

## Review

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# The present, past and future of blue carbon

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## Abstract

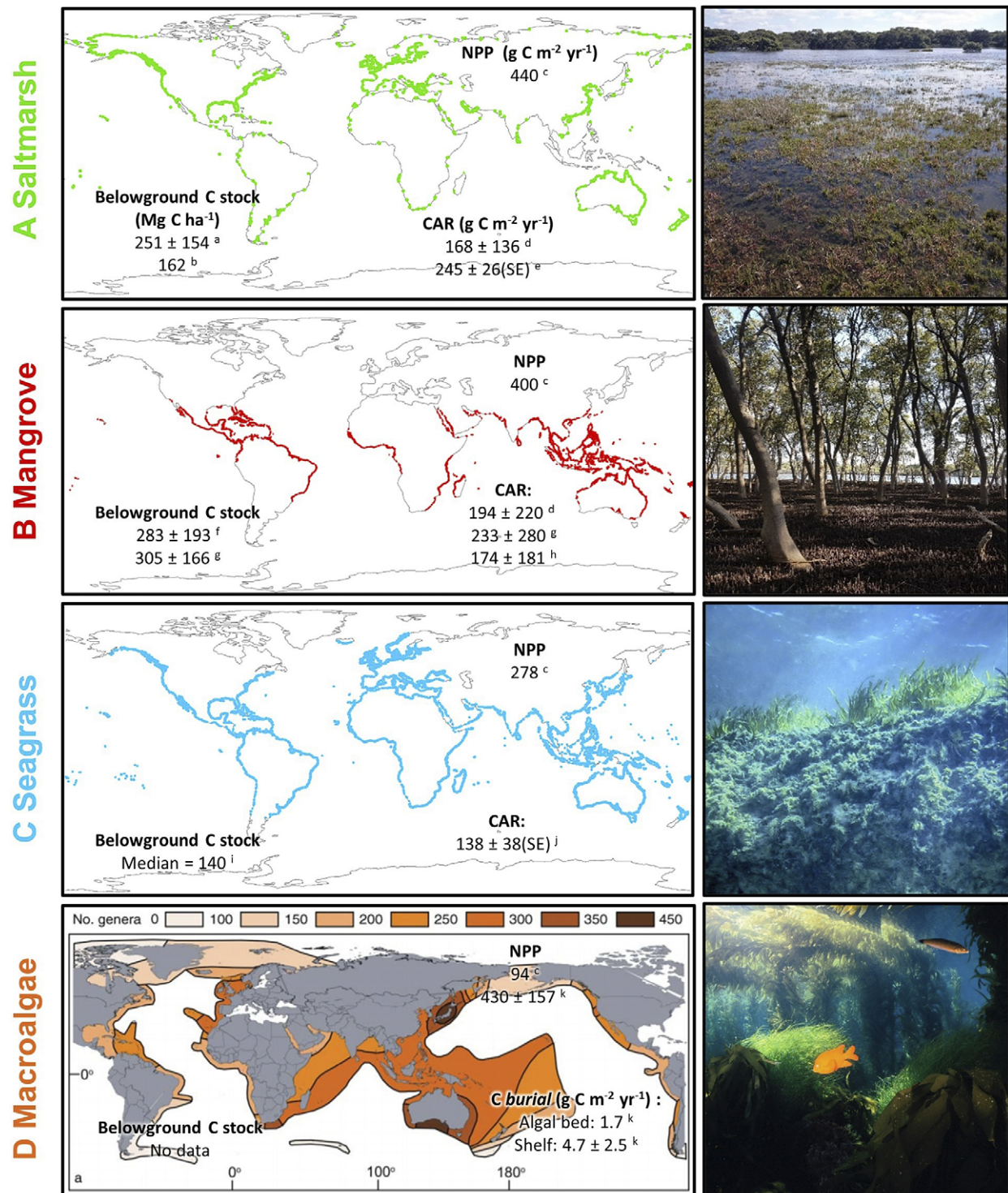
Blue carbon is identified as a natural climate solution as it provides multiple ecosystem services, including climate mitigation, adaptation, and other co-benefits. There remain ongoing challenges for blue carbon as a natural climate solution, particularly as blue carbon ecosystems are at risk from climate change. Concepts of uniformitarianism were applied to consider how the present and past behaviour of blue carbon ecosystems can inform decision-makers of blue carbon risks. Climate change may increase the capture and storage of blue carbon in the short to medium term; this is largely due to negative feedbacks between elevated atmospheric carbon dioxide and temperature, and supplemented by natural processes of sediment supply and accumulation. Opportunities for retreat and increasing carbon storage as sea levels rise are likely to be greater where sea level has a longer history of relative stability, largely in the Southern Hemisphere. Landward retreat will be crucial where millennia of sea-level rise have limited the capacity for in situ blue carbon additionality; this may be thwarted by highly developed coastal zones and coastal squeeze effects. Negative feedbacks may fail under higher emissions, greater warming and rates of sea-level rise exceeding  $\sim 5\text{--}7\text{ mm yr}^{-1}$ ; this tipping point may be surpassed within the next century under a high emissions scenario. Retreat of blue carbon ecosystems to higher elevations where they are afforded protection from the effects of sea-level rise will be critical for blue carbon additionality. Carbon markets are prepared to incentivise restoration of blue carbon ecosystems as they adapt to climate change; however, knowledge gaps remain, particularly regarding the behaviour of blue carbon ecosystems in the global south. Given the momentum in blue carbon research, scientists and practitioners are well placed to continue addressing blue carbon risks.

## Impact statement

The role of coastal ecosystems in sequestering atmospheric carbon has been demonstrated and efforts are underway to leverage this service for climate change mitigation. Focussing largely on mangroves and saltmarshes, this paper applies concepts of uniformitarianism to consider how the present behaviour of blue carbon ecosystems (BCEs), and their response to varying sea level and climate change in the past, provides knowledge of BCE futures. There is evidence BCEs are being modified by climate change, and losses are compounded by ongoing clearance and degradation. Consequently, atmospheric warming, sea-level rise and human modifications have important implications for greenhouse gas fluxes from BCEs. Observations of the response of BCEs to sea-level rise indicate some capacity to adapt by accumulating mineral and organic material and increasing substrate elevations. Contributions of organic matter to substrates as sea level rises, coupled with landward retreat of BCEs to maintain their intertidal position, bolsters capacity to sequester atmospheric carbon within substrates and biomass. However, evidence of the response of mangroves and saltmarshes to sea-level rise over the Holocene indicate a threshold for adaptation that is exceeded when sea-level rises at  $\sim 5\text{--}7\text{ mm yr}^{-1}$ . This rate of sea-level rise is anticipated to be surpassed by the end of the 21<sup>st</sup> century unless deep cuts to atmospheric carbon concentrations occur rapidly. Accordingly, the fate of BCEs remains uncertain. However, it is probable mangrove forests and saltmarshes high in the tidal frame will transition towards lower tidal positions as sea level rises and may survive for some time, offering some confidence when trading carbon with a 25-year permanence timeframe. Landward retreat will be critical for blue carbon additionality, and this will require concerted management to minimise coastal squeeze and preserve BCE services. This uncertainty should be accommodated when considering the permanence of blue carbon in financial markets.

## Introduction

Blue carbon is a collective term referring to the carbon associated with marine and coastal ecosystems, and includes all fluxes and stores that are biologically driven (Bindoff et al., 2019). Similar to carbon sequestered in terrestrial forests, blue carbon has piqued the interest of practitioners seeking to mitigate climate change by enhancing carbon storage within natural



**Figure 1.** Global mapped distribution and existing estimates of carbon cycling parameters of (A) saltmarsh and (B) mangrove; (C) modelled distribution of seagrass; and (D) genus richness of benthic marine macroalgae. All values are global mean values  $\pm 1$  standard deviation (where available) unless otherwise specified. Belowground carbon stocks are estimated to 1 m depth. CAR = (surface) carbon accumulation rate; NPP = net ecosystem primary productivity; SE = 1 standard error. Note that for macroalgae, CAR is replaced by estimates of carbon burial in situ (i.e. in algal beds) and exported particulate organic carbon buried in shelf sediments. Map data sources: saltmarsh (Mcowen *et al.*, 2017); mangrove (Bunting *et al.*, 2018); seagrass (Jayatilake and Costello, 2018); macroalgae (Kerswell, 2006). Carbon data sources: a (Rogers *et al.*, 2019a); b (Pendleton *et al.* 2012a); c (Duarte and Cebrían, 1996); d (Wang *et al.*, 2021); e (Ouyang and Lee, 2014); f (Atwood *et al.*, 2017); g; h (Alongi, 2012); i; j (McLeod *et al.*, 2011); k (Krause-Jensen and Duarte, 2016).

ecosystems and improving the provision of ecosystem services (Macreadie *et al.*, 2021). This interest is based on the high carbon storage potential of many blue carbon ecosystems (BCEs), a potential that is reported to be much higher on a unit area basis than other

ecosystem-based climate solutions (Donato *et al.*, 2011; Pendleton *et al.*, 2012; Duarte *et al.*, 2013). BCEs are typically vegetated with mangroves, saltmarshes (also termed tidal marshes) and seagrasses, and to a lesser extent macroalgae, cyanobacteria and supratidal

forests (Duarte et al., 2013; Raven, 2018; Bindoff et al., 2019; Lovelock and Duarte, 2019) (Figure 1). Carbon is drawn from the atmosphere via photosynthesis and stored within living biomass at a concentration of 40–50% of the mass, a value that is reasonably consistent among plants (Ma et al., 2018). Blue carbon is partitioned into above- and below-ground biomass and the soil carbon pool. Above-ground biomass is typically estimated from allometric equations, initially derived from destructive measurements that relate vegetation structure to mass (Thursby et al., 2002; Komiyama et al., 2008; Radabaugh et al., 2017), or by applying remote sensing techniques to extrapolate spatial relationships (Pham et al., 2019; Sani et al., 2019). The below-ground component is somewhat more difficult to quantify as substrates contain both living biomass and dead organic material that has accumulated over decades to thousands of years, as evident from radiocarbon dating of BCEs (Horton et al., 2018; Saintilan et al., 2020; Sefton et al., 2021).

The enhanced capacity for storage is dependent upon rates of carbon addition exceeding loss of carbon via the decomposition of organic material, and there is increasing agreement that this should also exceed in situ carbonate production (Saderne et al., 2019). High net primary production from in situ vegetation underpins the supply of organic matter to substrates, mostly from root material (Saintilan et al., 2013; Xiong et al., 2018). However, organic matter transported on tides can also become trapped and sequestered into substrates, and there is an increasing need to discriminate the varying role of autochthonous and allochthonous sources (Saintilan et al., 2013; Canuel and Hardison, 2016; Van de Broek et al., 2018; Macreadie et al., 2019). Periodic inundation by saline tidal waters creates anaerobic conditions in saturated substrates that suppress microbial activity and slow the decomposition of sequestered organic material (Duarte et al., 2013; Spivak et al., 2019). Addition of mineral sediments supplied by tides serves to trap sequestered organic material (Spivak et al., 2019) and saline substrates hamper methanogenic processes (Poffenbarger et al., 2011). While greenhouse gas emissions are not fully suppressed (Rosentreter et al., 2018), the general outcome is physicochemical conditions that favour slow decomposition of organic material, long-term preservation of a portion of fixed carbon within substrates, and limited release of powerful greenhouse gases (e.g. methane and nitrous oxide) to the atmosphere (McKee et al., 2007; McLeod et al., 2011; Kroeger et al., 2017). Storage may be further enhanced when coastal processes operate to ensure that space within substrates for carbon storage continues to be available, and this appears to be strongly influenced by rates of sediment supply, sedimentation, and coastal evolution in the context of changing sea levels (Rogers et al., 2019a). Together these conditions mean that BCEs can store orders of magnitude more carbon within their substrates than other terrestrial ecosystems, estimated to be in the order of 0.4–6.5 Pg. C in the upper 1 m of saltmarsh substrates globally, 9.4–10.4 Pg. C for mangrove forest substrates and 4.2–8.4 Pg. C for seagrass substrates (Duarte et al., 2013).

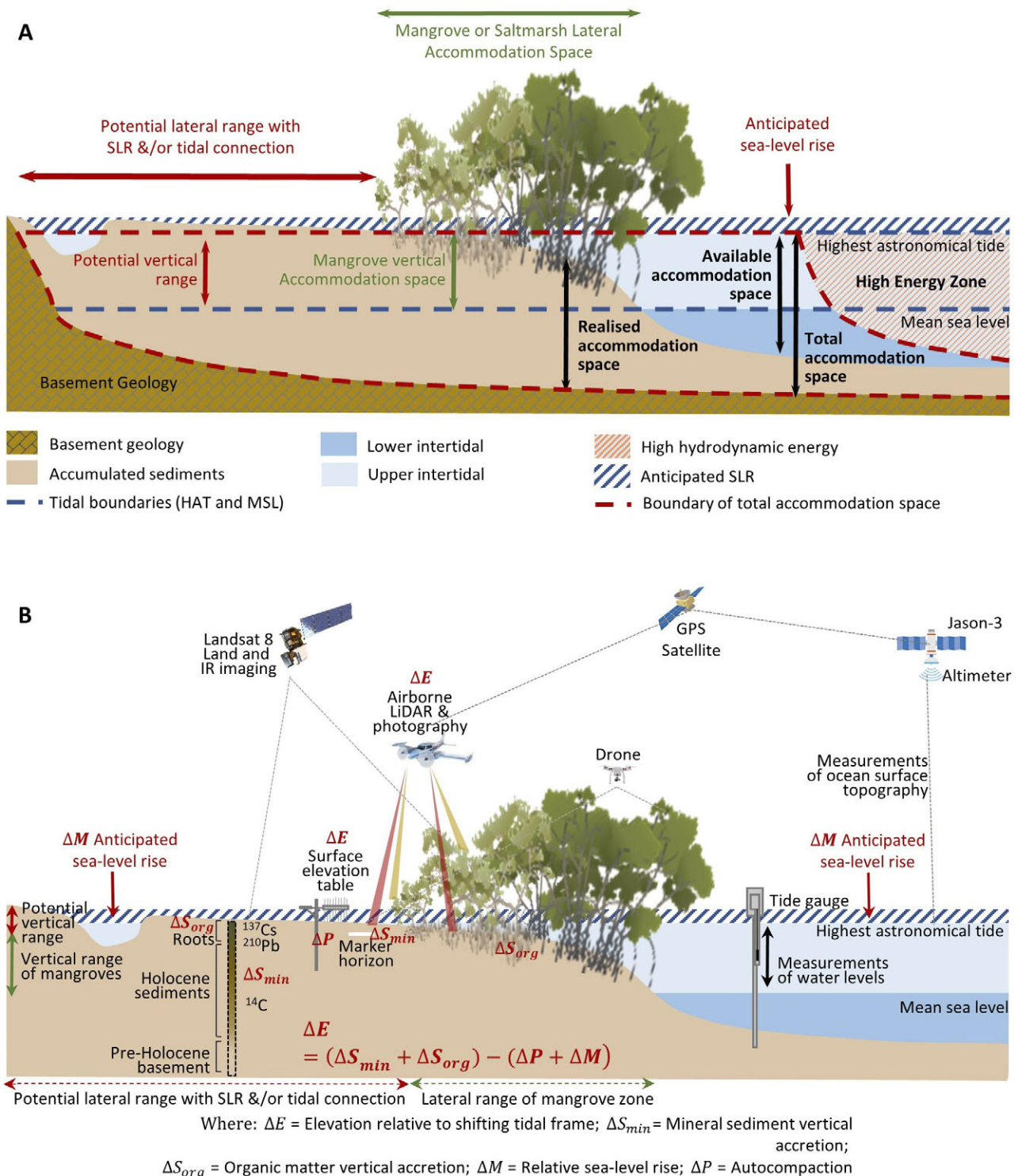
Estimates of carbon storage in BCEs are typically determined based on their current distribution. At the coarsest level, a central measure (e.g. mean, median) of carbon concentration is multiplied by BCE extent to estimate carbon storage in various components (above- and below-ground biomass, soil carbon pool) (Howard et al., 2014). As can be seen in Figure 1 such projections to a global scale will be subject to large uncertainties associated with the high variability, across multiple spatial scales, in estimates within each ecosystem type; spatial biases in data availability also influence confidence in global projections.

In spite of this increasing recognition of spatial and temporal variation in carbon storage, it is probable that additional soil organic carbon originating from BCEs is preserved within coastal floodplains and on continental shelves where conditions are now no longer favourable for BCEs, but where long-term preservation may have occurred over millennia as coastal landscapes evolved (Hanebuth et al., 2000; Grindrod, 2002; Rogers et al., 2019b). Additionally, there is also an imprint of direct human impacts on BCEs, with losses largely due to land cover change and gains largely due to restoration activities leading to a net decline in tidal wetland extent (inclusive of tidal flats, mangrove forests and tidal marshes) of ~4,000 km<sup>2</sup> between 1999 and 2019 (Murray et al., 2022). There is evidence that this rate of loss is diminishing (Friess et al., 2020; Campbell et al., 2022) and substantial gains to tidal wetland extent, in the order of 9,700 km<sup>2</sup>, have been related to the success of restoration activities and natural expansion (Friess et al., 2019; Murray et al., 2022). Accordingly, the current distribution of BCEs indicates where current storage and additionality occurs but does not indicate storage that occurred prior to changes in land cover at millennia timescales or over the record of Earth observations. This has important implications for the future of blue carbon, and it is probable that the geographic distribution of BCEs will continue to change as sea level rises, coasts evolve, and humans living in the coastal zone adapt to a new configuration of the coast and BCE distribution.

To characterise the future of blue carbon as a natural climate solution, we apply concepts of uniformitarianism to consider how the contemporary distribution and behaviour of blue carbon can inform our understanding of the long-term evolution of coastal carbon storage. In this regard, we consider processes that influence blue carbon over the observational record (i.e. the present) are the same as those that have operated for millennia (i.e. the past), and, by extrapolation, consider blue carbon futures. We specifically consider the evidence preserved in stratigraphic records of the evolution of BCEs and present the case that blue carbon storage is related to coastal evolution and influenced by sediment supply and Holocene sea-level change. We also recognise that coastal evolution and the influence of humans on coastal landscapes means that the response of BCEs in the past is not a direct analogue for their future adaptation to anticipated sea-level rise and climate change (Woodroffe and Murray-Wallace, 2012). Nevertheless, present-day coastal landscapes are an archive of information that can be used to parameterise models projecting the response of BCEs to environmental change; thereby providing the critical information needed to inform coastal zone planning and decision-making, improve the resilience of BCEs and ensure their long-term application as a nature-based solution that contributes to climate mitigation efforts.

### The PRESENT: Blue carbon in coastal landscapes

Mangroves and saltmarsh typically occupy the upper half of the intertidal zone, with mangrove forests dominating intertidal shorelines of the tropics and saltmarshes dominating intertidal shorelines of temperate zones (Figure 2). There is considerable overlap in the latitudinal distribution of mangroves and saltmarshes (Figure 1), with mangroves generally limited to ocean temperatures that exceed 20 °C during the coldest month (West, 1956; Quisthoudt et al., 2012; Osland et al., 2016), while saltmarsh distribution is influenced by substrate salinity (Bertness et al.,



**Figure 2.** Profiles of BCE landscapes indicating (A) accommodation space, delimited by the highest astronomical tide, basement or bedrock geology, and hydrodynamic conditions favourable for mineral and organic matter accumulation (modified from Rogers (2021)); and (B) the range of techniques that can be used to observe and measure changes in substrate volume, mineral and organic matter accumulation, and position within the tidal frame, with specific focus on changing tidal position with sea-level rise, as per Allen (2000).

1992; Silvestri *et al.*, 2005). Where salinity is very high and salts concentrate hypersaline flats/sandflats or sabkha predominate, often with cyanobacterial mats, and saltmarsh vegetation is sparse; in the tropics where rainfall is high, mangroves predominate in the upper half of the intertidal zone (Rogers and Woodroffe, 2014). Most seagrass species occupy fully inundated

substrates (i.e. subtidal elevations) where water clarity is a significant control on productivity (Madsen *et al.*, 2001). Where hydrodynamic conditions allow, a diversity of seagrass genera may also occupy the lower intertidal niche (i.e. below MSL) (Björk *et al.*, 1999). Depth-constrained species of seagrass and macroalgae can accumulate organic material within substrates as they

adjust to changing water levels (e.g. *Zostera* spp., *Halophila* spp. and *Phyllospadix* spp.) (Koch, 2001; Madsen et al., 2001). While seagrass meadows may be an exceptional carbon source for sequestration elsewhere, their capacity for in situ blue carbon storage is largely limited to that stored within the living biomass and some detritus. Increased sequestration is therefore largely dependent upon an increase in the lateral extent of seagrass meadows (Greiner et al., 2013) and should be balanced against the additional CO<sub>2</sub> that is released by carbonate sediment production (Howard et al., 2018). While net ecosystem primary production may be high for macroalgae, with potential importance for the export of carbon to other environments, in situ burial of carbon is limited (Figure 1; Krause-Jensen and Duarte, 2016). For these reasons, this review focuses on mangrove and saltmarsh blue carbon futures.

Geomorphological settings occupied by BCEs are delimited to areas where low-energy intertidal substrates support the establishment and maintenance of salt-tolerant vegetation. Globally, deltas are hotspots for BCEs due to high rates of sediment supply promoting the development of broad intertidal environments where resource availability is high (Rovai et al., 2018; Worthington et al., 2020; Murray et al., 2022). Along tide-dominated coasts, favourable conditions may arise on the open coast where tidally borne sediments can accumulate, or within the intertidal zone of tide-dominated estuaries. Along wave-dominated coasts, barriers at estuary entrances dampen wave energy and terrigenous sediments supplied from catchments via distributaries contribute to intertidal development of fluvial deltas, and to a lesser extent marine sediment delivered by tides contribute to the development of flood-tide deltas that support BCEs. These fluvial and flood-tide deltas associated with wave-dominated estuaries are also hotspots for blue carbon due to the development of low-gradient intertidal substrates (Kelleway et al., 2016a).

Global and continental scale analyses of above-ground biomass of mangroves and saltmarshes variably highlight the role of climatic factors that vary with latitude, proposing that optimal temperature and higher rainfall favours productivity and carbon addition to plants within BCEs (Kirwan and Mudd, 2012; Rovai et al., 2016; Sanders et al., 2016). For example, analyses of mangrove heights and biomass using the global shuttle radar topography mission altimetry dataset highlight the role of precipitation, temperature and cyclone frequency, explaining 74% of global trends in mangrove canopy height (Simard et al., 2019). Yet, these are also factors that modify substrate salinity and may promote decomposition of organic material (Chmura et al., 2003; Kirwan et al., 2014; Mueller et al., 2018). The outcome may be that once living standing stock reaches a threshold biomass, additions to the living biomass are offset by losses to the standing stock (Chmura et al., 2003).

Observations of mangrove above-ground biomass addition in forestry plots indicate that individual tree growth will asymptote at a threshold height and biomass addition is largely limited to small increments to woody components (i.e. thickening of trunks and stems) (Jin-Eong et al., 1995; Osland et al., 2020; Alongi, 2020b). It is this asymptotic nature of above-ground biomass addition over time that has led to many forestry-based carbon offsetting schemes having a minimum commitment period of at least 20 years before harvesting can occur (Galik et al., 2022) and this has translated into voluntary methods for blue carbon offsetting (Lovelock et al., 2022a). This aligns with the period over which biomass addition accelerates as plants establish and the rate of carbon sequestration is high. When mangrove forests and saltmarshes have reached their threshold capacity for standing above-ground biomass, then

increases in the standing living stock are largely achieved by lateral increases in extent as increases in plant density in mature forests will be resource limited. Increases in below-ground biomass are presumed to be limited by vertical space within substrates for net biomass additionality and addition of biomass will increasingly be offset by decomposition of below-ground biomass as substrates asymptote towards higher elevations; that is unless relative sea-level rise creates more vertical space for below-ground storage. Critically, lateral increases in extent are constrained by the availability of land where conditions are favourable within the intertidal and supratidal zone. In addition, although intense cyclones and storms are reported to have a return interval of approximately 20 years (Elsner et al., 2006), aligning with the commitment period for restoration projects before harvesting can occur (Galik et al., 2022), the feasibility of restoration projects in regions with a propensity for cyclone activity may decrease should projected increases in the frequency and intensity of major storms eventuate (IPCC, 2021).

Partitioning of mangrove biomass between above-ground and below-ground differs from terrestrial forests in that a relatively high proportion is allocated to below-ground root systems (Saintilan, 1997; Lichacz et al., 2009), a possible adaptation to saline conditions (Ball, 1988). However, below-ground biomass is somewhat difficult to determine because decomposition is limited by saline and anaerobic conditions of tidally inundated substrates, and differentiating living and dead components of below-ground biomass is difficult (Adame et al., 2017). The proportion of mass allocated to above and below-ground components is influenced by environmental conditions, most notable is variation arising from soil water salinity, observed in both laboratory (Ball, 1988; Ball, 2002) and field studies (Saintilan, 1997), but also soil water nutrient conditions (Darby and Turner, 2008) and atmospheric CO<sub>2</sub> concentrations (Langley et al., 2009). Observations of below-ground root addition have been undertaken using root ingrowth bags and 'marsh organ' experiments, indicating rapid root development (Muhammad-Nor et al., 2019; Kihara et al., 2022), an observation supported by repeat measures of root biomass (Lamont et al., 2020).

While the addition of carbon to living biomass makes an important contribution to carbon drawdown from the atmosphere, the substrates of BCEs are typically the largest carbon pool within BCEs with soil organic carbon to a depth of 1 m estimated to comprise 77% of the total global mangrove stock and 95% of the total global saltmarsh stock (Alongi, 2020a). Constraining controls on global below-ground carbon storage has been more elusive, and variably related to edaphic conditions associated with climate and substrate salinity (Chmura et al., 2003; Kirwan and Mudd, 2012; Sanders et al., 2016; Rovai et al., 2018; Sanderman et al., 2018). It took some time for the role of sea-level rise to be linked to soil organic carbon accumulation (Wang et al., 2019; Rogers et al., 2019a); this is surprising given the geographic position of intertidal BCEs near mean sea level and the well-established influence of sea-level rise on coastal geomorphology. Increasing mangrove extent with relative sea-level rise and warmer temperatures over the past few decades has been observed and is particularly notable in Australia, Brazil, the Gulf and Atlantic US Coastline, Mexico, and South Africa where mangroves have expanded landward to higher elevations and/or to more poleward positions (Saintilan et al., 2014; Godoy and de Lacerda, 2015; Ximenes et al., 2016; Osland et al., 2017). Increases in soil organic carbon storage have occurred in consort (Kelleway et al., 2016b; Simpson et al., 2019), implying that links between soil organic carbon storage and sea level are partly mediated by vegetation change.

Increases in organic carbon accumulation have been measured in wetlands subject to increased rates of sea-level rise in southwest Florida (Breithaupt *et al.*, 2020), and eastern Australia (Marx *et al.*, 2020). Extreme rapid subsidence beneath a coastal wetland in Australia, in the order of 1 m, has served as a natural laboratory for observing the influence of relative sea-level rise on carbon storage and addition to mangrove and saltmarsh ecosystems (Rogers *et al.*, 2019a). Here soil organic carbon addition accelerated following an increase in relative sea level. Following subsidence, conditions in the former higher elevation saltmarsh became favourable for mangroves, which rapidly established a deeper root network, supplementing the soil organic carbon pool. The submerged mangrove forest was inundated more frequently, providing more opportunities for carbon-rich tidally borne sediments to accumulate and increase the rate of carbon addition.

The great mangrove forests and saltmarsh plains prior to widespread human-driven change to the coastal zone have been reduced to remnants following decades of clearance for aquaculture, agriculture, coastal developments, and tidal obstructions (Gedan *et al.*, 2009; Friess *et al.*, 2019; Goldberg *et al.*, 2020). This is compounded by conversion to open water arising from land subsidence following groundwater and hydrocarbon extraction and/or associated with diminishing sediment supply arising from damming and diversions. Losses in recent decades of mangrove forests (0.7–3.0% yr<sup>-1</sup>), saltmarshes (1.0–2.0% yr<sup>-1</sup>) and seagrass meadows (0.4–2.6% yr<sup>-1</sup>) have contributed an estimated 0.15–1.02 Pg of CO<sub>2</sub> emission per year (Pendleton *et al.*, 2012) (by comparison, 3–19% of emissions from deforestation). These losses reverse decades of carbon sequestration within biomass and millennia of sequestration from substrates. In particular methane flux, a greenhouse gas with ~28 times higher global warming potential than carbon dioxide (Foster *et al.*, 2021), is markedly higher following substrate disturbance. A global review of methane emissions arising from conversion of mangroves, saltmarshes, seagrasses and tidal flats for coastal aquaculture estimated a rise in methane emissions per area 7–430 times higher than emissions from non-converted coastal habitats (Rosentreter *et al.*, 2021b). Fortunately, there is evidence that this trend of declining BCE extent is slowing (Pendleton *et al.*, 2012; Friess *et al.*, 2019; Friess *et al.*, 2020), and losses are being offset by the creation of new wetlands (Murray *et al.*, 2022).

### Conceptualising blue carbon accommodation space

Accommodation is a term used to define the three-dimensional space available for mineral sediments and soil organic matter (Jervey, 1988) (Figure 2A). The maximum elevation of tidal inundation delimits both the landward extent that tidally borne mineral and organic matter can accumulate, and delimits the zone supporting living mangrove and saltmarsh vegetation and in situ soil organic matter contributions (Rogers, 2021). In situ contributions are also delimited at the seaward margin and along tidal creeks by the low-energy hydrodynamic conditions required for vegetation establishment and ongoing survival; in these locations, it is only detrital material that can accumulate within sediments. Initially, bedrock or basement geology delimits the zone in which sediments can accumulate, but as accommodation becomes increasingly infilled, or ‘realised’, via the accumulation of mineral and organic material, substrate elevations increase and become progressively terrestrialised and exposed to the oxidising conditions underpinning aerobic processes of soil organic matter decomposition. In these circumstances, an increase in available accommodation,

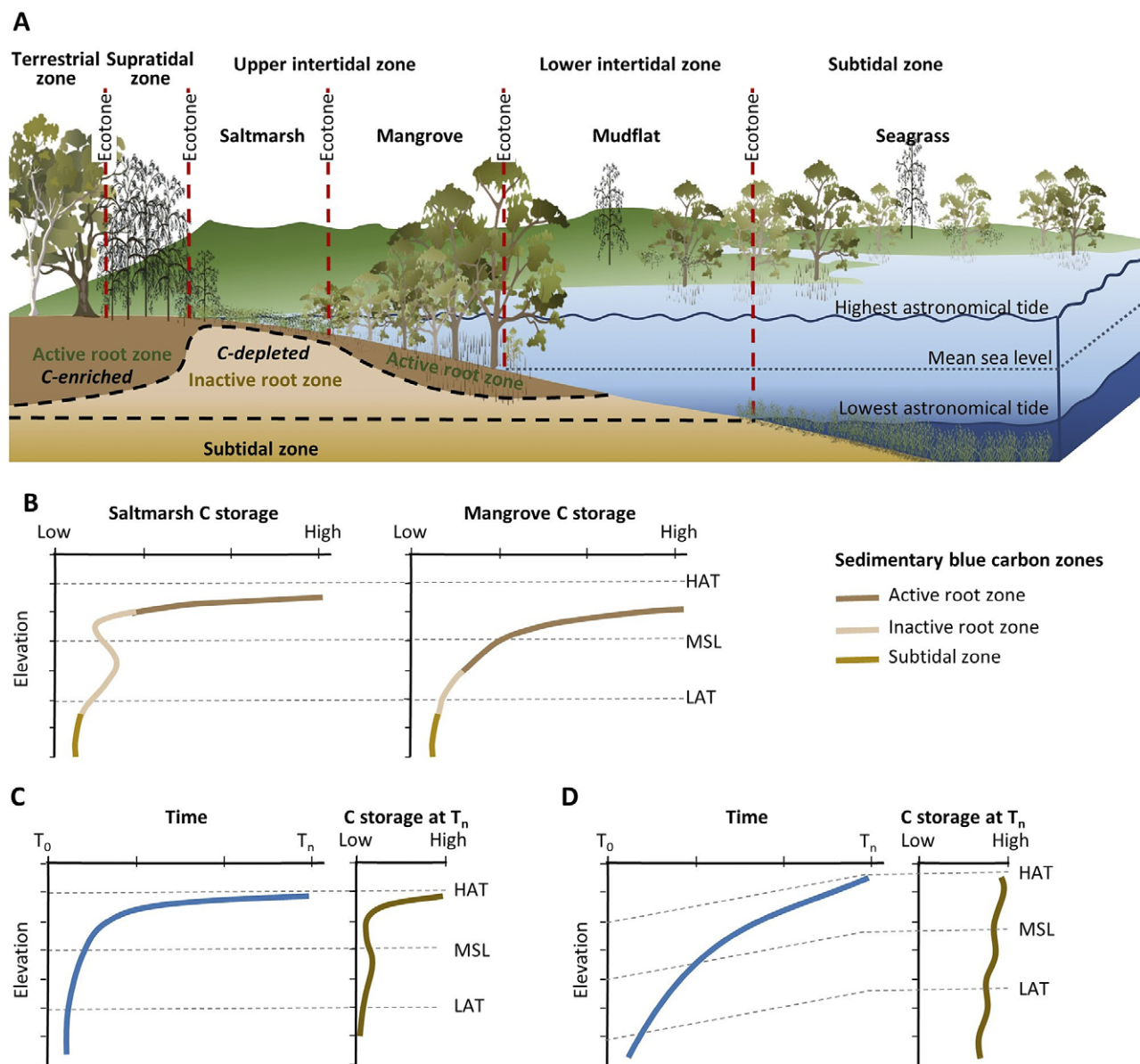
either via autocompaction of sediments that have accumulated within the ‘realised’ accommodation, subsidence of the basement, or sea-level rise, is required to reinstate tidal inundation, preserve the niche of BCEs, minimise decomposition of organic material by processes of oxidation or methanogenesis and provide new space for additional soil organic matter.

Observations of mangrove and saltmarsh substrate elevation changes using techniques such as surface elevation tables, marker horizons and radiometric dating (Figure 2B) confirm that sedimentation and surface elevation gain are proportional to position in the tidal frame, reflecting the influence of accommodation on accumulation of mineral and organic material in substrates (Webb *et al.*, 2013; Raw *et al.*, 2020; Cahoon *et al.*, 2021; Saintilan *et al.*, 2022). The effect of sea-level rise on the position in the tidal frame of BCEs has been conceptualised by Allen (2000) to account for the addition of mineral and organic material, autocompaction and relative sea-level rise. Providing accommodation is available, below-ground biomass from established vegetation increases substrate volume and the mass of the soil organic carbon pool; above-ground biomass baffles tidal energy, improving hydrodynamic conditions for the deposition of suspended sediments. As substrate elevations increase, the space available for below-ground organic matter additions and mineral sediment addition diminishes, and organic matter decomposition may increase due to an associated reduction in inundation depth, duration and/or frequency (often termed hydroperiod). In combination, these factors generate a self-organising negative feedback that favours the stabilisation of substrate elevations. As a small increment in sea level increases accommodation, the associated increase in tidal inundation serves to enhance conditions favouring the accumulation of mineral and organic sediments, thereby offsetting the small increment in sea level, and maintaining the intertidal position of the substrate; addition of organic material is a vital component of this negative feedback. The coupling between inundation and organic matter addition that contributes to this negative feedback was initially conceptualised for marshes of the SE coast of the USA (Morris *et al.*, 2002) and has formed the basis for models projecting the organic response of substrates to sea-level rise (Mudd *et al.*, 2009; Mack *et al.*, 2023). Field studies have also confirmed linkages between coastal wetland evolution, accommodation space and carbon concentrations in mangrove and saltmarsh substrates of SE Australia (Owers *et al.*, 2022) (Figure 3).

### The PAST: Sea-level rise, and blue carbon accommodation

For extended periods over Earth’s history, when the coincidence of rising sea level, favourable coastal geomorphology and suitable tidal range has been conducive to extensive coastal wetland development, blue carbon has been an important and arguably dominant control on global trends in atmospheric CO<sub>2</sub>. During the Oligo-Miocene, the combined influence of sea-level rise, high tidal range and a resultant extensive mangrove development in the South China Sea trapped up to 2000 Pg of organic carbon, equivalent to up to 60 p.p.m. of atmospheric CO<sub>2</sub> per Myr (Collins *et al.*, 2017). The development of these forests could have been a major contributor to the reduction in atmospheric CO<sub>2</sub> concentrations from circa 800 to 300 p.p.m. since the Late Oligocene (34–0 Ma) (Collins *et al.*, 2017).

At the peak of the last glacial maximum, sea level was 130–120 m lower than present; this low stand and the present high stand are indicative end points of global eustatic sea-level cycles (Murray-



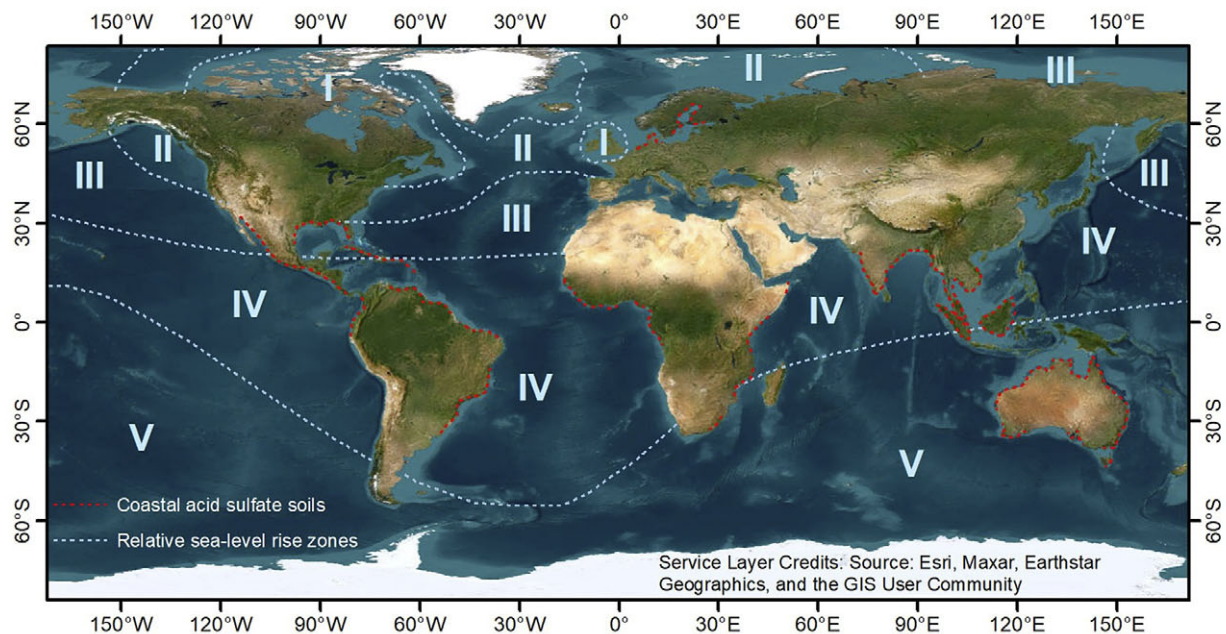
**Figure 3.** (A) Conceptual model of lateral zonation of BCEs of southeastern Australia with respect to tidal parameters, and varying distribution of soil organic carbon within the active root zone, inactive root zone and subtidal zone; and (B) associated generalised variation in carbon storage within BCEs (modified from Owers et al. (2022)). (C and D) Relationships between carbon storage and sea-level change (from  $T_0$  to  $T_n$ ) under conditions of (C) relatively stable sea level since the mid-Holocene and (D) rising sea level since the mid-Holocene (modified from Allen (2000)).

Wallace and Woodroffe, 2014). The response of mangrove forests and saltmarshes to sea-level rise since the last glacial maximum has been likened to the behaviour of coral reefs at the same period (Neumann and MacIntyre, 1985; Reed, 1990; Woodroffe and Davies, 2009), where, depending upon the rate of sediment supply relative to the rate of sea-level rise, mangrove forests and saltmarshes may be ‘drowned’, ‘backstep’, ‘catch-up’, ‘keep-up’, ‘pro-grade’ or ‘emerge’. When rates of sea-level rise exceeded 1 m per century during the late-Pleistocene and early-Holocene, the capacity of mangrove forests to accumulate mineral and organic material appears to have been exhausted, and evidence of ‘drowned’ mangrove peats overtopped by marine transgressive sand sheets have been preserved on the Sahul Shelf (northwest Western Australia (Nicholas et al., 2014) and the Sunda Shelf (on the western rim of the South China Sea) at water depths of up to 100 m

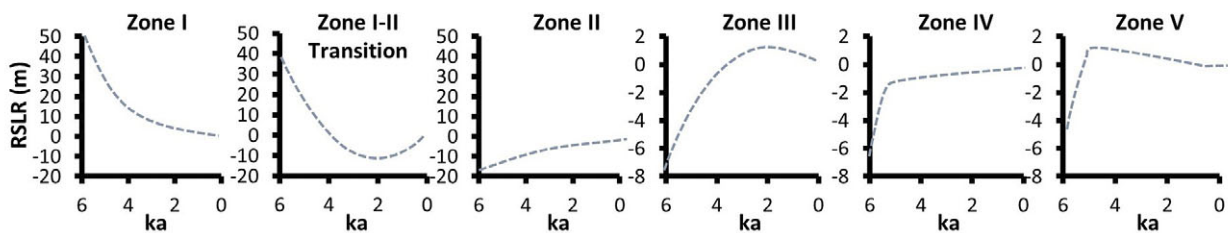
(Hanebuth et al., 2000). Extensive mangrove forest development at the time appears to have been terminated by Meltwater Pulse 1A, during which rates of relative sea-level rise increased to  $>20 \text{ mm yr}^{-1}$  (Lambeck et al., 2014).

Deceleration in the rate of sea-level rise in the early-Holocene was broadly marked by mangrove development in the millennia prior to sea-level stabilisation near present levels. In settings of high sediment yield, including the Ganges-Brahmaputra delta, India (Hait and Behling, 2009) and the Queensland continental shelf, Australia (Grindrod et al., 1999), mangrove forests adjusted in situ to sea-level rise from the early-Holocene (~9,000 BP), but were subsequently ‘drowned’ and then ‘backstepped’. By ~7,500 BP, relative sea-level rise had decelerated to less than  $6\text{--}7 \text{ mm yr}^{-1}$ , and ‘catch-up’, or mangrove landward transgression, followed by ‘progradation’ occurred where sediment supply was high, resulting

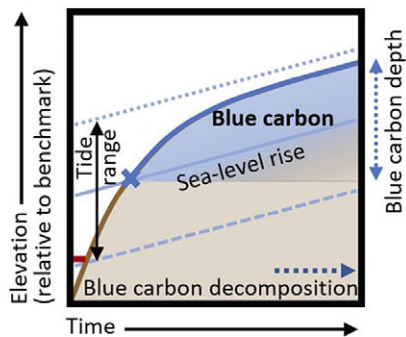
### A Holocene relative sea-level rise zones and coastal acid sulfate soils



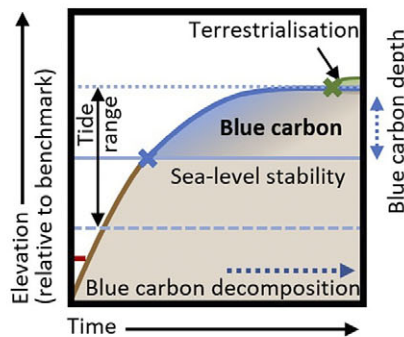
### B Generalised Holocene relative sea-level rise curves based on zones above



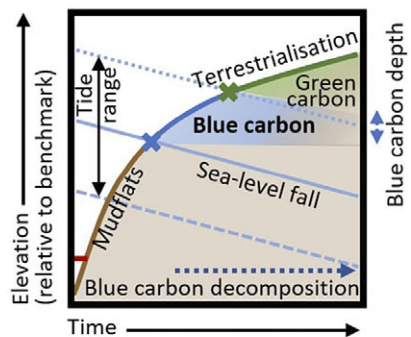
### C Blue carbon & sea-level rise



### D Blue carbon & sea-level stability



### E Blue carbon & sea-level fall



**Figure 4.** Relative sea-level change is a significant control on processes of carbon accumulation and decomposition, and varies globally according to the generalised Holocene relative sea-level zones (A) (Clark *et al.*, 1978) and generalised Holocene relative sea-level curves across these zones (B). Note the distribution of coastal acid sulphate soils in (Michael, 2013) (A), which corresponds broadly with regions where sea-level conditions facilitated widescale mangrove and saltmarsh development throughout the late-Holocene. When sea levels are rising (C), sedimentary carbon continues to accumulate within available accommodation and pathways of decomposition are dampened under increasingly anaerobic conditions. Where sea level has been relatively stable (D), blue carbon additionality is limited by the upper limit of tidal inundation and substrates become increasingly mineral dominated and support terrestrial vegetation as accommodation diminishes. Under conditions of falling sea levels (E), substrates become increasingly terrestrialised (i.e. with terrestrial vegetation) and conditions favour aerobic decomposition and methanogenesis of blue carbon.



in extensive mangrove forests in tropical minerogenic settings. In many places, these forests were considerably greater in extent than contemporary mangrove forests, including Australia (Woodroffe et al., 1985), the Mekong and Red River deltas of Vietnam (Tran and Ngo, 2000; Li et al., 2012), and the Great Songkla Lakes, Thailand (Horton et al., 2005). High rates of organic matter accumulation in this globally synchronous phase of blue carbon development sequestered an estimated 20–60 Pg C, contributing to a 5 p.p.m. decline in atmospheric CO<sub>2</sub> concentrations in the early Holocene (Saintilan et al., 2020). An early-mid Holocene decline in methane, primarily in the Southern Hemisphere, according to ice-core data (Beck et al., 2018), commenced over the same period, with reductions in Southern Hemisphere emissions estimates of ~19 Tg CH<sub>4</sub> yr<sup>-1</sup> (Beck et al., 2018). The δ<sup>13</sup>C signals in methane in the Southern Hemisphere for the period show a 1.5 p.p.t. depletion (Beck et al., 2018) consistent with a replacement of vegetation utilising the C<sub>4</sub> photosynthetic pathway (tropical grasslands and saltmarsh adapted to low atmospheric carbon dioxide) with mangroves utilising the C<sub>3</sub> pathway (Sowers, 2010).

By the mid-Holocene, eustatic sea level stabilised within approximately 2 m of its current elevation (Clark et al., 1978; Khan et al., 2015). However, the initiation of mangrove and saltmarsh transgressive phases was globally variable due to the influence of glacio-isostatic adjustment on varying rates of mid- to late-Holocene relative sea-level rise (Ribeiro et al., 2018), and the modulating effect of other climatic variables (e.g. droughts and/or frequent storms) on conditions conducive to intertidal vegetation expansion or decline (Sherrod and McMillan, 1985; Jones et al., 2019). Global scale variation in relative sea-level trends, largely arising from glacio-isostatic adjustment, had a profound influence on blue carbon accumulation throughout the mid- to late-Holocene and storage since this time (Rogers et al., 2019a; 2019b). Principally related to distance from regions of maximal ice sheet extent during the last glacial period, relative sea-level rise modifies the accommodation available for blue carbon. The delineation of zones across oceans globally where post-glacial sea-level trends are relatively similar (Figure 4A and 4B, Clark et al., 1978) therefore provides an indication of the accommodation available for blue carbon storage over the past few millennia. While more is known of post-glacial sea-level change since these zones were initially demarcated, their broad correspondence with what we now know of relative sea-level trends (Khan et al., 2015) provides some confidence in the geographic position of zones (noting that boundaries between zones are diffuse and not definite). Clark et al. (1978) delineated five zones across oceans globally (a sixth zone was associated with continental coastlines) that can be broadly grouped into three regions: (i) near-field locations are proximal to ice sheets of the last glacial maximum and typically exhibit continuous patterns of relative sea-level fall (i.e. Clark et al., 1978, zone I); (ii) intermediate locations exhibit complex sea-level trends; however, relative sea-level rise over the past few millennia is typical; and (iii) far-field locations are distal from ice sheets and eustatic sea-level trends dominate processes of glacio-isostatic adjustment. For brevity, we focus on end members: far-field locations (Zones IV and V) where the relative sea level has been relatively stable for millennia (or may have fallen); intermediate locations where relative sea level has been rising over the mid- to late-Holocene (Zones II and III); and near-field locations (Zone I) where relative sea level has been falling (Figure 4A).

Far-field locations (Zones IV and V), distal from regions of maximal ice sheet extent, exhibit patterns of mid-Holocene infill in mangrove (Woodroffe et al., 1993; Cohen et al., 2005; Hashimoto et al., 2006; Proske and Haberle, 2012; França et al.,

2013; Boski et al., 2015; Punwong et al., 2018) and saltmarsh settings, with coastal barriers typically enclosing bays along the more southern wave-dominated coastlines (Compton, 2001; Vilanova et al., 2006; Fornari et al., 2012; Kennedy et al., 2021). Ongoing coastal and estuarine sedimentation, and a fall in sea level to present levels where a high stand occurred in the late Holocene, caused coastal floodplains to increasingly 'prograde' or become 'emergent', with accommodation being limited, and BCEs restricted to the fringes of estuarine shorelines (Woodroffe and Davies, 2009). BCEs were replaced by floodplain terrestrial forests and freshwater wetlands, a shift that may have contributed to gradual increases in atmospheric methane concentrations in the late-Holocene after declining in the early- to mid-Holocene (Beck et al., 2018). Preservation of soil organic carbon in far-field locations is limited by decomposition as coastal floodplains become increasingly terrestrialised and support grasses and sedges, else soil organic matter may be vulnerable to metabolisation and formation of pyrites when sulphate and sulphate reducing bacteria are present. This sets up the conditions for generation of acid sulphate soils when coastal floodplains are drained, and oxidisation occurs. The relationship between former distribution of saltmarshes and mangrove forests, relative sea-level stability and coastal acid sulphate soil development is well established (Pons et al., 1982; Van Breemen, 1982) and reflected in the greater extent of actual and potential coastal acid sulphate soils in SE Asia, Africa, Australia and South America (Michael, 2013) and their virtual absence from intermediate-field locations (see Figure 4A).

Intermediate field locations also exhibit broad agreement in geomorphological evolution over the Holocene (Woodroffe, 1981; Digerfeldt and Hendry, 1987; Parkinson, 1989; Parkinson et al., 1994; McKee, 2011). In Florida and the northern Gulf of Mexico, the early Holocene was marked by rates of relative sea-level rise that were too high for broadscale mangrove development (<~7,500 BP) (Sherrod and McMillan, 1985; Parkinson, 1989). Evident from interbedded peats and marls, the onset of the transgressive 'catch-up' phase occurred from about 3,500 BP (Scholl, 1964; Parkinson et al., 1994; Jones et al., 2019), although the occurrence of continuous vertical peat growth, typical of 'keep-up' behaviour, is modulated in some locations by other climatic factors, including a period of cooling, that may not have been conducive to widespread mangrove expansion and vertical growth (Sherrod and McMillan, 1985; Jones et al., 2019). Where conditions were favourable, vertical growth of mangrove peats is near continuous. In particular, the cenotes of the Yucatan Peninsula are reported to have among the highest mangrove carbon stocks globally, and their accumulation has been related to ongoing relative sea-level rise over the late-Holocene (Adame et al., 2021). The later onset of transgressive phases of mangrove development in intermediate field locations reflect stronger rates of relative sea-level rise throughout the mid-Holocene, ongoing sea-level rise in the late-Holocene, the influence of other climatic variables, as well as limited capacity for vertically adjustment to sea-level rise due to low rates of sediment supply in some carbonate dominated settings. Accordingly, ongoing sea-level rise and limited mineral sediment supply since the late-Holocene may explain the preservation of carbon-rich mangrove peats in this region (McKee, 2011). Similar preservation of saltmarsh peats and associated foraminifera is evident at intermediate-field sites with a history of increasing accommodation with sea-level rise throughout the mid- to late-Holocene (Redfield, 1972; Orson et al., 1998; Gehrels, 1999).

Saltmarshes at near-field locations (climate not suitable for mangroves throughout the Holocene), those proximal to regions

of maximum ice sheet extent at the last glacial maximum, exhibited a highly variable pattern of vertical growth and carbon accumulation dependent upon the influence of glacio-isostatic adjustment on relative sea-level rise (Khan *et al.*, 2015). Analyses of radiocarbon dated saltmarsh sequences in the UK differentiated both transgressive sequences (i.e. 'catch-up'), representing increasing marine influence and regressive sequences (i.e. 'progradation' or 'emergent') indicating increasing terrestriation (Horton *et al.*, 2018). The presence of these sequences aligned with Holocene sea-level history, with 'catch-up' transgressive sequences predominating in southern England where relative sea-level rise exhibited a pattern of deceleration, while regressive sequences were more prominent in Scotland, where relative sea level fell in both the early- and late-Holocene. Complex spatio-temporal patterns of postglacial relative sea-level change throughout the mid- to late-Holocene are also preserved in saltmarsh peats of near-field locations across the coastline of the North Atlantic (Vacchi *et al.*, 2018; Cohen *et al.*, 2022; Creel *et al.*, 2022).

Patterns of relative sea-level change over the Holocene and its influence on the distribution of BCEs have provided important lines of evidence about the future of BCEs. Global analyses of soil organic carbon stocks in saltmarshes indicate that regions where sea level has a longer history of rising over the mid- to late-Holocene, that is intermediate and some near-field locations, exhibit higher soil organic carbon stocks and deeper soil organic carbon pools than far-field locations (Rogers *et al.*, 2019a). This has been linked to the influence of relative sea-level rise on accommodation for blue carbon within substrates, the largest carbon pool within BCEs. Where sea level has been rising at a moderate rate for a few millennia, vertical space is created for storage of blue carbon within below-ground biomass and soils (Figure 4C). In contrast, where sea level has been relatively stable over the mid- to late-Holocene, that is across much of the Southern Hemisphere, carbon pools may be depleted and shallower (although the depth is dependent upon tidal range), and this has been related to the limitations placed on accommodation as substrates become increasingly dominated by mineral sediments (Figure 4D). Where sea level has been falling, substrates become increasingly terrestriated with brackish to fresh substrate salinities that are aerobic and favour decomposition and methanogenesis (Figure 4E). These differences in organic matter content between far-, intermediate- and near-field locations are also reflected in the character of contemporary sediment accumulating in wetlands. Intermediate- and near-field locations have higher organic carbon accumulation above artificial marker horizons (Saintilan *et al.*, 2020), reflecting both the comparatively higher contemporary rates sea-level rise, and possibly the more organic sub-tidal reservoirs of sediment contributing to marsh accretion (Hopkinson *et al.*, 2018).

### The FUTURE: The present and past as a guide to blue carbon futures

The spectre of climate change has focussed attention on reducing atmospheric carbon concentrations and limiting warming well below 2 °C, a commitment established in the Paris Agreement at COP21 (Iyer *et al.*, 2015). Accordingly, the capacity of BCEs to draw carbon from the atmosphere is being leveraged as a climate mitigation strategy, and received considerable recognition in the latest IPCC report (Cooley *et al.*, 2022). Conservation of BCEs aimed at minimising losses in extent through land use and land cover change (LULCC) and restoring condition through improved management

will be important. The Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+) program of the United Nations Framework Convention on Climate Change (UNFCCC) specifically targets the improved management of forests to minimise loss and release of greenhouse gases, and conservation efforts are increasing in developing countries (Ahmed and Glaser, 2016). Similar programs for non-forested ecosystems, such as saltmarshes, do not exist; however, there is a global peatland initiative that could be applied to saltmarshes. In many jurisdictions BCEs are already protected from loss because of the benefits they provide to society (Romañach *et al.*, 2018). Despite these policies, loss of BCEs is ongoing (Gedan *et al.*, 2009; Friess *et al.*, 2019; Goldberg *et al.*, 2020), and this increases the burden for carbon additionality by other mechanisms, such as restoration.

Restoring BCEs, achieved by planting vegetation, seeds or propagules, or managing barriers to tidal exchange that have been put in place to facilitate past LULCC, may enhance carbon sequestration as blue carbon vegetation re-establishes. Analyses suggest that restoration to recover BCE habitat that has been lost due to human activities in the coastal zone is potentially feasible for mangroves, less so for seagrasses and saltmarshes (Griscom *et al.*, 2017; Macreadie *et al.*, 2021). However, the capacity for large-scale restoration is constrained by socio-economic factors, particularly where the coastal zone is critical for maintaining livelihoods and food security (Herr *et al.*, 2019). Efforts are in place globally to restore mangrove forests (Friess *et al.*, 2019), but success is highly variable; often there is a lack of understanding of the geomorphological and hydrological controls on restoration success, and mangrove restoration efforts have been plagued with failure (Lee *et al.*, 2019; Lovelock *et al.*, 2022c). Saltmarsh restoration is also occurring, but receives considerably less scientific attention beyond North America; this likely reflects an efficient policy environment and sufficient financial capacity for restoration (Billah *et al.*, 2022). Despite these challenges, restoration of BCEs is likely to accelerate, being buoyed by the United Nations declaration that 2021–2030 is the "United Nations Decade on Ecosystem Restoration" to help meet sustainable development goals (Billah *et al.*, 2022).

Market mechanisms have been developed to incentivise BCE restoration, and currently there are two primary markets; the compliance and voluntary markets (Sapkota and White, 2020). Compliance markets are underpinned by regulations to offset greenhouse gas emissions and typically require offsets to be accounted for under existing standards and using approved methodologies, such as the Verified Carbon Standard (VCS) methodology for tidal wetlands (VM0033) (Emmer *et al.*, 2015a; Emmer *et al.*, 2015b). In some jurisdictions, the voluntary market is also highly regulated; for example, the Australian Government administers a voluntary market, the Emissions Reduction Fund, which provides tradeable credits (Australian Carbon Credit Units) for tidal restoration activities that increase blue carbon storage (Lovelock *et al.*, 2022a; Lovelock *et al.*, 2022b). The payment period for these programs is well-defined as the carbon benefits are likely to diminish in the above-ground carbon pool once vegetation has reached maturity, and in the below-ground pool when substrates are saturated with mineral and organic material (i.e. when accommodation is limited). The 25-year permanence time frame aligns with the period for which woody vegetation is anticipated to reach maturity and exhibit high rates of carbon addition to substrates (Osland *et al.*, 2020), while the 100-year timeframe aligns with what is regarded to be permanently sequestered soil organic carbon (i.e. permanence) (Dynarski *et al.*, 2020). Payments are dependent upon forward projections and ongoing verification.

Use of BCEs as a mechanism for carbon removal has received some criticism (Williamson and Gattuso, 2022) due to the high variability and errors in carbon burial rates, lateral carbon transport (Maher et al., 2018), methane and nitrous oxide fluxes (Rosentreter et al., 2021a; Malerba et al., 2022), carbonate formation and dissolution (Saderne et al., 2019; Van Dam et al., 2021), vulnerability to future climate change and non-climatic factors, and cost-effectiveness and scaleability (Macreadie et al., 2021). Confidence in forward projections is likely to be improved as data collection continues and knowledge gaps are addressed (Macreadie et al., 2019).

Permanence (i.e. beyond the 25-year and 100-year time frames) of blue carbon is fundamental to the success of BCEs as a natural climate solution. Critically, conservation and restoration activities will not occur in the absence of sea-level rise, warming and elevated atmospheric carbon dioxide concentrations, placing considerable uncertainty regarding permanence. The fate of sequestered carbon from BCEs once they succumb to sea-level rise is difficult to project, but likely to be highly variable. Palaeo-records provide the opportunity to validate projections of the response of BCEs to sea-level rise; however, do not fully indicate blue carbon futures as sea-level rise is now occurring on coastal landscapes that developed throughout the Holocene, have been highly modified and do not have a historic analogue (Woodroffe and Murray-Wallace, 2012). Projecting blue carbon futures therefore requires integration of information from the past and present behaviour.

Recent analyses have indicated that rising seas associated with ice melt following the last glacial maximum exceeded the capacity of tropical mangroves (Saintilan et al., 2020) and saltmarshes (Horton et al., 2018; Törnqvist et al., 2021) to remain in situ (i.e. 'keep-up') when sea level increased at rates exceeding  $\sim 5\text{--}7\text{ mm yr.}^{-1}$ . However, mangrove and saltmarsh sediments have been preserved since the Holocene (Hanebuth et al., 2000; McKee et al., 2007; Wang et al., 2009) following sea-level rise at rates higher than currently encountered (Redfield, 1972; McKee et al., 2007; Saintilan et al., 2020). Long-periods of sea-level stability across much of the Southern Hemisphere have contributed to the development of broad, mature coastal floodplains (i.e. considerable elevation capital) when conditions are conducive. These floodplains are not typically saturated with carbon (Rogers et al., 2019a), may be hot spots for potential and realised acid sulphate soils (Michael, 2013), and could become extensive BCEs, much like those of the mid-Holocene (Woodroffe et al., 1985). Many BCEs in the northern hemisphere have been adapting to sea-level rise for millennia and are likely to be lower-lying (i.e. less elevation capital) and have limited capacity to adapt to anticipated sea-level rise as the coastal zone is highly contested and coastal squeeze is likely.

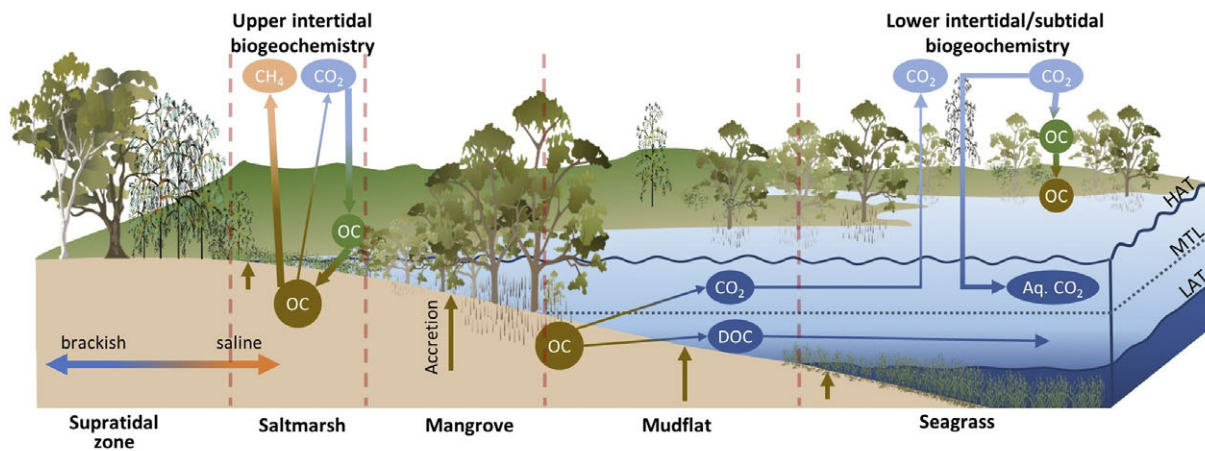
The permanence of organic material exposed to drowning is an important consideration. Since it takes some time for mature trees and tidal marshes, that are high in the tidal frame to drown with incremental increases in sea level, it is feasible that submergence and death may occur beyond the minimum 25-year permanency time frame applied in managed blue carbon markets. Loss of standing biomass that is currently lower in the tidal frame or in the interior of saltmarshes may be high (Kearney et al., 1994), and depending on exposure to erosion, soil carbon may be variably preserved (Krauss et al., 2018; Rogers et al., 2019a) or reworked and transported elsewhere (DeLaune and White, 2012; Haywood et al., 2020). Increasing atmospheric carbon dioxide concentrations may enhance productivity of BCE vegetation, with enhanced root allocation contributing to sea-level rise adaptation and carbon sequestration via addition of carbon volume to substrates (Ball et al., 1997;

Langley et al., 2009; McKee et al., 2012; Reef et al., 2017). Widespread mangrove dieback has been associated with short-term methane flux to the atmosphere (Jeffrey et al., 2019); this has potential implications on atmospheric carbon budgets in the event of broadscale mangrove mortality under high rates of sea-level rise, or short-term sea-level fluctuations. Figure 5 conceptualises the hypothesised carbon storage and greenhouse gas flux outcomes under scenarios of atmospheric carbon dioxide concentrations, warming and relative sea-level rise.

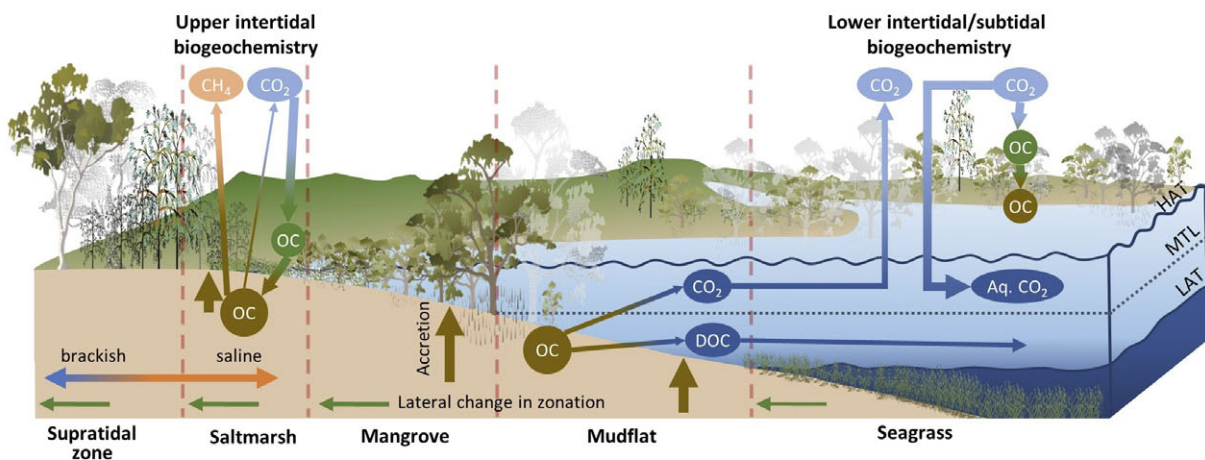
The degree to which climate change modifies BCEs is difficult to project as shoreline erosion is poorly preserved in the stratigraphy of depositional environments, limiting the capacity to parameterise models. In addition, multiple coastal processes contribute to shoreline change and observations indicate considerable local and regional variability in the operation of processes. Studies that project BCE dynamics with sea-level rise and infer carbon implications are therefore typically undertaken at the local scale, and at data-rich sites, and the outcomes can rarely be extrapolated to other locations. Otherwise, projections are dependent upon simplification of processes and apply reductive estimates of carbon concentrations (Lovelock and Reef, 2020; Wang et al., 2021), or explore future scenarios using simplified idealised models (Kirwan and Mudd, 2012). Spatial models typically require decisions regarding whether landward retreat of BCEs is parameterised, and, invariably, the projected outcomes are highly dependent upon model parameterisation. For example, recent projections estimated net gains in blue carbon in the order of 1.5 Pg to 2100 when coastal squeeze impacts are minimised and climate change impacts are high (i.e. RCP8.5 scenario), while net blue carbon gains are in the order of 0.8 Pg to the year 2100 when under moderate climate change scenario (i.e. RCP4.5 scenario) (Lovelock and Reef, 2020).

Models have consistently indicated the importance of minimising coastal squeeze to enhance climate adaptation and mitigation benefits from BCEs (Schuerch et al., 2018; Lovelock and Reef, 2020; Wang et al., 2021). Managing structures that modify tidal exchange and sediment supply will be crucial for maximising blue carbon benefits. Indeed, storm surge barriers are already managed to reduce coastal flooding impacts (Haigh et al., 2022) and engineering structures could be modified to meet design requirements anticipated with sea-level rise and to manage for blue carbon services (Sadat-Noori et al., 2021; Haigh et al., 2022). In many cases 'holding back the tide' will become challenging and costly, and it is likely that difficult land use decisions will be made to increase BCE extent and the provision of co-benefits (Rogers et al., 2022). Sea-level rise will reduce the viability of large tracts of low-lying coastal land for agriculture and grazing purposes, and the efficacy of existing structures to hold back tides, many of which were designed when rates of sea-level rise were negligible, will be tested. In these circumstances, the benefits of land cover conversion for BCEs should therefore be weighed against the costs associated with upgrading existing structures to meet future design requirements that account for the effects of sea-level rise and storm surges on tidal regimes. Momentum towards recognising BCE co-benefits for biodiversity, coastal fisheries and water quality is increasing (Rahman et al., 2021; Hagger et al., 2022), and efforts are underway to develop a 'blue chip' carbon markets that provide payments for blue carbon additionality and co-benefits (Macreadie et al., 2022). These blue-chip markets may sufficiently incentivise land managers to reconsider upgrades of tidal barriers and instead receive a blue carbon income as the land is restored to a BCE (Rogers et al., 2022).

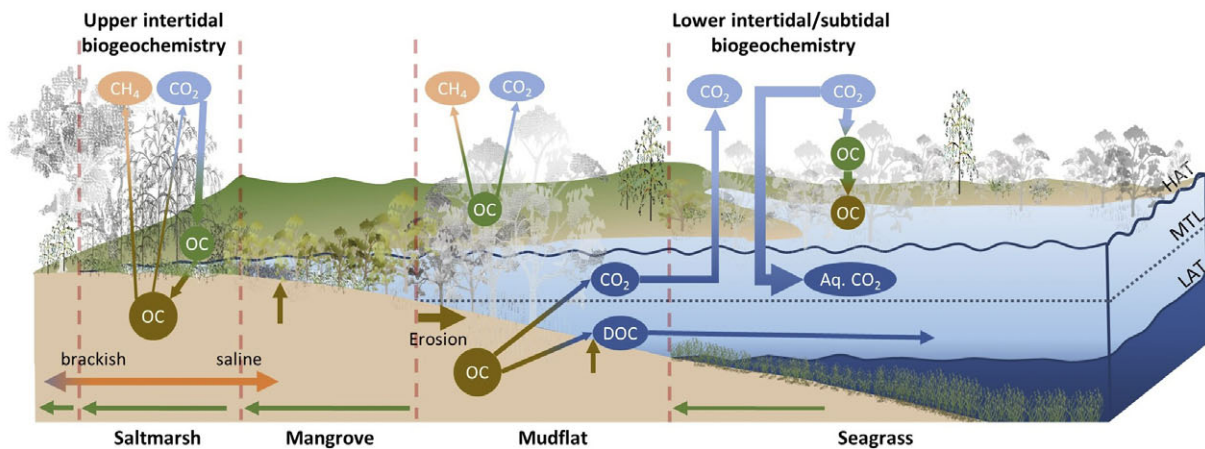
**A**  $\text{CO}_2 = 300$  p.p.m.; Temp =  $0^\circ\text{C}$ ; RSLR =  $2$  mm  $\text{yr}^{-1}$



**B**  $\text{CO}_2 = 600$  p.p.m.; Temp =  $+1.5^\circ\text{C}$ ; RSLR =  $5$  mm  $\text{yr}^{-1}$



**C**  $\text{CO}_2 = 900$  p.p.m.; Temp =  $+3^\circ\text{C}$ ; RSLR =  $8$  mm  $\text{yr}^{-1}$



**Figure 5.** Conceptualisation of the interacting effects of atmospheric carbon dioxide, warming and relative sea-level rise on BCE projected to occur under a range of emissions scenarios. Under the baseline scenario (A) carbon is fixed by in situ vegetation and contributes to soil carbon accumulation and substrate volume via accretion. The landward margin under brackish conditions is a source of methane. Under the mid-range emissions scenario (B) the feedbacks between elevated atmospheric  $\text{CO}_2$  and organic carbon sequestration and between relative sea-level rise (RSLR) and organic carbon production, preservation, and vertical accretion are strengthened. Saline intrusion reduces methane emissions in the landward fringe, although this may be counterbalanced by increased emissions resulting from increases in NPP induced by  $\text{CO}_2$  and warming. Under the high-range emission scenario (C) a tipping point is reached where RSLR exceeds vertical accretion leading to mortality and shoreline retreat. Mortality of terrestrial vegetation contributes to elevated methane production in the short term. Note that the relative strength of interactions with greenhouse gases is indicated by the thickness of lines, and greyed-out vegetation is indicative of dieback or loss associated with the effects of rising sea levels.

## Conclusion

In the short- to medium-term, climate change may increase the capacity of BCEs to capture and store atmospheric CO<sub>2</sub>, largely due to processes that respond to elevated CO<sub>2</sub> and temperature, and influence carbon capture and storage. These processes include in situ responses such as CO<sub>2</sub> fixation, biomass storage, biogeochemical enhancement of burial efficiency, as well as the expansion of BCEs at local and global scales. The magnitude and duration of the negative feedback on climate may vary between hemispheres. Climate change is expected to squeeze mangrove and saltmarsh areas in the Northern Hemisphere between accelerating relative sea-level rise and hard barriers. In the Southern Hemisphere, opportunities for landward expansion of mangrove and saltmarsh may be available where late-Holocene sea-level history coupled with ongoing sediment supply and lower contemporary rates of relative sea-level rise has facilitated the development of broad coastal floodplains and where coastal squeeze effects are minimised. The long-term future for these negative feedbacks on radiative forcing is dependent upon decisions made in the coming decades. At the global scale, the rate of sea-level rise projected under high emissions scenarios will lead to degradation and loss of existing coastal wetlands. Sea-level rise of ~5–7 mm yr<sup>-1</sup> is likely to be a critical tipping point at which the predominantly negative climate feedbacks driven by blue carbon sequestration become positive feedbacks driven by plant decomposition and remineralisation. This tipping point will be surpassed under high emissions scenarios within the next century.

The threat to in situ coastal wetlands makes local land-use and coastal protection the key determinant of long-term survival, driven by retreat of BCEs to higher elevations. Investment in coastal wetland conservation and restoration provides benefits not only for the preservation of ecosystem services such as coastal fisheries, but also a promising opportunity for nature-based mitigation. National governments are developing a broad spectrum of climate adaptation and mitigation responses with innovative approaches to financing these activities, including some focused specifically on blue carbon. Carbon markets are rapidly expanding as a tool for governments, private corporations, and individuals to reduce greenhouse gas emissions. While currently only a few blue carbon projects have reached the point of generating finance through carbon markets, projects are in development in Mexico, Kenya, Colombia, Madagascar and other locations, and blue carbon credits are in high demand due to the multitude of co-benefits provided. This suggests that carbon markets are promising to finance coastal restoration, climate adaptation, and livelihoods for coastal communities.

Critical knowledge gaps need to be overcome before the full benefit of blue carbon can be realised. Priorities include: establishing the full global extent of BCEs and developing ongoing monitoring at management-relevant resolutions; addressing the permanence and temporal continuity of blue carbon storage and sequestration subject to SLR, changing climatic conditions and their impact on the distribution of mangroves, tidal wetlands, seagrass and macroalgae at high latitudes; establishing the factors that determine the carbon storage and sequestration capacity at the site scale and how these might be managed to increase mitigation benefit; and establishing the carbon mitigation potential and pathways for other coastal and marine ecosystems such as macroalgae and tidal forests. Given the recent momentum in blue carbon research, scientists and policy makers are well placed to address these gaps, providing research is sufficiently supported. Crucial to the effectiveness of blue carbon research for policy and

management application is actively focussing on the highly under-studied regions, particularly in the global south, where the distribution of mangrove forests is greatest.

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