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Spatial Variation in Carbon Storage: A Case Study for Currambene Creek, NSW, Australia

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ABSTRACT

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Quantifying carbon storage in coastal wetland environments is important for identifying areas of high carbon sequestration value that could be targeted for conservation. This study combines remote sensing and sediment analysis to identify spatial variation in soil carbon storage for Currambene Creek, New South Wales, Australia to establish whether vegetation structure influences soil carbon storage in the upper 30 cm. Wetland vegetation was delineated to capture structural complexity within vegetation communities using Light detection and ranging (Lidar) point cloud data and aerial imagery with an object-based image analysis approach. Sediment cores were collected and analysed for soil carbon content to quantify below-ground carbon storage across the site. The total soil carbon storage in the upper 30 cm for the wetland (59.6 ha) was estimated to be 3933 ± 444 Mg C. Tall mangrove were found to have the highest total carbon storage (1420 ± 198 Mg C), however are particularly sensitive to changes in sea-level as they are positioned lowest in the intertidal frame. Conservation efforts targeted at protecting areas of high carbon sequestration, such as the tall mangrove, will lead to a greater contribution to carbon mitigation efforts.

ADDITIONAL INDEX WORDS: *Coastal wetlands, mangrove, saltmarsh, object-based image analysis, loss on ignition, vegetation structure.*

INTRODUCTION

Saline coastal wetlands, particularly mangrove and saltmarsh, are globally recognised as valuable sinks of organic carbon (Barbier *et al*., 2011; Chmura *et al*., 2003). These environments are important for mitigating climate change by sequestering atmospheric carbon in plant biomass through photosynthesis. Organic material from biomass is subsequently sequestered within sediments for long periods until broken down by microbes (Duarte *et al*., 2005). Current knowledge of the spatial and temporal variation of carbon storage in these systems, both carbon storage in plant biomass and carbon storage in sediments, is limited (Gilman *et al*., 2008; Mcleod *et al*., 2011). Capturing spatial variation in carbon storage is important for evaluating carbon stocks within wetland ecosystems, and targeting areas for conservation and restoration that will more efficiently sequester carbon. This is particularly significant given projected changes in sea level, as the influence of sea-level rise on processes that drive carbon sequestration, such as sedimentation, soil biogeochemistry, and primary productivity, will vary spatially and temporally in wetlands (see review by Mcleod *et al*., 2011).

Current soil carbon estimates for wetlands largely focus on major vegetation communities, such as mangrove and saltmarsh (Chmura *et al*., 2003; Saintilan *et al*., 2013). Soil carbon storage may vary within these communities due to variation in structural forms of vegetation. These structural variations include species composition, height and density of vegetation. Established mangroves are often taller and have larger canopies than younger or stunted mangroves. This is likely to influence the depth of root zones, with taller mangroves having extensive and more developed roots than shorter, immature mangroves (Ong *et al*., 2004). Saltmarsh vegetation structure varies with species composition. *Juncus kraussii* and *Sporobolus virginicus* differ in height and density which is likely to influence plant biomass and soil carbon storage. Identifying variation in vegetation is useful for managing ecosystem services (Ewel *et al*., 1998). Capturing variation in vegetation structure may be important to improve estimates of soil carbon storage within a wetland.

This study aims to establish whether vegetation structure influences soil carbon storage in the upper 30 cm and whether this variation in vegetation is an important component when estimating total soil carbon storage within a wetland. This was achieved by combining remote sensing and carbon content analysis from sediment cores to provide an estimate of total below-ground soil carbon storage in the upper 30 cm of a wetland. Remote sensing was used to delineate wetland vegetation structure and capture vegetation complexity in greater detail than previous wetland vegetation mapping (Chafer, 1998; Oliver *et al*., 2012; Saintilan and Wilton, 2001). Sediment core extraction across the site in several vegetation forms will enable estimates of landscape scale carbon storage that are more accurate than approaches used previously (Howe *et al*., 2009; Rogers *et al*., 2013). In combination, this approach demonstrates the spatial variability of below-ground carbon storage. This is an important consideration when developing

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conservation and restoration priorities for coastal wetlands, particularly considering potential changes in vegetation composition due to sea-level rise.

Study area

Currambene Creek is a mature barrier estuary situated in Jervis Bay (35.0653ºS, 150.7347ºE) , New South Wales (Roy *et al*., 2001). The estuary supports temperate saline coastal wetlands comprising mangrove and saltmarsh. Mangroves are commonly positioned lower in the tidal frame than saltmarsh. Jervis Bay has a semi-diurnal tidal range of approximately 2 metres. Two species of mangrove are present in this region; predominantly *Avicennia marina* and also *Aegiceras corniculatum*. Commonly present saltmarsh species include *Sporobolus virginicus*, *Samolus repens*, *Juncus krausii* and *Sarcocornia quinqueflora* (Clarke, 1993).

METHODS

Wetland vegetation was delineated to structural forms using Lidar and aerial imagery coupled with an object-orientated image analysis (OBIA) approach (Owers *et al*., in review). These structural forms included: three classifications of mangroves based on height and diameter at breast height (DBH), tall mangrove (> 3 m height, > 15 cm DBH), shrub mangrove (1.3 – 3 m height, < 15 cm DBH), and dwarf mangrove (< 1.3 m height); saltmarsh species that were classified as rush (*Juncus krausii*), or herbs, grasses and sedges (*Sporobolus virginicus*, *Samolus repens*, *Sarcocornia quinqueflora*); mixed and sparse vegetation areas that comprised ecotone communities of mangrove and saltmarsh, where sparse vegetation had a sandy surface substrate; and *Casuarina glauca* woodlands that were positioned at higher elevations beyond tidal inundation. The OBIA methodology utilised the multiresolution segmentation algorithm to derive image objects from the remote sensing data that were then classified using the nearest neighbor algorithm. A hierarchical approach for segmentation and classification was used to delineate vegetation structural forms of mangrove and saltmarsh independently by initially delineating vegetation communities (see Owers *et al*., in review). The vegetation structural classification was validated using groundtruthed data. Spatial extents were extracted for each vegetation structure.

Sediment cores (twelve in total) were collected and analysed for soil carbon content and sediment characteristics. Core locations were selected to capture the spatial variability of vegetation structure, including position in the landscape and variation in environmental gradients such elevation and distance to shoreline (Figure 1c). Each core was analysed for soil carbon content and sediment characteristics to 30 cm depth and sub-sampled at depths of 0-2 cm, 2-4 cm, 5-6 cm, 10-15 cm, 15-16 cm, 20-21 cm, 25-26 cm, 30-31 cm. Particle size distributions were determined for all samples using a Malvern Mastersizer 2000. Wet samples were weighed and then dried at 60°C to a constant weight to estimate dry bulk density. Each sub-sample was then homogenised by grinding to a fine powder using a Retsch three-dimensional Vibrator Mill (Type-MM-2:Haan, Germany). Carbon content for all twelve cores was calculated using the Loss on Ignition (LOI) method in accordance with Ball (1964). Percent LOI was calculated to give an estimate of the percentage of organic matter present in the sample.

Commonly, percent organic matter is converted to percent carbon on the basis of relationships established for mangrove and saltmarsh elsewhere (Howard *et al*., 2014). These established relationships were assessed to determine if they were appropriate for use in this study. Of the twelve sediment cores, four (4) were selected to be analysed for percent carbon content using a dry combustion technique; more specifically using continuous flow isotope ratio mass spectrometer (CF-IRMS) at the Australian Nuclear Science and Technology Organisation (ANSTO) in accordance with Mazumder *et al*. (2010). These cores were selected to capture the dominant vegetation communities at Currambene Creek; mangrove (1 core), mixed ecotone (1 core), and saltmarsh (2 cores). The selected cores were 140 cm in length and analysed at 5 cm intervals. Established LOI to carbon conversion equations for mangrove (Kauffman and Donato, 2011) and saltmarsh (Craft *et al*., 1991) were compared against percent carbon in this study to assess their validity for use in this study. Analysis of variance (ANOVA) was used to establish whether carbon content estimated using these conversion equations differed from the quantitative assessments of carbon undertaken using dry combustion techniques. On the basis of this analysis (results presented later), the percent carbon results from the four sediment cores were used to develop unique LOI carbon conversion equations to reliably estimate carbon content using LOI at this study site. After testing for normal distribution, non-parametric generalised linear models were used to determine whether there were significant differences in the relationship between percent LOI and percent carbon for the different vegetation communities. On the basis of these results conversion equations were generated using linear regression analysis, with LOI as the fixed variable and carbon content as the dependent variable. Post hoc Tukeys HSD was performed to establish the appropriate equation to calculate carbon content for *Casuarina*.

After identifying the statistical distribution of our data, statistical analyses were also carried out to determine relationships between particle size, soil depth and carbon content, as well as vegetation structure and carbon content. Generalised linear models were selected for carbon bulk density as the distribution was log normal (log normal distribution, $p = 0.15$); ANOVA was used to establish relationships between carbon content as the data was found to be normally distributed ($p = 0.96$). All statistical tests completed in this study were carried out using a 0.05 level of significance.

Below-ground soil carbon content (C g cm^{-3}) was estimated by multiplying bulk density and percent carbon. Soil carbon content for each sediment core was estimated by fitting a linear model between each soil sub-sample and aggregating each centimetre interval. The area of each vegetation structure, delineated by remote sensing, was multiplied by the corresponding soil carbon content to determine the carbon storage of the system.

RESULTS

Vegetation was delineated to capture the structural morphology and complexity across Currambene Creek (Figure 1d). This map classification was validated to an accuracy of 95% (kappa coefficient of agreement = 0.932).

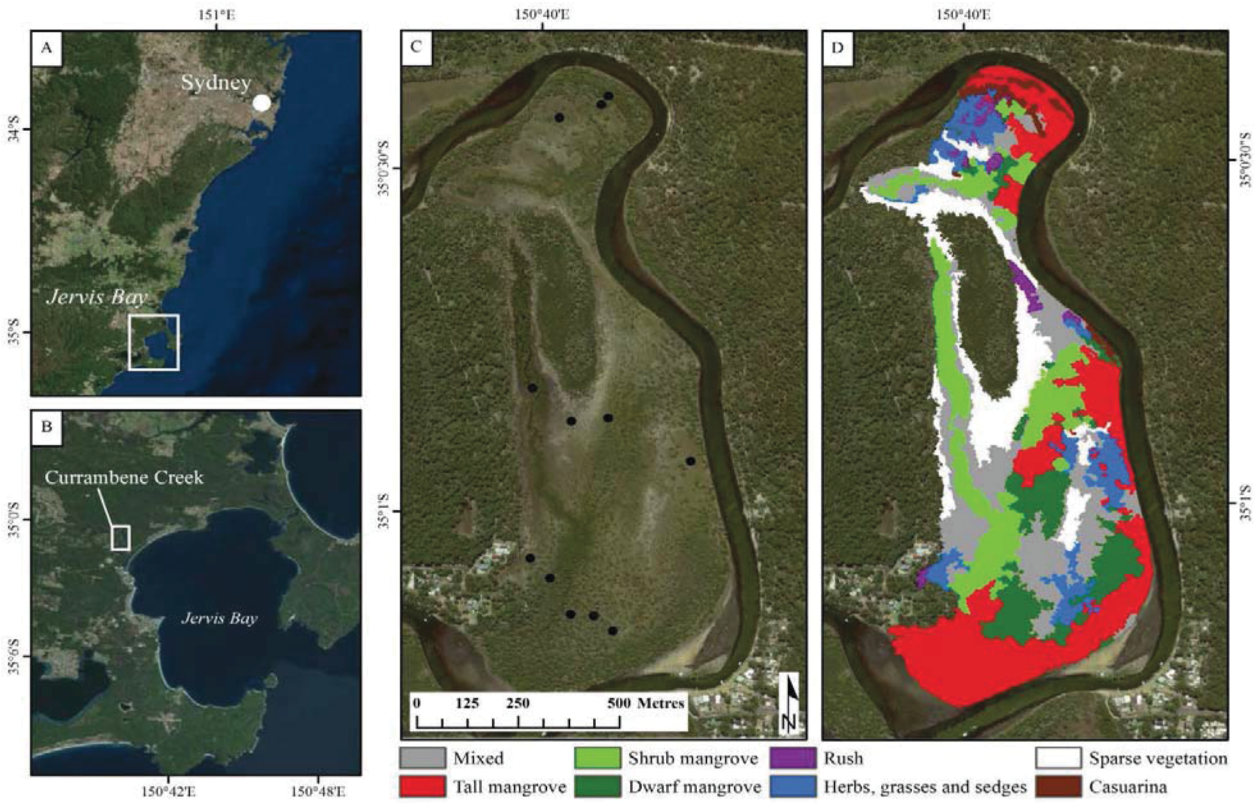

Figure 1. Location of (a) Jervis Bay and (b) Currambene Creek; (c) sediment core locations within the wetlands adjacent to Currambene Creek; and (d) vegetation structural classification. Data source: Imagery © ESRI Basemaps and Land and Property Information (LPI) NSW. Vegetation structural classification from Owers *et al*. (in review).

We found that carbon content estimated using established conversion equations was significantly different to quantitative estimates of carbon content for both mangrove ($p < 0.001$) and saltmarsh ($p < 0.001$). Furthermore, generalised linear models demonstrated that no significant relationship exists between percent carbon and vegetation community ($p = 0.44$), however the interaction between vegetation community and LOI was significant ($p = 0.0022$). Consequently, three separate equations for calculating carbon from LOI were generated for mangrove, saltmarsh and mixed vegetation communities (Figure 2). Post hoc Tukeys HSD indicated that *Casuarina* percent LOI was not significantly different to Tall mangrove ($p < 0.001$). Hence, the mangrove conversion equation was used to estimate carbon content for *Casuarina*.

Soil carbon content in the upper 30 cm varied on the basis of vegetation structure ($p = 0.0319$). Carbon storage was highest for *Casuarina* followed by tall mangrove > shrub mangrove > dwarf mangrove > rush saltmarsh > mixed > herbs, grasses and sedges > sparse vegetation (Table 1). However, total carbon storage within the wetland for each vegetation type was mediated by the spatial extent of each vegetation type; tall mangrove had the greatest area (16.1 ha) and constituted the largest carbon storage, while *Casuarina* had the second lowest storage, despite having the highest carbon content in the upper 30 cm. Similarly sparse vegetation had lower carbon content in the upper 30 cm than both saltmarsh forms; however the total carbon storage was similar to the combined carbon storage of all saltmarsh vegetation. Soil carbon increased with depth ($p < 0.001$) and was inversely related to mean particle size ($p < 0.001$). The total soil carbon storage in the upper 30 cm for the wetland was estimated to be 3933 ± 444 Mg C.

DISCUSSION

Variation in vegetation structure is an important component when estimating soil carbon storage within a wetland. In this study we found soil carbon content in tall mangrove to be higher than shrub mangrove, which is higher than dwarf mangrove (Table 1). This variation would not be captured if soil carbon estimates for mangrove were not delineated to capture structural variation. Similarly for saltmarsh and mixed vegetation, where variation exists between species composition and substrate, capturing wetland vegetation structure distinguishes vegetation complexity that was not demonstrated in previous research (Chafer, 1998; Oliver *et al*., 2012; Saintilan and Wilton 2001). Current estimates of below-ground carbon storage rarely

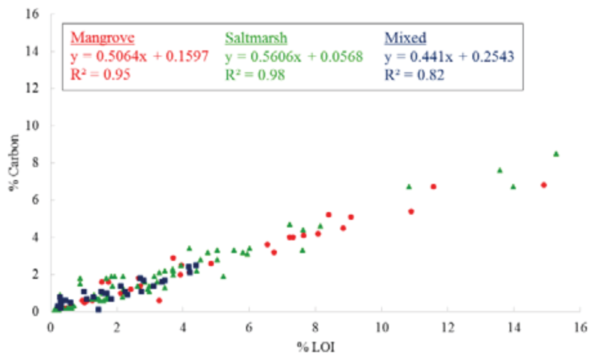

Figure 2. Relationship between percent carbon and percent LOI for mangrove (red, circle), saltmarsh (green, triangle) and mixed (blue, square) vegetation communities used to develop LOI conversion equations.

consider variation in structural forms of wetland vegetation. Sediment cores are often taken in vegetation communities; mangrove, saltmarsh, mixed, *Casuarina*, and results are extrapolated to estimate carbon storage at the landscape level using manually delineated vegetation areas from aerial photography (Howe *et al*., 2009; Rogers *et al*., 2013). Failing to capture variation in vegetation structure can result in erroneous estimates of carbon storage across the landscape. Aggregating the data presented in this study for vegetation communities yields a total soil carbon storage of 3845 ± 1114 Mg C in the upper 30 cm for Currambene Creek. When soil carbon content variation due to vegetation structure is captured, the total soil carbon storage in the upper 30 cm for Currambene Creek is 3933 ± 444 Mg C. For this study using vegetation communities to estimate total soil carbon storage in the upper 30 cm gives an underestimate with larger uncertainty. Further research is required to confirm if these differences may be even greater due to the limited depth of sediment core analysis presented in this study. A component of further research is to analyse sediment cores to 1.5 m depth, enabling a better estimate of total soil carbon storage in the system.

Services provided by coastal ecosystems are spatially and temporally variable (Barbier *et al*., 2011; Ewel *et al*., 1998). We found that carbon storage varies with vegetation structure within vegetation communities. Tall mangrove had the highest total carbon storage (1420 ± 198 Mg C) due to the combination of high soil carbon content and large spatial extent. *Casuarina* and rush saltmarsh where shown to be important carbon stores despite having the smallest spatial extents. Rush saltmarsh was shown to have the highest soil carbon content of the saltmarsh and mixed ecotone communities, however had the smallest total carbon storage in the upper 30 cm due to small spatial extent. Capturing variation in carbon storage services provided by these vegetation structures is an important tool for management as it highlights where different ecosystem services are concentrated. This is important for directing management towards improving specific services within an ecosystem, particularly efforts to improve climate change mitigation.

Exposure of ecosystem services to coastal processes is spatially complex. Capturing spatial variability in carbon storage services enables pressures of climate change to these services to be better distinguished. Sea-level rise, projected to increase between 0.18m and 0.59m by the end of this century (IPCC, 2013), poses significant concern for the vulnerability of current carbon storage and may limit future carbon sequestration. Tall mangrove are positioned lowest in the intertidal frame and are therefore particularly sensitive to erosion related to sea-level rise or other anthropogenic activities such as boating and wake-related erosion (Gilman *et al*., 2008; Mosisch and Arthington, 1998). Increased pressure to dredge the channel for navigation purposes may also have significant implications for the capacity of these systems to adapt. In contrast, wetland vegetation that occupies areas in the upper intertidal frame is sensitive to the effects of coastal squeeze; the inability of coastal vegetation to migrate landward with rising sea levels due to natural or artificial impediments (Doody, 2004). *Casuarina* and rush saltmarsh occupy areas in the upper intertidal frame, increasing their vulnerability to coastal squeeze and subsequent degradation. This has been observed at Currambene Creek as a considerable extent of rush saltmarsh has been degraded due to human interference.

Table 1. *Below-ground soil carbon content in the upper 30 cm for each vegetation structure.*

Vegetation structure	Soil carbon content (Mg C ha^{-1})	Area (ha)	Total soil carbon storage (Mg C)
Tall mangrove	88.5	16.1	1420 ± 198
Shrub mangrove	79.2	9.1	722 ± 153
Dwarf mangrove	74.5	6.7	498 ± 37
Mixed	50.7	12.4	628*
Sparse vegetation	31.3	8.1	255*
Herbs, grasses and sedges	41.7	4.8	200 ± 27
Rush	55.1	1.2	65*
Casuarina	118.3	1.2	145*
	Total	59.6	3933 ± 444

*standard deviation could not be calculated due to insufficient replicates

Identifying spatial variability in carbon storage services can aid targeted management for improving carbon sequestration potential and protecting current carbon stores from pressures of climate change. Mangrove and saltmarsh have some capacity to adapt to accelerated sea-level rise by accumulating sediment and adjusting their elevation in the soil profile relative to sea level (Rogers *et al*., 2013). This requires contributions from both autochthonous and allochthonous sources of sediment for vertical accretion (Saintilan *et al*., 2013). Activities in the catchment may reduce the availability of allochthonous material to aid elevation adjustment as the sea rises. Similar adaptive capacity has been demonstrated for landward migration of wetland vegetation (Rogers *et al*., 2013). Removing artificial impediments to facilitate landward migration may increase carbon sequestration potential by preventing further losses of vegetation and encouraging recolonisation.

CONCLUSIONS

Ecosystem services are not spatially homogenous throughout coastal wetlands, and we have demonstrated that carbon storage services varied on the basis of vegetation structure. Similarly, exposure to coastal processes is spatially complex, with lower intertidal areas being particularly sensitive to sea-level rise related erosion, and upper intertidal areas sensitive to the effects of coastal squeeze. Identifying spatial variability in carbon storage services can aid targeted management for improving carbon sequestration potential and protecting current carbon stores from pressures of climate change. In particular we found that tall mangrove fringing Currambene Creek exhibited the greatest carbon mitigation ecosystem services, yet was also particularly sensitive to coastal processes and management activies occurring within the catchment, including sea-level rise and dredging.

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