# How Sydney Olympic Park's mangroves are responding to climate change

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**The Badu Mangroves precinct within Sydney Olympic Park supports the largest remnant mangrove forest in the Sydney Harbour-Parramatta River estuary. The forest has been continuously monitored using the Surface Elevation Table-Marker Horizon technique for nearly 20 years, providing insights into the response of mangroves to two decades of sea-level rise. Surface elevation gain in the wetland has been strongly linear over the time period and corresponds to approximately 6cm of vertical accretion comprising mineral and organic matter accumulation. Mangrove root material is contributing to over 40 tonnes of carbon sequestration per year within the wetland, contributing to vertical adjustment of the wetland surface. Sea-level rise over the period has been higher than the rate of mangrove vertical adjustment, though is more variable. Mangrove dieback within the wetland is consistent with a ponding of water during the spring tide cycle and has been ameliorated by the cutting of a direct channel from the dieback zone to the main creek channel. The long-term fate of mangroves within the parklands will be determined by emissions pathways over the coming decades and local decisions concerning land use, coastal protection and floodgate operation.**

## Introduction

Sydney Olympic Park supports some of the largest mangrove forest within Sydney Harbour, with forests located in each of the precincts of Badu Mangroves, Haslams Reach, Newington Nature Reserve and Nuwi Wetland. The mangrove is dominated by the grey mangrove *Avicennia marina*, with minor representation of the river mangrove *Aegiceras corniculatum*. The largest forest, Badu Mangroves, has been modified since the 1950s with the training of Powells Creek (initially causing extensive dieback of mangrove lining the former channel) and the deposition of dredge spoil and brick dust on the site, subsequently colonised by saltmarsh (Rogers et al. 2005). Mangroves have since expanded to cover most of the area of original saltmarsh.

The mangroves at Sydney Olympic Park, in common with mangroves across the globe, are facing the pressure of accelerating sea-level rise. Global eustatic sea-level rise has accelerated through the past century, increasing from an average rise of 2.0 ± 0.3 mm yr $^{-1}$ in the period 1966-2009 to 3.4 ± 0.4 mm yr $^{-1}$ in the period 1990-2009 (White et al. 2014). Sea-levels in Australia are influenced year-to-year by large-scale ocean-atmosphere drivers such as the El Nino Southern Oscillation and the Indian Ocean Dipole. When adjusted for these influences, the mean rate of sea-level has risen from 1.4 ± 0.2 mm yr $^{-1}$ in the period 1966-2009 to 4.5 ± 1.3 mm yr$^{-1}$ for the period 1993-2009 (White et al. 2014). Tide gauges within the Badu Mangroves suggest a similar rate of rise over the past two decades.

Sea-level rise poses challenges and opportunity for mangroves. Mangroves respond dynamically to changing inundation patterns and increases in inundation frequency can lead to increases in the rate of sedimentation and plant productivity. However, upper thresholds to these feedbacks are suggested by the palaeo-stratigraphic archive (Saintilan et al. 2020). Monitoring networks are being established to carefully explore the response of mangroves across the globe to sea-level rise. Badu Mangroves is one such wetland, and this paper presents results emerging from nearly two decades of observations of mangrove adjustment to sea-level rise.

## Monitoring Elevation Gain

The surface elevation table is an elevation benchmark inserted deep into a wetland substrate, against which changes in the elevation of the wetland surface are measured. At the same time a small quadrat is covered with white feldspar powder, which serves as a marker horizon against which sediment accretion can be measured. The two techniques, when used together (referred to as the Surface Elevation Table-Marker Horizon or SET-MH method), allow both the estimation of elevation gain and the extent to which sediment accretion is contributing to surface elevation gain. If elevation gain is less than accretion over the same time period, the difference is the degree of subsidence occurring in the wetland between the surface and the base of the SET benchmark pole (Figure 1).

A network of SET-MH stations was installed in the Badu Mangroves and saltmarsh in 2000 and has been continuously monitored for 20 years. This is one of the longest SET-MH records in the world, and the unusual longevity of the buried feldspar horizons makes this the longest mangrove MH record known globally (Figure 2). The Badu Mangroves at Sydney Olympic Park are therefore providing a unique record of the

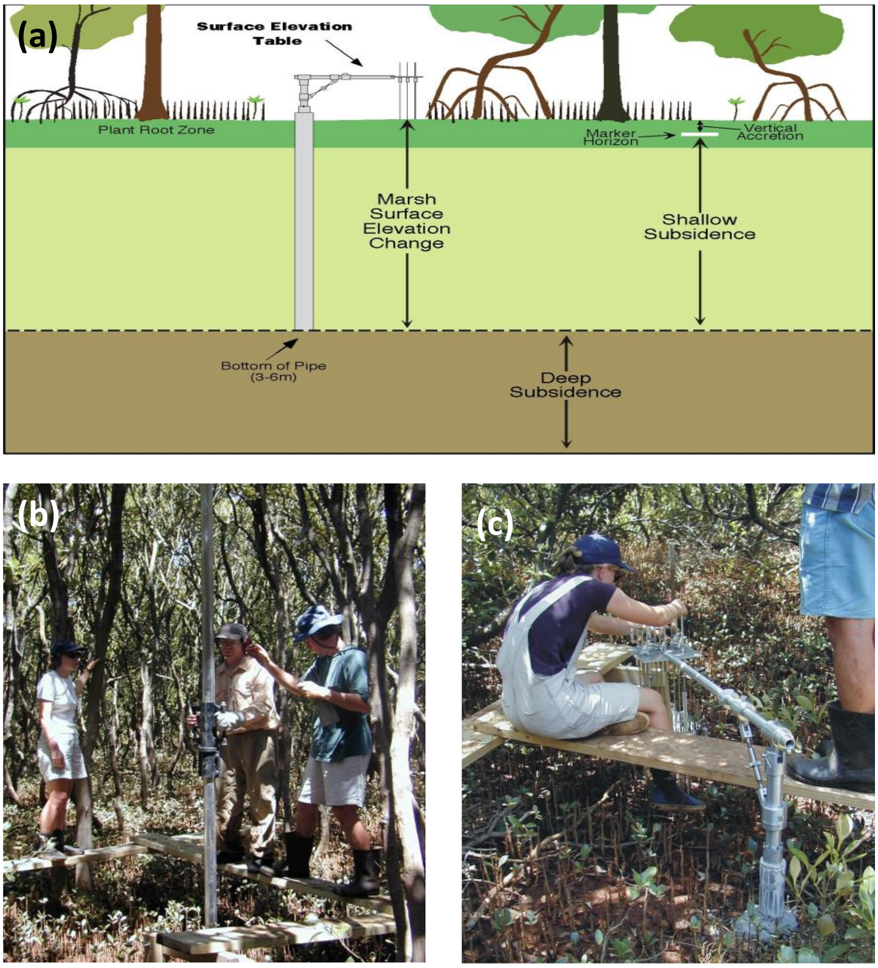

**Figure 1.** (a) The SET-MH monitoring station as installed in the Badu mangrove and saltmarsh. (b) Installation of the SET benchmark pole and (c) first readings in 2000

relationship between sea-level rise, wetland accretion and elevation gain. The Greater Sydney Local Land Services has produced an excellent video featuring the SET-MH method in the Badu Mangroves, accessible through this link https://vimeopro.com/littlegeckomedia/gslls-saltmarsh-and-mangrove-ecosystems/video/322132198).

At the Badu Mangroves wetland, three SET-MH stations were installed in the mangrove, three in the saltmarsh, and three in a mixed mangrove-saltmarsh zone. Each SET was accompanied by three feldspar MH plots. Badu Mangroves wetland is one of seven sites in SE Australia established at the time (the others being Tweed River, Hunter River, Hawkesbury River, Minnamurra River, Jervis Bay and Westernport Bay). Since then, SET-MH monitoring stations have been established in Queensland, the Northern Territory and Western Australia, part of an international network of SET stations in more than 20 countries (Webb et al. 2013). Pooling of data across this network has clarified the vulnerability of mangroves to sea-level rise and reductions in sediment input due to water resource developments in large river catchments (Lovelock et al. 2015).

The mangroves in the Badu Mangroves wetland have largely increased in elevation at a remarkably linear rate ($r^2$ = 0.97), corresponding to a linear increase in accretion ($r^2$ = 0.97). The rate of elevation gain in the mangroves (about 6cm over 20 years) is slightly lower than the annual rate of surface accretion, though both are approximately similar to the rate of sea-level rise as measured at a tide gauge within Powells Creek (Figure 3). As can be seen in the tide gauge data, sea level in any given year is variable, being influenced by local meteorological and oceanic conditions. For example, water levels within Powells Creek in 2016-2017 were 13cm higher on average than in 2002-2003, the year of tide gauge installation (Figure 3).

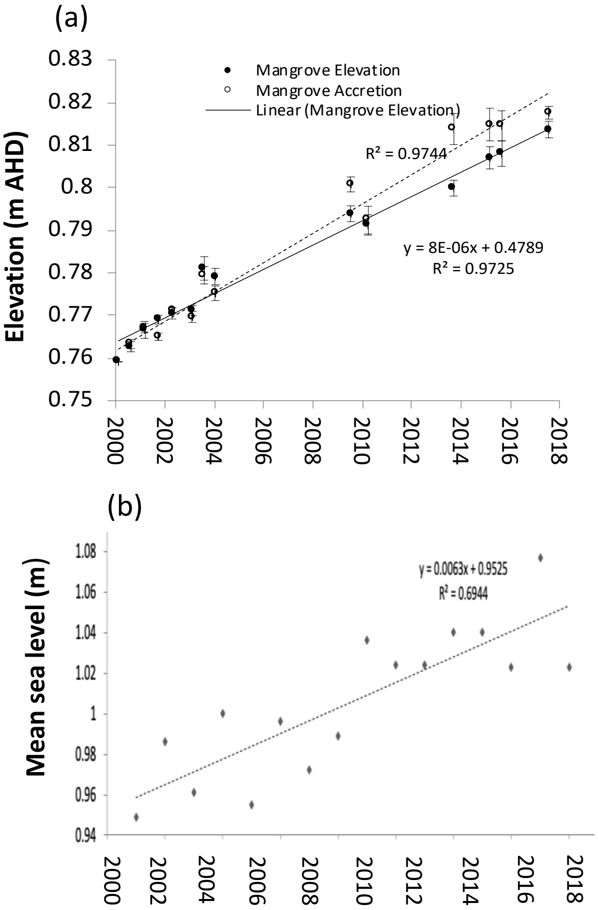

**Figure 3:** (a) Change in elevation 2000-2018 in the Mangrove SET-MH stations. (b) average annual mean sea level within Powells Creek 2002-03 until 2017-18

**Figure 2.** A Badu Mangroves feldspar marker horizon at installation (a) and soil core retrieved from the plot 17 years later, showing 7cm of organic and sediment accretion.

## Carbon sequestration in the Badu Mangroves

An important component of vertical elevation gain in the Badu Mangroves is new root accumulation. Mangroves, like all plants, fix atmospheric carbon dioxide during photosynthesis and use the resulting organic carbon to build plant mass, including their root system. These roots accumulate both at the surface (Figure 2b) and at depth to increase the volume of the soil, contributing to surface elevation gain. Mangrove carbon fixation is therefore a small negative feedback on increased atmospheric carbon dioxide concentrations. Elevated atmospheric $CO_2$ increases mangrove growth rate through both the atmospheric fertilisation effect and elevated temperatures (McKee et al. 2012). Accelerating sea-level rise also increases new root formation, and the efficiency of root carbon storage in mangrove sediment (Rogers et al. 2019a). The constantly saturated conditions protect mangrove organic material from exposure to oxygen, greatly reducing the rate of decomposition and conversion back to atmospheric $CO_2$.

The Badu Mangroves have a high percentage of carbon in the upper 25 cm of their soil, reflecting the strong contribution of new root material in this zone (Rogers et al. 2019b). The accumulation of new organic carbon on the surface as measured by the SET-MH stations in Badu Mangroves suggest an accumulation of organic carbon of 1.13-1.16 tonnes per hectare per year, or about 40 tonnes of carbon sequestered per year across the wetland. This is likely to be a conservative estimate. Old mangrove root material was found at a depth of 1 metre (dating to approximately 1200 years before present), but modern root material was also found at these depths (Rogers et al. 2019b), suggesting that new mangrove root material is being incorporated across the whole profile, as also observed on the Hawkesbury River (Lamont et al. 2020) and Port Stephens (Kelleway et al. 2017).

One obvious change since the SET-MH stations were installed in 2000 has been the proliferation of mangroves in the saltmarsh along the western edge of the wetland. SET plots in a 'mixed zone' of saltmarsh plus occasional mangroves in 2000 are now devoid of saltmarsh, and the saltmarsh zone has transitioned to a mixed mangrove-saltmarsh. Rogers et al. (2019b) found little increase in carbon storage as a result of this mangrove thickening, a finding corresponding to short-term encroachment studies in the United States Gulf Coastline (Osland et al. 2012; Doughty et al. 2016). It is probable that a longer time (40-50 years) is required before the influence of encroachment of mangroves is obvious in soil carbon storage (Kelleway et al. 2016).

**Figure 4:** Mangrove dieback in the Badu Mangroves wetland

## Mangrove dieback

An area of mangrove dieback covering over 2000 m$^2$ was noticed in Badu Mangroves during annual inspections in 2014. Examination of aerial photography indicated that the dieback had commenced in 2013, two years after a "step-change" in average sea-level between 2010 and 2011 (Figure 3). The area was waterlogged, and poor drainage was noticed relating to impediments to flow between the dieback area and feeder channels to Powells Creek (Sydney Olympic Park Authority 2014). The area expanded to cover over 6000 m$^2$ by 2017 (Figure 4). Water level recordings within the dieback zone in 2016 suggested that up to 10 cm of water was ponding at the site over the duration of a spring tide cycle (Manly Hydraulics Laboratory 2016). This is a sufficient depth to inundate the aerial roots (pneumatophores) leading to anoxia and dieback of *Avicennia marina.*

The dieback of interior mangroves due to impediments to the ebbing tide is an anticipated outcome of sea-level rise (Rodriguez et al. 2017). Flat areas within wetland interiors cannot be efficiently drained, increasing the timeframe of inundation (hydroperiod) of larger tides

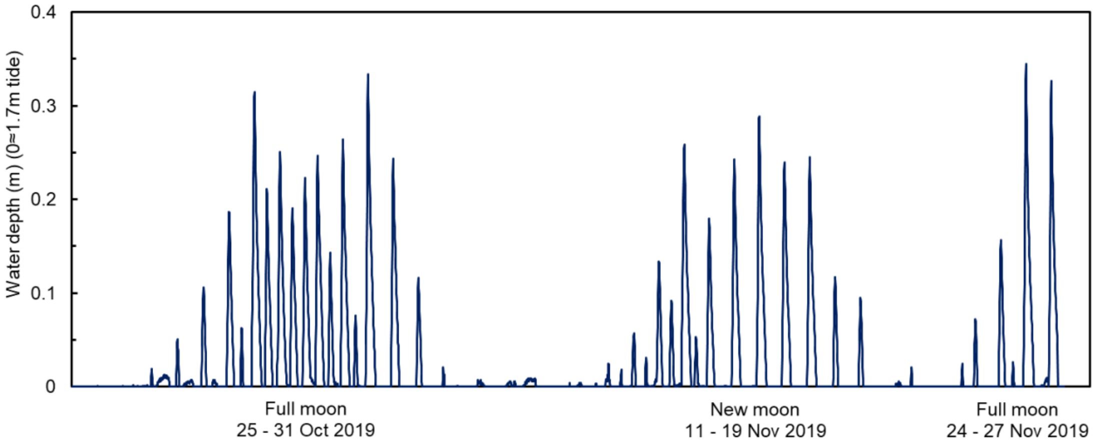

**Figure 5:** Water level within the Badu Mangroves dieback zone following the cutting of an auxiliary channel.

beyond that encountered at the more steeply sloping seaward edge of the wetland. This gives rise to the counter-intuitive but widely observed result that coastal wetlands break up from the inside out when under anoxic stress from sea-level rise (Rodriguez et al. 2017). The natural infilling of the Badu Mangrove surface observed since 2000 (Figure 2) has reduced elevation gradients between the seaward and landward edge of the forest, providing a further impediment to the egress of water on the ebb tide.

In 2019, a 70-metre-long channel was cut linking the dieback area directly to Powells Creek. The objective of the intervention was to improve drainage from the wetland, reducing hydroperiod during the spring tide cycle, with the aim of promoting mangrove recruitment and forest recovery at the dieback site. Water level measurements over two spring tide cycles in October-November 2019 within the dieback zone demonstrated the complete drainage of the wetland on all tides (Figure 5). Recruitment of seedlings and juveniles was observed over the 2019-2020 summer.

## Conclusions

Mangroves within the Badu Mangroves wetlands are accreting vertically, offsetting the effect of recent sea-level rise. An important component of this vertical elevation gain is organic carbon, which has been stored within the wetland for over 1000 years. The Badu Mangroves fix and store over 40 tonnes of organic carbon every year. The interaction between sea-level rise, organic and mineral sediment deposition, and elevation gain suggest that simple "bath-tub" models of wetland response to sea-level rise are inappropriate and underestimate the resilience of wetlands within Sydney Olympic Park to sea-level rise.

However, the dieback of a patch of mangroves within the Badu Mangroves wetland due to hypoxic conditions demonstrates that the mangroves are not immune from the impact of sea-level rise, even under current rates. This dieback resulted from impediments to the egress of the ebb tide, continuously ponding water during spring tide cycles above the level of pneumatophores. The flattening of the wetland profile observed from a transect of Surface Elevation

Tables over 17 years (Rogers et al. 2019b) would also have contributed to resistance to ebb tide flow. The outcome has been anticipated from modelling of relative sea-level rise impacts on wetlands in the region (Rodriquez et al. 2017) and suggests that the interior of mangroves rather than the seaward edge is likely to show the first signs of deterioration under sea-level rise. Monitoring of the seaward edge of mangrove forests may be ineffective in rapid identification of stress in these situations.

The intervention of a direct channel linking the dieback zone and the main creek channel appears to have been successful in the short term and may be a useful model for interventions in other high value wetlands impacted by flooding stress. The long-term fate of the mangroves of Sydney Olympic Park will depend on decisions made concerning greenhouse gas emissions, because mangrove capacity to accrete is directly linked to the rate of relative sea-level rise (Krauss et al. 2017; Saintilan et al. 2020). Under mid- to high- emissions scenarios, mangroves will be unable to retain their current position and seek refuge in parkland areas currently above the reach of the spring tides.

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