams and Flanagan, 2009 Hancock <i>et al.</i> , 2011	Basic description of method Used gamma spectrometry to determine ^{137}Cs
Plutonium isotopes (^{239}Pu and ^{240}Pu)	Hancock <i>et al.</i> , 2011	Plutonium mainly determined by alpha spectrometry

that have been widely applied in other diverse systems. First, an overview of state changes in tropical intertidal systems is presented. Second, the relatively recent concept of alternative stable states in the context of tropical intertidal systems is considered. Third, to facilitate analysis of long-term trends pertinent to intertidal tropical systems, the review provides a summary of palaeo-ecological tools, referring, where possible, to applications in intertidal tropical systems. The tools include biological indicators, such as pollen, foraminifera, and diatoms; biochemical indicators, such as stable isotope analysis and geochemical indicators; and indicators of time, such as core chronology and stratigraphic characterisation. Details of the methods are to be found in the literature and are summarised with references in Table 1. Finally, it is suggested that taken together, the various approaches can potentially inform management about likely scenarios of change in dynamic intertidal environments. This will facilitate developing priorities for protecting imminently vulnerable systems and developing policies and strategies to manage precursors of state changes.

STATE CHANGES IN TROPICAL INTERTIDAL SYSTEMS

Mangroves and salt marshes are diverse and dynamic environments, and efforts to understand their patterns and processes have a relatively long history. These efforts illustrate

that state changes have occurred in the recent past and so are likely to have occurred over geological timescales. Examples include investigations of tidal inundation (Watson, 1928), salinity (De Haan, 1931), longer-term tidal patterns and investigations of the relationships between tidal patterns and species distributions (Chapman, 1944), and development of a range of zonal schemes based on dominant species distributions (Davis, 1940; Duke, Ball, and Ellison, 1998; Macnae, 1966). Early palaeo-ecological research on tropical intertidal systems found evidence of mangroves underlying a salt marsh surface and identified this as a precursor to a state change creating salt marsh (Saintilan and Hashimoto, 1999; Saintilan and Wilton, 2001).

The distribution, structure, and function of intertidal wetlands are controlled by environmental factors at a range of spatial and temporal scales. The combined effect of climate and anthropogenic change has been shown, over relatively recent time frames, to alter wetland hydrology, salinity, sediment processes, nutrient flux, and chemical pollutant inputs, leading to state changes (Eslami-Andargoli *et al.*, 2009, 2010; Nicholls and Ellis, 2002; Rogers, Saintilan, and Heijns, 2005; Williams and Meehan, 2004). Vegetation can indicate states and their changes. For example, Wang and Temmerman (2013) described how positive feedback between vegetation growth and sediment accretion can shift a bare intertidal flat to a vegetated state. In addition, recent shifts from salt marsh to mangrove observed in eastern Australia

Figure 1. Schematic representation of ecosystem states in the subtropics-tropics intertidal zone showing (A) intertidal zones and (B) state change trajectories (after Figure 7 in D'Odorico *et al.*, 2013). The three states shown are bare intertidal flat, mangrove, and salt marsh. In (B), the solid circles show the intertidal states and the patterned circles show the tipping points between states, with state change trajectories indicated by the solid black line (forming a cloverleaf shape).

have been linked to a slight increase in relative sea level, higher rainfall, and higher sediment input as a result of catchment modification (Eslami-Andargoli *et al.*, 2009, 2010; Krauss *et al.*, 2014; Saintilan and Hashimoto, 1999).

ALTERNATIVE STABLE STATES

The main advance from the relatively simple models of intertidal wetland state noted earlier to multiple or alternative stable states models is that the latter enable transition complexity to be considered and potentially managed. The concept is clearly reviewed in Moffett *et al.* (2015) in the context of global wetlands. The changes may be described as bistable, tristable, or more stable states. Research into alternative stable states in intertidal systems has been mainly carried out in temperate high-latitude areas (*e.g.*, Kirwan and Murray, 2007). Salt marsh or bare tidal flats are examples of bistable wetlands (*e.g.*, Fagherazzi *et al.*, 2006, 2012; Wang and Temmerman, 2013). Tristable state systems include the subtidal platform as a third state (*e.g.*, D'Alpaos, Da Lio, and Marani, 2012; Marani *et al.*, 2007, 2009).

Alternative bistable, tristable, or more stable state concepts can also be applied to research at lower latitudes in tropical intertidal zones, as illustrated in Figure 1. The system may be considered a tristable state of mudflats, mangroves, and salt marsh, constrained at the upper elevation by terrestrial

systems, as shown in Figure 1A. The inclusion of mangroves with salt marsh and bare tidal flats in a stable state model is illustrated in Figure 1B. The state line (solid black cloverleaf-shaped line) extends from each of the three states (grey filled circles: intertidal flat, mangrove, and salt marsh) through a transition, potentially crossing a threshold (patterned circles) to either of the other states. Examples include Eslami-Andargoli *et al.* (2010), which although not specifically referring to alternative bistable states, identified a positive feedback mechanism in which the proportion of mangrove forest adjoining salt marsh positively affected mangrove encroachment into the salt marsh, resulting in a state change. In addition, Dale and Dale (2002) identified, at the microscale, state changes over 14 years that showed both bistable state characteristics (tropical salt marsh to mud and back) and apparently irreversible state changes over a spatial extent of less than 1 ha (from salt marsh to bare mud, possibly passing a threshold).

EARLY-WARNING SIGNALS

Early-warning signals are needed if efforts to manage environmental change have a chance of success. Some early-warning signals have been developed theoretically, though they have not been applied in a long time frame in tropical intertidal systems. These use stochastic features in time

series data sets, whereby patterns in the data over time indicate changes in the ecosystem that may not be otherwise apparent (Carpenter *et al.*, 2011). A prerequisite is that the variables observed are relevant to the states that are being modelled. Critical slowing down is one indicator, which occurs in most nonlinear transitions when the regime shift is gradual. A state change point may occur when an ecosystem becomes increasingly slow in recovering from small perturbations (Scheffer *et al.*, 2009). This requires detailed knowledge of the behaviour of the indicative parameter or parameters. Signals that can be explained by critical slowing down include slower recovery rates, an increase in autocorrelation and in the variance of the system's state variable, changes in the pattern of skewness, and self-organised patchiness (Carpenter and Brock, 2006; Dakos *et al.*, 2008; Scheffer *et al.*, 2009). However, empirical evidence for these indicators is rare and so is not incorporated into management. An example of an application of early-warning indicators and a summary of current limitations are provided in Eslami-Andargoli *et al.* (2015), in which an existing 20-year salt marsh data set was retrofitted, demonstrating some indicators, such as declining mean values (slowing down), data variance, and skewness, using simple vegetation attributes.

In summary, research on the existence of alternative stable states and application of early-warning indicators has been constrained by a lack of long-term studies. In a recent review paper, Moffett *et al.* (2015) referred to long-term assessment of multiple stable states in coastal wetlands using remote sensing. Although of undoubted value for monitoring and identifying relatively recent changes, it cannot be used for very long time frames. This limitation may be overcome by applying palaeo-ecological tools to identify environmental change, thereby providing information on alternative stable states, rates of change, and possible triggering mechanisms (Perry, Berkeley, and Smithers, 2008; Willis *et al.*, 2010).

IDENTIFYING PAST COASTAL WETLAND STATES FROM PALAEO-ECOLOGICAL DATA

Study of the palaeo-ecological record can provide multiproxy data to identify changes occurring over long periods, before direct observation was possible (Birks and Birks, 2006). These data have potential to indicate the progress of change as it occurs, identifying potential early-warning signals. Much of the research has used pollen analysis, because pollen is directly linked to vegetation (*e.g.*, Aragón-Moreno, Islebe, and Torrescano-Valle, 2012; Crowley *et al.*, 1990; Crowley and Gagan, 1995; do Amaral *et al.*, 2006; Ellison, 2008; González and Dupont, 2009; Grindrod, Moss, and Kaars, 1999; Guimarães *et al.*, 2012, 2013; Horton *et al.*, 2005; Urrego *et al.*, 2013). Other studies have used a combination of stable isotopes, sediment dating, and stratigraphy to identify habitats and to date the sediments (Cohen, Behling, and Lara, 2005; Cohen *et al.*, 2012, 2014; Monacci *et al.*, 2009, 2011; Woodroffe, 1981).

The following sections consider the identification of past ecosystems and their change based on a range of palaeo-indicators, including pollen, foraminifera, and diatoms; stable isotope analysis; sediment stratigraphy; and radioactive sediment dating.

Pollen

Pollen is useful as an indicator of vegetation assemblages. Pollen has a hard coating and can persist in the substrate for thousands of years. It can provide information about the history of vegetation dynamics applicable to mangroves. This was reviewed in Ellison (2008). In several studies, palynology has provided insight into transition phases of mangrove and salt marsh while also providing detailed information on the specific taxa present during transitions (Cohen *et al.*, 2012; do Amaral *et al.*, 2006; França *et al.*, 2012, 2013, 2014; Grindrod, 1985, 1988; Guimarães *et al.*, 2012, 2013; Monacci *et al.*, 2009, 2011; Pessenda *et al.*, 2008, 2012; Smith *et al.*, 2011, 2012). For example, Monacci *et al.* (2011) used pollen analysis, showing that reduced *Rhizophora* and increased *Avicennia* were related to decreased sedimentation rates in Belize. It perhaps follows that sedimentation rates may provide an early warning of mangrove state change.

Foraminifera

Foraminifera have potential to indicate sea level and ocean warming. Foraminifera are ubiquitous across coastal and marine environments and comprise an extensive taxa of planktic and benthic species (epifaunal and infaunal), most of which have a carbonate shell (or test) that persists through burial in sediment and conversion into the fossil record extending back more than 500 million years (Van der Zwaan *et al.*, 1999). In their review, Van der Zwaan *et al.* (1999) found that foraminifera were limited as proxies for palaeo-environmental reconstructions, because they tolerate only a narrow range for most variables. Nevertheless, they found that oxygen and oxygen flux, which are of significant ecological importance, affect patterns of foraminiferal distribution and are therefore proxies of redox state (and anoxia). Furthermore, Berkeley *et al.* (2007) noted that processes of decay may affect buried foraminifera differentially. This could make interpretation difficult. However, foraminiferal assemblages have been widely used as proxies for identifying palaeo-environments and for providing high-resolution indicators of sea-level variation because of similarities between living assemblages and those in the fossil record (Berkeley *et al.*, 2007, 2009; James and Bone, 2007; Wang and Chappell, 2001; Woodroffe *et al.*, 2005). Woodroffe *et al.* (2005) suggested that the contemporary foraminiferal assemblages that were related to sea level found in Australian mangrove systems had potential to be used in fossil cores to identify past sea-level changes. Changing patterns in foraminiferal distribution could potentially provide information that indicates changing conditions. Relevant to current concerns about ocean warming, James and Bone (2007) also found a relationship between foraminiferal assemblages and past changes in ocean temperature. Given the issue of reliability, further research is needed in tropical intertidal systems, as concluded by Laut *et al.* (2016) in their research on foraminifera and pollution in Brazilian estuarine systems.

Diatoms

Diatoms are potentially useful indicators of disturbance and thus indicative of state changes. Diatoms are a group of algae that have a cell wall composed of silica, making them long lasting. For details of methods, refer to Taylor, Harding, and Archibald (2007). Reconstructing sedimentary environments

from diatoms in clastic deposits was codified by Vos and Wolf (1993), who used seven environmental codes (life form, salinity, pH, nutrient content, temperature, tides, and currents) to construct a list of the most common diatom species within Holocene coastal deposits. A relatively recent review paper identified the potential use of diatoms (as well as of other indicators) in the palaeolimnology of Australian estuaries, citing research in a subtropical environment (Tibby and Taffs, 2011). However, the authors also pointed out that diatom data are scarce in Australia, especially in estuaries. Although assemblages for tropical areas may not be known, the technique used in temperate areas could be applied to tropical situations (Vos and van Kesteren, 2000). Diatoms have been used to assess the effects of disturbance and land management, showing that diversity was affected by disturbance (Chipps *et al.*, 2006; Pan *et al.*, 2004), and to assess risk (*e.g.*, the review by Stevenson, 1998). These two studies were not in tropical or intertidal systems, because there is a paucity of diatom information for those areas. Nevertheless, diatoms have potential to elucidate environmental conditions that in turn may contribute to driving change.

Stable Isotope Analysis ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^{18}\text{O}$) and C:N Ratio

Stable isotopes can provide proxies of past physiology and ecosystem structure (Monacci *et al.*, 2009). The commonly used ones (given later) have some limitations but together have the potential to provide useful information about state changes. Carbon is a commonly used tool. For example, carbon isotope composition ($\delta^{13}\text{C}$) and the ratio of organic carbon to total nitrogen (C:N) in bulk organic sediments can provide information about the origin of organic matter and the abundance of various types of biota that produced it (Guimarães *et al.*, 2012; Lamb, Wilson, and Leng, 2006). There are diverse, isotopically distinct sources of organic carbon in intertidal wetland sediments, including C_3 and C_4 photosynthetic plants and marine and freshwater phytoplankton. For intertidal wetlands, the mangroves (Monacci *et al.*, 2011) and salt marsh halophytes provide C_3 inputs, while salt marsh grass species provide C_4 inputs (Adam, 1990). The approach has been usefully summarised by Guimarães *et al.* (2012), showing indicative values for C_3 and C_4 and for C:N ratios. Some studies used atomic elemental ratios of nitrogen to carbon (N:C) rather than the C:N ratios (Goñi, Teixeira, and Perkey, 2003; Monacci *et al.*, 2011), mostly because source mixing calculations for N:C are simpler and more precise than for C:N ratios (Perdue and Koprivnjak, 2007). A recent application that identified vegetation change and conservation management in southern Africa (not intertidal) was reported in Gillson (2015).

However, decomposition processes and the influence of transported sediment may inhibit accurate distinction of organic carbon sources and thus the reconstruction of palaeoenvironments (De la Rosa *et al.*, 2012; Lamb, Wilson, and Leng, 2006). To overcome these potential issues, other tracer techniques can be applied, because they are often source specific (De la Rosa *et al.*, 2012; Kemp *et al.*, 2010).

Identifying $\delta^{15}\text{N}$ values in plant remains can indicate variations in the source of nitrogen in sedimentary environ-

ments. In addition, the isotopic differences of nitrogen and carbon in plant leaves can indicate past physiological changes in specific species (McKee *et al.*, 2002; Monacci *et al.*, 2009; Wooller *et al.*, 2003). However, nitrogen in plant subfossils can be changed by microbial and invertebrate or nitrogen immobilisation during the decomposition process. For example, a peak in $\delta^{15}\text{N}$ in intertidal wetlands (which are usually nitrogen limited) could indicate a nitrogen source such as bird droppings or, more recently, pollution from urban sewage or agriculture (Monacci *et al.*, 2009; Wooller *et al.*, 2003, 2007). This restricts the use of nitrogen isotopes alone for palaeo-ecological reconstruction unless nitrogen has been preserved in tannin rich or anoxic sediments, such as in many mangrove systems (Wooller *et al.*, 2003).

Oxygen isotopes ($\delta^{18}\text{O}$) also can be used to reconstruct palaeo-environments. The $\delta^{18}\text{O}$ of the available water is the primary factor controlling the $\delta^{18}\text{O}$ compositions of organic matter in plant leaves. The $\delta^{18}\text{O}$ value of ocean water is higher than that observed in coastal rainfall. This isotopic difference can be reflected in the $\delta^{18}\text{O}$ values of coastal vegetation, with higher associated values if the source water is composed of a greater proportion of seawater relative to precipitation (Monacci *et al.*, 2009; Wooller *et al.*, 2007). Therefore, it has been suggested that $\delta^{18}\text{O}$ of mangrove subfossils can be used as an indicator of the $\delta^{18}\text{O}$ of past surface waters and sea-level change (Sternberg and Swart, 1987; Swart *et al.*, 1989; Wooller *et al.*, 2007).

Sediment Analysis

Facies analysis (*e.g.*, description of colour, lithology, texture, and structure loss), as well as loss on ignition (LOI), magnetic susceptibility (MS), and dry bulk density can be used to investigate the changes in the stratigraphic characteristics of sediments. The LOI can determine the contribution of biogenic deposition (organic material and calcium carbonate) and lithogenic deposition (residual material, noncarbonate or inorganic) to sediment accretion in intertidal wetlands over recent and prehistoric timescales (Heiri, Lotter, and Lemcke, 2001; Monacci *et al.*, 2011; Watson *et al.*, 2011). The MS measures the 'magnetisability' of sediment and can be used to indicate the potential sediment source areas. For example, Watson *et al.* (2011) suggested that the near-surface increase in MS at their California study sites (temperate) was related to increased oxidised iron from upland areas and was related to land use. Schindler *et al.* (2014) described a cost-effective method for measuring dry bulk density as an effective indicator of sediment processes and vertical accretion that is relevant to sea-level changes. Although the subject area was in the Netherlands, the method would be applicable to other areas, including tropical ones.

Radioactive Sediment Dating

Sea level is a critical driver of mangrove communities, and most of the palaeo-ecological evidence reviewed here identified past sea levels and the associated vegetation or state of the landscape, showing state changes. As an example, Seddon *et al.* (2011), using carbon dating and stable carbon isotopes, found a decrease in relative sea level and a transition from mangrove to bare land in the Galapagos. Further examples are provided in Table 2.

Table 2. Examples of coastal intertidal wetland state changes during transgressive and regressive phases.

Marine Phase	State Change	Core Location	Date (cal YBP)	References
Transgressive	Mudflat to mangrove	Spanish Lookout Cay, Belize	8000	Monacchi <i>et al.</i> , 2009
		Twin Cays, Belize	8000	Wooller <i>et al.</i> , 2007
		North Australian continental shelf	14000	Grindrod, Moss, and Kaars, 1999
		Doce River mouth, SE Brazil	7400–5100	Cohen <i>et al.</i> , 2014
		Island of Marajo, Amazon River	7500–3200	Franca <i>et al.</i> , 2014
	Mudflat to salt marsh	Cariaco Basin, Venezuela	Several times during 60000–25000	González and Dupont, 2009
Regressive	Salt marsh to mangrove	Rufiji floodplain, Tanzania	14800	Bouimetarhan <i>et al.</i> , 2015
		Guajira Peninsula, Colombia	6000–4000	Urrego <i>et al.</i> , 2013
		Doce River mouth, SE Brazil	1313–1405	Cohen <i>et al.</i> , 2014
	Mangrove to salt marsh			

cal = calibrated.

Radioactive sediment dating estimates the time since an event occurred or deposition of an attribute and can be used to estimate the rate of sediment accumulation. Radioactive dating is usually based on a comparison between the concentration of a radioisotope and its decay isotope, using a known decay rate (half-life). Frequently used radioisotopes that provide high-resolution dating are likely to be of use in identifying change in intertidal wetlands, include carbon-14 (^{14}C) and lead-210 (^{210}Pb). Distinctive temporal markers that are characteristic of defined periods can also be used and include radionuclides derived from atomic testing caesium-137 (^{137}Cs) and plutonium isotopes (^{239}Pu and ^{240}Pu). Hancock *et al.* (2011) reviewed and compared ^{210}Pb , ^{137}Cs , and ^{239}Pu and ^{240}Pu methods in an Australian context.

With a half-life of 5715 years, ^{14}C has been widely used to determine the age of organic materials up *ca.* 50,000 years old. The ^{14}C concentration in living organisms is constant. After the organism has died, the concentration of ^{14}C decreases through radioactive decay, enabling the date when the organism was alive to be estimated. A limitation for using ^{14}C techniques occurs with material produced in the last 50 to 100 years because of inaccuracy resulting from artificial ^{14}C produced by atomic testing and ^{14}C emitted from industrial activity.

Lead-210 (half-life = 22.2 y) is part of the uranium decay series and is continually being renewed in the environment. For details of its decay, see Appleby and Oldfield (1978). Lead-210 is particularly useful for deriving high-resolution age by depth profiles in rapidly accreting environments common to coastal wetlands, particularly in an environment of rapid sea-level rise. Recent applications of ^{210}Pb dating in intertidal systems include Sanders *et al.* (2012) and Smoak *et al.* (2013), both investigating sediment accretion in mangrove forests related to sea-level rise.

Caesium-137 is present in the environment because of fallout from atmospheric nuclear weapons testing that commenced in 1945, peaked in 1963–64, and then diminished subsequently. As such, ^{137}Cs has been widely used since the 1970s to provide a chronomarker of known age in sediment corresponding to its first appearance in 1954–55, providing an independent validation for ^{210}Pb . However, ^{137}Cs (with a relatively short 30.02-y half-life) has become scarce as radioactive decay has continued since the bomb-testing era. There is little reported application of ^{137}Cs in intertidal wetlands. Two relatively recent studies include those of Wang, Gao, and Ja (2006), which modelled tidal flat sediment accretion on the Jiangsu coast, China, and Williams and Flanagan (2009), which found that

storm surges accounted for a large proportion of long-term sedimentation in Louisiana coastal marshes.

Plutonium isotopes ^{239}Pu and ^{240}Pu have half-lives of thousands of years (24,000 and 6563 y, respectively) and so offer persistent chronomarkers, ideally of peak concentrations corresponding to the peak fallout period (~1963) and not present before 1945. Plutonium-239 is an alternative approach that may be more reliable than ^{137}Cs (Hancock *et al.*, 2011). However, Pu analysis is comparatively expensive. Three studies have been identified in which Pu has been analysed in sediment cores from estuarine environments: Sanders *et al.* (2010) analysed sediment from an intertidal mangrove mudflat in SE Brazil, Alonso-Hernández *et al.* (2012) analysed a sediment core extracted at a water depth of 6 m adjacent to a mangrove forest in coastal Cuba, and Pan *et al.* (2011) analysed mud deposited in the Yangtze River estuary, China, in 14 m of water 40 km east from the coast. The pattern of Pu activity in the three studies was similar, with relatively uniform Pu throughout the section of core where Pu was present; that is, none exhibited an unambiguous 1963 peak deposition date useful as a chronomarker.

The various studies highlight a limitation of dating techniques. Sediments deposited in complex depositional environments with disturbances, bioturbation, resuspension, or erosion processes operating may not result in chronologically meaningful records. For example, the accuracy of dating approaches combined with possibly poor preservation of older strata (*e.g.*, the Sadder effect; Sadder, 1981) means that more recently changed coastal wetland system states will be more easily identified and could distort interpretation unless this is taken into account. Other limitations for using chronomarkers stem from the need to corroborate date by depth profiles with independent dating evidence.

DISCUSSION

Alternative stable state concepts offer opportunities to consider options that are not constrained to a linear unidirectional transition and provide a new paradigm for restoration activity in intertidal wetlands. For example, this could be by taking action to reverse a state change through applying pressures to the driver of change or breaking positive feedback loops by major interventions.

Palaeo-ecological data are potentially important sources of information for examining alternative states in intertidal coastal wetlands over geological time. This establishes the long-term range of potential states defining the pre-anthro-

pogenic baseline condition and thresholds at regional or local scales (Watson *et al.*, 2011). This type of information is useful for considering which combinations of biotic and abiotic processes are likely to result in ecological resilience or whether a system is approaching a threshold (Seddon *et al.*, 2011; Willis *et al.*, 2010). Caution is needed when using palaeo-ecological data for studying contemporary responses because of the differences in scales (both temporal and spatial) between contemporary data collected from existing ecosystems (potentially spatially unconstrained and constrained to a relatively short time frame) and palaeo-ecological data (spatially confined, such as with coring sites, but with a relatively unconstrained time frame; Bennington *et al.*, 2009). Given the dynamic nature of intertidal wetlands, extracting a high-resolution temporal record from palaeo-ecological data can also be challenging because of biotic and abiotic disturbances and redistribution of materials (Grindrod, 1988). Nevertheless, according to Perry, Berkeley, and Smithers (2008), state changes can be identified at a geological timescale. In addition, environmental reconstructions using biomarkers, such as pollen, foraminifera, and diatoms, need to be interpreted in the light of ecological and taphonomic factors (origin, burial, decay, and preservation) that affect assemblages in sediments and in the fossil record (Berkeley *et al.*, 2007; Chappell and Grindrod, 1985; Ellison, 2008; Lamb, Wilson, and Leng, 2006; Sherrod, 1999; Wang and Chappell, 2001). These factors are also critically important when examining palaeo-environmental variables, such as salinity or past tide level, from diatom and foraminiferal assemblages (Grenfell *et al.*, 2012; Haynes *et al.*, 2011; Tibby and Taffs, 2011).

A key aspect of understanding state changes and thresholds identified in palaeorecords is determining when they occurred. An important aspect of dating with respect to state changes is determining the speed of change (*e.g.*, decades, years, or millennia). In addition, it may be important to understand the length of time over which a system exists in a particular state before tipping into a new state. Many dating techniques have been applied to wetlands, including ^{14}C , ^{210}Pb , and ^{137}Cs . These techniques are generally complementary, because they provide dating over different timescales.

The limitations of each method can be minimised by integrating evidence from several sources to provide triangulation and to corroborate the interpretation of results. For example, combining pollen data with stable isotope analysis to track past changes in vegetation composition and structure (Cerling *et al.*, 1997; Ficken *et al.*, 2002; Wooller *et al.*, 2003) can mitigate some of the uncertainty of pollen assays. The transdisciplinary approach of Dahdouh-Guebas and Koedam (2008) is a well-developed approach that includes social aspects, which are important for management.

CONCLUSION

Because intertidal areas are vulnerable to climate change, sea-level rise, and anthropogenic factors, it is a priority to identify the past record of state changes to establish base information from which to extrapolate to current situations and to develop management strategies to maximise sustaining ecosystem services into the future. Although palaeo-ecological

data have the capacity to provide information for testing the applicability of early-warning indicators of regime shift, their application to intertidal wetlands is challenging given the dynamic nature and potential confounding of the record. However, there may be some existing data that could be retrofitted to assess at least some of the indicators, such as data variance and skewness. In addition, taking a multiproxy integrative approach that tests the combinations of indicators to ascertain the optimal combinations would be useful for applying to the scarcer data available for the focus here—the intertidal landscape.

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