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Global change biology

Mangrove dynamics and blue carbon sequestration

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We monitored coastal wetland vertical accretion, elevation gain and surface carbon (C) at Homebush Bay, Australia over 18 years (2000–2017) in three settings initially characterized by saltmarsh, mixed saltmarsh–mangrove ecotone and mangrove-dominated zones. During this time, the saltmarsh transitioned to mixed saltmarsh–mangrove ecotone, and the mixed saltmarsh–mangrove ecotone transitioned to mangrove, consistent with vegetation transitions observed across the east Australian continent in recent decades. In spite of mangrove recruitment and thickening in the former saltmarsh zone, and the dominance of mangrove root material as a contributing C source, the rate of C accumulation in the former saltmarsh zone did not change over the study period, and there was no significant increase in surface elevation. This contrasted with the response of sites with a longer history of mangrove colonization, which showed strong accretion and C accumulation over the period. The result suggests that the C accumulation and surface elevation gains made as a result of mangrove colonization may not be observable over initial decades, but will be significant in the longer term as forests reach maturity.

1. Introduction

Climate change is driving shifts in the distribution of vegetation communities across the globe [1], including the poleward movement of cold-intolerant species [2]. Along several sub-tropical and temperate coastlines where mangrove forests occur seaward of saltmarshes, mangroves have been observed replacing saltmarsh as the dominant vegetation community [3], a trend set to continue as temperatures warm and sea-level rises [4,5].

Appropriate management responses to these transitions depend on a clear understanding of the multiple and often related ecosystem services at the local scale. In southeastern Australia, where mangrove encroachment has been observed as a regional-scale trend extending more than half a century [6], experimental mangrove removal for the protection of bird habitat has become increasingly common. However, this might be detrimental to the long-term survival of the wetland if mangrove encroachment proves to be a mechanism for elevating the wetland surface. In this regard, mangrove replacement of saltmarsh may contribute towards building elevation by trapping sediment and sequestering atmospheric C into below-ground root matter, providing a negative feedback to relative sea-level rise. By sequestering atmospheric C at a rate higher than saltmarsh, mangrove may be more effective at providing the dual services of carbon mitigation coastal adaptation.

The effect of mangrove forest encroachment of saltmarsh on elevation gain and C sequestration has proved equivocal. Given the elevation building potential of mangrove root systems and generally higher root productivity [7,8], it would be

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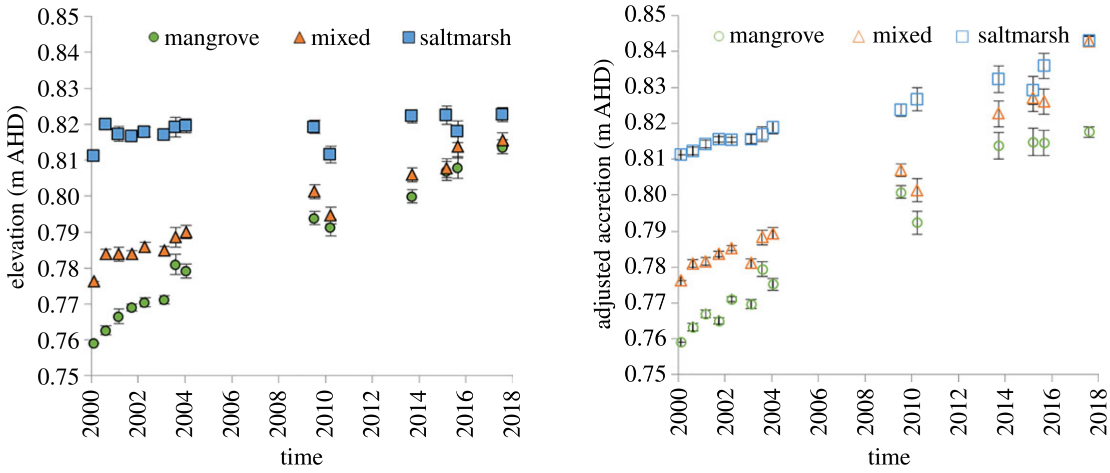

Figure 1. (*a*) Elevation changes of mangrove, mixed ecotone and former saltmarsh zones using SETs (standardized to m AHD), and (*b*) accretion trends in mangrove, mixed ecotone and former saltmarsh zones using MHs (standardized to m AHD). Data are provided in electronic supplementary material, S2. (Online version in colour.)

Table 1. Accretion rates above MH. Elevation (m above Australian Height Datum (AHD)) is reported as the mean of three SET-MH stations. Real-time kinematic (RTK) GPS measurement in 2015 corrected to the commencement of the experiment (2000).

zone	elevation (mean ± 1 s.d.) (m AHD)	accretion trend (mm y^{-1})	r^2	*p*-value
mangrove	0.76 ± 0.06	3.66	0.93	<0.001
mixed ecotone	0.78 ± 0.06	3.18	0.92	<0.001
former saltmarsh	0.81 ± 0.05	1.29	0.97	<0.001

Table 2. Density and rate of surface C accumulation above MH, derived from replicate cores taken from the mangrove forest and former saltmarsh zones, adjacent to SET-MHs. National estimates of surface C accumulation (mean ± 1 s.d.) from literature derived from SET-MH or radiometric dating.

ecosystem	surface C density (g C cm^{-3})	surface C accumulation rate (Mg C ha^{-1} y^{-1})	reference
mangrove 1	0.033	1.13	This study
mangrove 2	0.029	1.16	
former saltmarsh 1	0.029	0.30	
former saltmarsh 2	0.035	0.54	
mangrove (Australia)		1.3 ± 0.9	[22]
saltmarsh (Australia)		0.55 ± 0.34	[23]

reasonable to assume that mangrove forest encroachment of saltmarsh would encourage sediment trapping, C sequestration and hence elevation gain. However, comparisons of elevation gain in mangrove forests and saltmarshes produce contrasting findings. Studies in eastern Australia have pointed to the higher C sequestration rate in mangrove forests compared with saltmarshes [9,10], and a higher rate of surface elevation gain [11,12]. However, such comparisons are confounded by differences in elevation and hydroperiod between the two communities, with saltmarsh occurring in more landward, less frequently inundated locations. By contrast, on the US Gulf coast, mangrove forests often grow at similar or higher elevations than saltmarshes, and here analyses of accretion over short and longer time scales have suggested similar rates of accretion in both ecosystems [13–16], though mangrove forests may be lower [17] or higher [18] depending on climatic and geomorphic setting. Although similar rates of accretion were observed between mangrove forests and saltmarshes at restoration sites at Ten Thousand Islands National Wildlife Refuge, mangrove forest surface elevation decreased while saltmarsh remained steady [19].

A better test of the implications of mangrove–saltmarsh vegetation transition on accretion and elevation gain would require *in situ* observations over the period of encroachment, thereby removing the confounding effect of elevation in space-for-time substitutions. Here, we examine C accumulation and elevation gain at a site subject to considerable mangrove thickening and expansion over an 18-year period

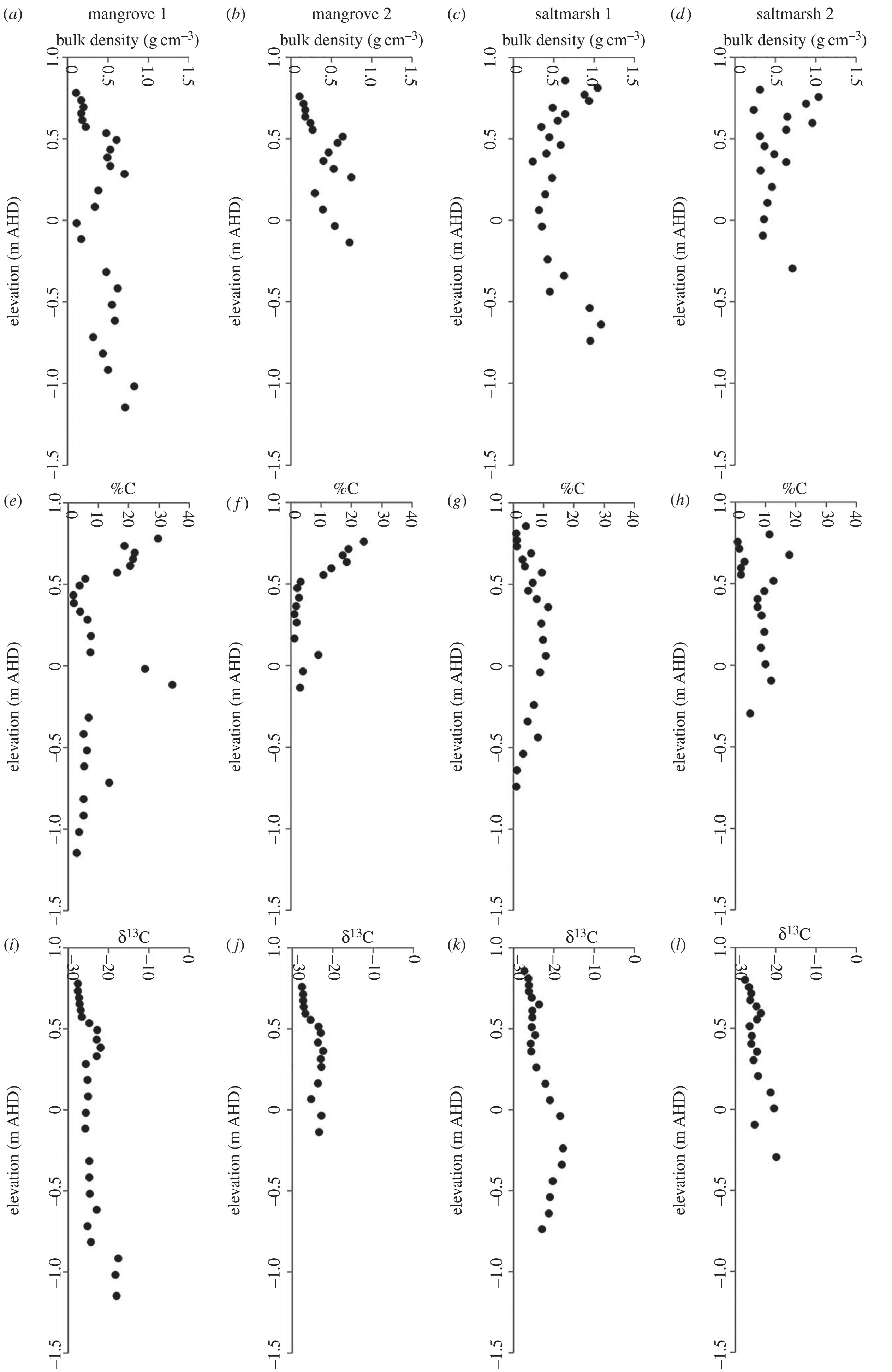

Figure 2. Bulk density (*a–d*), per cent organic C (*e–h*) and $\delta^{13}C$ (*i–l*) from mangrove and (former) saltmarsh zone core samples. Data are provided in electronic supplementary material, S3.

of observation. Our hypothesis was that the saltmarsh would transition to a mangrove forest and in doing so the rate of surface C accumulation and surface elevation gain would increase rapidly.

2. Material and methods

The Powells Creek wetlands are situated within Homebush Bay, Sydney Harbour, Australia (33°50′38″ S; 151°04′42″ E). The current mangrove forest appears to have been saltmarsh in photographs from the 1930s and 1950s, though became mangrove-dominated by the 1970s. During the 1980s, landward colonization of mangrove vegetation was disrupted by deposition of brick dust from an adjoining construction site, causing mangrove defoliation and the restoration of saltmarsh. Mangroves began to re-sprout and recolonize this area in the early 2000s [20]. In 2000, we installed surface elevation tables and feldspar marker horizons (SET-MHss) [21] in the saltmarsh, mixed saltmarsh–mangrove ecotone and mangrove zones of Powells Creek to determine trends in surface elevation change and vertical accretion. We took repeated measures over an 18-year period during which the saltmarsh zone transitioned to dense shrub-form mangrove, and the mixed saltmarsh–mangrove ecotone zone transitioned to tall mangrove of heights greater than 5 m (naming of vegetation zones henceforth follows original nomenclature). Towards the latter stages of the experiment, we took cores from the mangrove and (former) saltmarsh settings to document changes in C content and provenance (using δ^{13}C analyses), and sediment bulk density, and undertake radiocarbon dating. Detailed methods are provided in the electronic supplementary material, S1.

3. Results

All three zones showed linear trends in accretion over the 18-year record (table 1). The rate of accretion in the mangrove and mixed ecotone zones was twice that of the former saltmarsh zone, and the accretion rate in the former saltmarsh zone was not notably influenced by the thickening of mangrove vegetation (table 1, figure 1*a*).

Despite similarities in the density of C in surface sediments, accumulation above the MH suggests differing surficial rates of C accumulation between the mangrove and former saltmarsh zones (table 2). These estimates of C accumulation are likely to be particularly conservative in the mangrove zone, given the evidence of new root accumulation at depth.

The higher rate of accretion in the mangrove and mixed ecotone zones translated into an increase in surface elevation over time, and a gradual equilibration of surface elevation across the three zones (figure 1). The consistent low rate of accretion in the former saltmarsh zone did not translate into significant elevation gain, in spite of mangrove thickening.

Mangrove sediments have high %C and low bulk density throughout the surface 25 cm (figure 2). We interpret this as the modern mangrove rooting zone, reflected in the consistent δ^{13}C signature. A second C peak at approximately 0 m AHD, with similar C concentration and depleted δ^{13}C signatures as surface sediments, was regarded to be old, but also contained modern material, returning radiocarbon ages of 1200 years and 40 years.

Former saltmarsh-dominated sediments show higher bulk density relative to the mangrove sediments in the upper 40 cm (figure 2). Heterogeneous C concentrations in surface depths may correspond to contemporary mangrove roots in some locations, given the depleted δ^{13}C, though the chenopod *Sarcocornia quinqueflora* may also contribute to the isotopic signature. Below 40 cm in both saltmarsh cores, the material becomes increasingly enriched in δ^{13}C, associated with a higher %C (and lower bulk density).

4. Discussion

Most studies seeking to deduce the likely effects of mangrove forest encroachment on C storage and sequestration rates draw comparisons between mangroves and adjacent saltmarshes, showing higher C storage in the former [9,24]. Other studies are equivocal; Yando *et al*. [15] found differences in C storage to be significant only in drier locations, and Henry & Twilley [14] could find no difference in C storage within the sediments of mangroves and saltmarshes, an outcome attributed to the more oxidizing environment of the mangrove sediment in coastal Louisiana. Osland *et al*. [25] and Kelleway *et al*. [26] compared below-ground C across a chronosequence of encroachment dated from historical imagery, on the US Gulf coast and SE Australia, respectively, leading Kelleway *et al*. [26] to suggest that the identification of a significant contribution may take several decades.

Our study is the first to our knowledge to explore changes in C accumulation *in situ* as mangroves encroach and thicken within a saltmarsh. Our findings support that transitional zones do not quickly show increases in C storage [17,18]. After 18 years of mangrove forest development, the former saltmarsh zone showed little increment in %C or the rate of C accumulation within the soil, which is comparable to saltmarshes elsewhere in the region. Furthermore, what modest accretion occurred in the former saltmarsh zone failed to translate into vertical elevation gain. We therefore rejected our hypothesis that the rate of surface C accumulation and surface elevation gain would increase rapidly as mangrove encroached upon saltmarsh. Further work is required to determine whether this lack of change corresponds with a temporal lag in the proliferation of mangrove roots in the early stage of encroachment [27] or is related to the local hydrodynamic conditions in our study site. By contrast, areas that appeared as saltmarsh in early aerial photography (1930s–1950s) but were identified as mangrove forest or mixed mangrove–saltmarsh ecotone by 2000 showed rates of C sequestration consistent with other environments in the region, indicating that several decades are required before mangrove forest encroachment translates into increased C storage and surface elevation gain.

Data accessibility. The datasets supporting this article have been uploaded as part of the electronic supplementary material.

Authors' contributions. N.S. and K.R. designed the experiment, collected and analysed data and wrote the manuscript. D.M. and J.J.K. analysed the data and contributed to the writing of the manuscript. All authors gave final approval for publication and agreed to be held accountable for the work described herein.

Competing interests. The authors declare no conflicts of interest.

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