Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise

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Coastal wetlands (mangrove, tidal marsh, seagrass) sustain the highest rates of carbon sequestration per unit area of all natural systems[1,2], primarily due to comparatively high productivity and preservation of organic carbon within sedimentary substrates[3]. Climate change and associated relative sea-level rise (RSLR) is proposed to increase the rate of organic carbon burial in coastal wetlands in the first half of the 21st century[4], but these carbon-climate feedbacks have been modelled to diminish over time, as wetlands are increasingly submerged and carbon stores compromised by erosion[4,5]. Here we show that tidal marshes in coastlines experienced rapid RSLR over the late Holocene (~4.2 ka to present) have, on average, 1.7 to 3.7 times higher soil carbon concentrations (%C) within the surface 0-20 cm than those subject to a long period of sea-level stability. This disparity increases with depth, with %C reduced by a factor of 4.9 to 9.1 in the 50-100 cm depth range. We analyse the response of a wetland exposed to recent rapid RSLR following subsidence associated with pillar collapse of an underlying mine and demonstrate that carbon accumulation and elevation gain is proportional to accommodation space created by RSLR. Our results suggest that coastal wetlands characteristic of tectonically stable coastlines have lower carbon storage due to a lack of accommodation space into which a wetland can accumulate mineral and organic material, and that carbon sequestration increases according to the vertical and lateral accommodation space[6] created by RSLR. These wetlands will provide long-term mitigating feedbacks that are relevant to global climate-carbon modelling.

Broad biogeographic drivers, such as vegetation, climate, topography or water chemistry, are often emphasised as important global-scale controls on organic matter accumulation, decomposition and carbon stocks within tidal wetlands[7]. However, relative sea-level trends over the Holocene vary across the globe, principally on the basis of distance from maximal ice-sheet extent during the last glacial period, and have a profound influence on the contemporary character of coastal wetlands[8,9]. In Europe and North America, where studies of coastal wetland SLR impacts are concentrated, sea levels have been rising over the past few millennia, at a decelerating rate up to the present (Fig. 1a-b). Tidal marshes in these locations, particularly when sediment supply is low-moderate, are often characterised by deep sediments that are highly organic[4,10,11], and this contrasts with coastal wetlands in locations where sea level has been stable for the past few millenia[12], in spite of similarities in floristics[13].

We review published data, contribute new observations on carbon in tidal marsh sediments, and compare %C over the active root zone (0-20 cm) and sub-surface depths (20-50 cm, 50-100 cm, >1 m) for 345 locations in which sea level was rising, stable or falling over the late

Holocene (Supplementary Information). We found that variation in RSLR over past millennia is a primary control on carbon storage. Overall %C varies consistently between RSLR zones, with concentrations over the upper 1 m significantly higher in zones subject to high rates of RSLR over the late Holocene (i.e. I-II, II) compared with zones subject to relative sea-level stability over the same period (i.e. IV, V) (Fig. 2, Extended Data Tables 1-3; $P<0.001$). The upper metre is the IPCC-endorsed standard for tidal wetland carbon stock estimation[14], and in stable sea-level zones integrates processes over several thousand years[15,16]. Where data was available at depths exceeding 1 m, we found that this pattern of high storage in zones exhibiting RSLR over past millennia persisted (Fig. 2). Furthermore, the decline in %C with depth was greater in zones where sea level was relatively stable (i.e. IV, V), yet remained relatively high in zones where rates of RSLR were high (Fig. 2, Extended Data Table 4; $P<0.001$). Trends were consistent with these findings in zones I and III, as well as in transitional regions, though relatively few data were available from these locations (Extended Data Fig. 1; Extended Data Table 4).

Models emphasising biotic controls over coastal wetland elevation response to SLR have been largely derived from coasts with ongoing long-term SLR[11,17], where the vertical space available for mineral and organic material accumulation (henceforth termed available accommodation space) continued to expand as the sea rose over the past few millennia (Fig. 1c). In these situations, high rates of RSLR over the Holocene had the combined effect of promoting mineral and organic matter accumulation, and slowing rates of decomposition. That is, as sedimentation is positively correlated with patterns of inundation frequency[18], rapid accumulation of mineral and organic material is an outcome of the effect of RSLR on increasing inundation. Material that accumulates under conditions of RSLR becomes progressively submerged, creating more anoxic conditions that inhibit more rapid aerobic pathways of organic matter decomposition. A significant proportion of the world’s tidal marsh[19] occurs in locations regarded to be relatively tectonically and isostatically stable, and their capacity to respond to accelerated RSLR has received little attention. For these coastal wetlands, several millennia of sea-level stability (Fig. 1d) provides considerable time for decomposition of organic material, and as organic material is progressively stored near the limit of tidal inundation, decomposition increasingly occurs under comparatively aerobic conditions.

Available accommodation space is a useful framework for considering response of tidal wetlands to SLR as it integrates the influence of both tide range and position within the tidal frame[20]. We describe effective accommodation space within tidal coastal wetlands as being bounded by the bedrock basement, highest astronomical tides (HAT) and hydrodynamic conditions that favour vertical accretion and/or lateral progradation, rather than sediment entrainment (Fig. 1e). As mineral and organic sediments accumulate, the available accommodation space diminishes (i.e. a portion of the effective accommodation space is converted from available to realised accommodation space, Fig. 1e). This is only relieved by RSLR, achieved either by subsidence associated with isostatic or tectonic processes, autocompaction of sediments associated with consolidation or decomposition of mineral and organic material, or eustatic SLR, which increases both vertical accommodation space for sediment accumulation and lateral accommodation space for landward encroachment[6]. Addition of bulk organic material from roots further acts to decrease the volume of available accommodation space[21,22].

The coastline of southeastern Australia is an ideal location to explore alterations to wetland accommodation space and SLR as the region is regarded to be relatively tectonically stable

[23,24]. Geochronological analyses from a range of biological markers indicate that present sea level was attained approximately 7.8 thousand years ago (ka) and continued to rise up to 1.5 m above present levels approximately 7.5 ka, falling again to present levels approximately 2 ka[23]. The relative sea-level stability over the past 2 ka creates favourable conditions for decreasing accommodation space and progradation via accumulation of sediments, providing sediment is available for deposition (i.e. as per Fig. 1c).

Wetlands in this region grade from primarily mineral-dominated tidal marshes at elevations high in the tidal frame near HAT, toward shoreline fringing mangrove that are relatively lower in the tidal frame. Elevation of the wetland surface in the tidal frame is the relevant variable that indicates accommodation space. As such, low elevation mangroves at this study site are functionally equivalent to low elevation tidal marshes in climatic regimes that do not support mangroves. Accordingly, mangroves, like lower tidal marsh elsewhere, have more available accommodation space than the adjacent tidal marsh (i.e. as per Fig. 1e). *In situ* vegetation (i.e. mangrove and tidal marsh) differentially modulate organic matter additions with deeper root systems of mangrove able to add living biomass to greater depths within substrates[25], but additions remain proportional to available accommodation space, as conceptualised in Fig. 3. Under stable sea levels we might expect organic matter additions to decline as mineral sediment continues to be delivered by tides and deposited on wetland surfaces, and the wetland surface approaches the upper limit of available accommodation space, represented by HAT under most conditions as periodic salt stress prevents encroachment of terrestrial vegetation. Increases in the contribution of organic material lower in the tidal frame would continue as long as accommodation space is available. Accordingly, as SLR increases available accommodation space we might expect to see an increase in both mineral additions and carbon storage through burial near wetland surfaces.

To test the effect of RSLR on available accommodation space and soil organic carbon accumulation in a zone V wetland, we selected a study site that experienced recent rapid RSLR following subsidence caused by removal of pillars in an underlying coal mine (Chain Valley Bay, Lake Macquarie, Australia; 33°10'S, 151°35'E, Supplementary Information). Subsidence corresponded to high-end IPCC projections of SLR at 2100 (~1 metre) but was concentrated in the space of a few months in 1986. Following subsidence, tidal marsh and adjoining terrestrial vegetation rapidly transitioned to mangrove and mangrove transitioned to subtidal wetland over a 5-10 year period. We determined sediment chronologies from cores extracted from substrates that are currently mangrove and submerged.

Vertical accretion in both the mangrove and submerged wetland increased following RSLR, with high proportional contribution of carbon-dense organic matter in both settings (Fig. 4). Bulk density rapidly declined following RSLR despite the higher sediment accumulation rate. Sediment accumulation in the new mangrove post-subsidence is approximately double the pre-subsidence tidal marsh and mangrove rate, whilst organic carbon accumulation had a four-fold increase. The sediment and organic carbon accumulation rate within the newly created subtidal wetland, now a seagrass bed, was still accelerating 30 years after the subsidence event.

We argue that under relatively stable or slightly falling sea levels, as occurred throughout much of the southern hemisphere over the past few millennia, wetlands become increasingly mineral-dominated and favour carbon loss over accumulation as accommodation space diminishes. Our global analysis demonstrates the latent capacity for high organic carbon accumulation contributing towards elevation gains under conditions where available accommodation space increases, as occurs under accelerated RSLR.

These results substantiate that carbon accumulation and storage is related to available accommodation space, which is influenced by rates of RSLR. They imply that SLR will lead to increases in carbon sequestration and storage in many places where vertical accommodation space has previously been constrained by stable or declining sea levels, including southern Africa, Australia, China and South America which contain half of the global tidal marsh extent[19]. This feedback will be further enhanced where lateral expansion of wetlands in response to RSLR can be accommodated, unless interrupted by storms or other perturbations. A doubling of carbon sequestration rates across wetlands along these coasts could potentially sequester an additional 5 Tg C yr^{-1} [19], which might provide an important mitigating negative feedback with atmospheric carbon. Wetland loss to clearance[26,27] and impediments to tidal exchange continues to threaten the capacity of coastal wetlands to mitigate climate change[28] both now, or in the future as seas continue to rise[29]. Reversing these trends will further improve the carbon sequestration value of coastal wetlands under future, more rapid SLR.

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Supplementary information. This file contains Supplementary Methods, Supplementary Table and Supplementary References. The Supplementary Methods includes a detailed site description of Chain Valley Bay, Lake Macquarie, Australia, and the method for analysing C density, and the influence of global scale climatic and sea surface salinity variability on carbon concentration. The Supplementary Table includes the compilation of tidal marsh soil carbon concentration used in this study and associated Supplementary References.

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Author contributions. KR, NS and CW developed the premise of the paper. JK, NS, JPM, JBA, JRH, ML, LSB and KR gathered and produced input data for the global analysis. JK undertook global scale statistical analyses. KR, DM and AZ undertook local study fieldwork, sample preparation, laboratory and statistical analyses. KR, JK, NS and CW wrote the paper. All authors contributed to editing and revising the paper.

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Fig. 1. Millennial-scale influence of relative sea level on wetland evolution and accommodation space. a) Generalised RSLR zones over the Holocene (from Clark et al.[9]), and sample data used in this study, shown as green spots (n=345 locations). b) Generalised relative sea-level history over past 6 millennia (from Clark et al.[9]). c) Wetland surface evolution within accommodation space, defined by highest astronomical tides (HAT) and mean sea level (MSL), which elevates as the sea rises. d) Wetland surface evolution within stable accommodation space, as occurred in southeastern Australia over late Holocene (from Allen[17]). e) Conceptualised wetland accommodation space, shown here in two-dimensions.

Figure 2: Influence of late-Holocene RSLR on C concentration. Tidal marshes located along coasts with rapid RSLR in the late Holocene contain higher %C than marshes along coasts with relatively stable sea level. %C over various depths from late Holocene RSLR a) zone I-II (rapid RSLR), b) zone II (rapid RSLR), c) zone IV (stable RSL) and d) zone V (stable RSL). Letters represent significant difference in %C among depths in the 0-100cm range within each RSLR zone. Boxplots for data poor RSLR zones (including I and III) are presented in Extended Data Fig. 1.

Fig. 3. Conceptual links between mineral and organic matter accumulation and realised accommodation space. Model of sediment characteristics with respect to realised accommodation space, here shown in two-dimensions to represent the three-dimensional wetland accommodation space. Sedimentation may vary between sites based on mineral and organic sediment availability, and the addition of root material, which is a function of the productivity of vegetation. For simplicity, and following others[30], mineral sediment addition was conceptualised to increase linearly with accommodation space, but may diminish with elevation in an exponential or polynomial manner. Accommodation space varies because of mineral and organic sediment accumulation, SLR and autocompaction.

Fig. 4. Sediment accumulation and character related to available accommodation space. a) Calculated sedimentation rate (± standard error) and b) mass accumulation rate (± standard error) derived from ^{210}Pb dating; and c) bulk density and d) carbon density of mangrove (previously saltmarsh and terrestrial vegetation) and submerged (previously mangrove) sediments from Chain Valley Bay (outliers representing modern live root material at depth). The depth and associated age of sediments at which the subsidence event is evident indicated by dashed line. ^{210}Pb activity for mangrove and submerged cores and ^{137}Cs validation of ^{210}Pb chronology provided in Extended Data Fig. 2 and 3, respectively.

Methods

Review of global tidal marsh carbon accumulation. Tidal marshes were the focus of our global analysis due to their global distribution relative to other tidal wetlands (i.e. mangroves). We collated published records of carbon concentration (%C) and/or organic matter concentration (%OM) in tidal marshes as these are the two most widely reported measures related to carbon content and are less confounded by variation in mineral content and methodological error than values that incorporate bulk density (e.g. g C cm^{-3} or g OM cm^{-3}). We tested the sensitivity of our results to the choice of carbon content versus bulk density as response variables and confirmed that the two metrics produce similar patterns with respect to the role of RSLR variation on C sequestration (Supplementary Information, Extended Data Fig. 5, Extended Data Tables 5-8). This collation of records included research theses, national data collations, unpublished data, studies identified by previous reviews[19,31], and incorporated new literature identified using the same search terms as Ouyang and Lee[19], (Supplementary Information). We then identified records that contained data across the active root zone (0-20 cm), mid (20-50 cm), deeper (50-100 cm) depth intervals and beyond. This was undertaken to i) compare the influence of the active root zone among RSLR zones; and ii) assess carbon accumulation across a period approaching centuries to millennia, based on global rates of tidal marsh accumulation of <10 mm y^{-1} [19]. Organic matter concentration data were converted to %C[32]. When multiple cores were available for a study location, we calculated mean %C values across replicate cores for each depth interval. Study locations with different geomorphic and/or floristic characteristics within a marsh were deemed to be different study locations for this purpose. The vast majority of studies retained live and dead roots in their analysis, though there were regional exceptions to this. For example, all Chinese records (Zone IV) removed roots prior to %C analysis. To account for the potential of confounding effects of zones and methods, we recorded the aperture of the sieve and included it as a covariate in statistical analyses.

This approach resulted in a database comprising 1266 depth interval records, across 345 locations (Supplementary Information). Data were assigned to RSLR zones based on local or regional Holocene sea-level curves[24,33,34]. A linear mixed model[35] was used to assess the relationships between the dependent variable soil %C and the fixed factors of soil depth (three repeated measure levels: 0-20cm, 20-50cm, 50-100cm) and RSLR zone (eight levels: Zones I through V and I-II, II-III and IV-V transitional regions). The influence of climate and salinity was also tested using a linear mixed model (Supplementary Information). Climate was found to be insignificant (Extended Data Table 1), whilst extremely weak linear regression relationships between salinity and %C were identified over three depth intervals ($R2<0.07$, $P<0.001$, Extended Data Fig. 4), with little effect on the significance of RSLR zone on %C in the linear mixed model (Extended Data Table 2).

To further assess variations in %C with soil depth, a separate repeated measures analysis of variance (RM-ANOVA)[36] was completed for each RSLR zone. Linear mixed model pairwise comparisons and RM-ANOVA outcomes are reported for data rich RSLR Zones: II (156 locations), IV (68 locations), V (63 locations) and I-II transition (36 locations). Other RSLR Zones (I and III) and transitional regions were considered data poor, and were excluded from these pairwise comparisons.

Core extraction and sediment characterisation. Continuous cores of approximately 1.5-2 m length were extracted within vegetation zones along two transects that were normal to vegetation zonation and the shoreline of Chain Valley Bay, Lake Macquarie (See detailed site description in Supplementary Information). The sediment character of all cores was described. Detailed analysis of bulk density, grain size, carbon and nitrogen content and carbon and nitrogen stable isotope analysis was undertaken on selected cores. This paper presents information on the submerged wetland and mangrove core. Grainsize analysis was undertaken using a Malvern Mastersizer 2000 laser diffractometer. Elemental analysis and stable isotope analysis was undertaken using continuous flow isotope ratio mass spectrometer (CF-IRMS), model Delta V Plus (Thermo Scientific Corporation, USA) interfaced with an elemental analyser (Thermo Fisher Flash 2000 HT EA, Thermo Electron Corporation, USA).

Radiometric sediment dating. Sediment samples from cores that underwent detailed sediment characterisation were also processed for ^{210}Pb and ^{137}Cs radiometric dating to determine rates of sediment accumulation. Sediment cores were sliced at 1 cm intervals and prepared for analysis of excess ^{210}Pb activities using alpha-particle spectrometry[37]. Bulk samples were prepared for ^{137}Cs activity analysis using gamma-ray spectrometry. All analyses were undertaken at the Australian Nuclear Science and Technology Organisation (ANSTO). Recent sediment chronologies derived from analysis of excess ^{210}Pb activities were determined using the Constant Rate of Supply (CRS) model and validated using the presence of a subsurface peak in the ^{137}Cs activity concentration for each core, which marks the 1963 depth[38].

Data availability. The data that support the global analysis of carbon concentration with respect to Holocene RSLR is provided in Supplementary Information. The data that support the Chain Valley Bay study site analysis are available from the corresponding author upon reasonable request.

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Extended Data Fig. 1 Relationship between late-Holocene RSLR and C concentration for data poor late Holocene RSLR zones and transitional zones. Boxplots of tidal marsh soil C concentration (%) for data poor Holocene relative sea-level rise (RSLR) zones and transitional regions: zone I (a), zone II-III transition (b), zone III (c), and zone IV-V transition (d).

Extended Data Fig. 2 ^{210}Pb activity of submerged and mangrove sediments. Supported, total and unsupported ^{210}Pb activity (Bq/kg) for the submerged core sediments (a-c) and mangrove core sediments (d-f).

Extended Data Fig. 3 ^{137}Cs activity of submerged and mangrove sediments and ^{210}Pb chronology. ^{137}Cs activity (Bq/kg) and constant rate of supply (CRS) based ^{210}Pb chronology for submerged core sediments (a-b) and mangrove core sediments (c-d). The grey validation lines indicate that the ^{137}Cs activity peak, which approximates to 1964, corresponds to the CRS based ^{210}Pb chronology (NB: core dating occurred in 2014).

Extended Data Fig. 4 Relationship between sea surface salinity and C concentration over three depth intervals. Regression analysis of C concentration and global scale sea surface salinity, derived from the NASA Aquarius Satellite Mission, exhibited extremely weak relationships over the depth interval of a) 0-20 cm (R^2=0.07, $P<0.001$), b) 20-50 cm (R^2=0.07, $P<0.01$), and c) 50-100 cm (R^2=0.06, $P<0.001$).

Extended Data Fig. 5 Relationship between late-Holocene RSLR and C density for data rich late Holocene RSLR zones and transitional zones. Boxplots of tidal marsh soil C density (g/cm^3) for data rich Holocene relative sea-level rise (RSLR) zones and transitional regions: zone I-II transition (a), zone II (b), zone IV (c), and zone V (d).