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Spatial variation of above-ground carbon storage in temperate coastal wetlands

Abstract

Carbon mitigation services provided by coastal wetlands are not spatially homogeneous. The scale of assessment at which above-ground biomass is measured will directly influence carbon storage estimates. Greater confidence in estimates is obtained with approaches that describe more variation. There is a need to improve accuracy while optimising assessment effort efficiency. Accurate quantification of carbon storage is dependent upon accurate assessment of biomass, carbon content and the extent of vegetation for which carbon storage is being assessed. This study demonstrates that vegetation structure influences above-ground biomass of mangrove and saltmarsh, resulting in considerable variability in biomass estimates and associated carbon storage of temperate coastal wetlands in southeast Australia. For mangrove, variability in above-ground biomass ($\text{Mg ha}^{-1} \pm \text{SE}$) was best described by measuring height, stem diameter, crown area and vegetation density, whereby tall mangrove (3–8 m in height; $71.50 \pm 12.53 \text{ Mg ha}^{-1}$) had higher biomass than both shrub (1.3–3 m in height; $53.06 \pm 6.94 \text{ Mg ha}^{-1}$) and dwarf mangrove (<1.3 m in height; $10.68 \pm 1.77 \text{ Mg ha}^{-1}$). Saltmarsh above-ground biomass was best described by height, species and vegetation density, which demonstrated significant differences between rush saltmarsh ($15.97 \pm 2.35 \text{ Mg ha}^{-1}$) and herbs, grasses and sedges saltmarsh ($7.51 \pm 0.91 \text{ Mg ha}^{-1}$). The effect of this variation was compounded by carbon content (% C), which varied markedly between vegetation structural form and species (30.9–49.8% C). Maintaining accuracy when assessing carbon storage requires mapping units that correspond to the scale of biomass assessments. Results from this study suggest that recognition of variation in biomass and carbon content of mangrove and saltmarsh vegetation structure will enhance the accuracy of estimates of carbon storage, and provide the confidence necessary for carbon storage inventories.

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4.1 Introduction

Coastal ecosystems, particularly mangrove and saltmarsh, provide a range of ecosystem services beneficial to society (Ewel et al., 1998; Barbier et al., 2011). Their role as a natural carbon sink, achieved by sequestering atmospheric carbon dioxide in biomass and as organic matter stored in substrates, is important to help counterbalance anthropogenic climate change (Duarte et al., 2005; Mcleod et al., 2011). Despite this benefit, a significant extent of mangrove and saltmarsh continues to be lost or degraded due to deforestation and anthropogenic activities in the coastal zone (Laegdsgaard, 2006; Donato et al., 2011; Murdiyarso et al., 2015; Atwood et al., 2017; Macreadie et al., 2017a). Carbon off-setting initiatives such as REDD+, designed to reduce global carbon emissions, provide an opportunity to conserve coastal wetlands and the ecosystem services they provide (Alongi et al., 2015). Fundamental to these off-setting initiatives is the accurate assessment of carbon storage in vegetated ecosystems to facilitate a low carbon economy (Gibbs et al., 2007; Chave et al., 2014).

Standardised methodologies have been developed to assess carbon storage of mangrove and saltmarsh vegetation, providing guidelines on sampling design, collection methods, data interpretation and reporting protocols (Kaufmann and Donato, 2012; Howard et al., 2014). Sampling design is typically site-specific, and little evidence is provided in these guidelines that will facilitate extrapolation of sampling approaches to larger spatial scales. The IPCC provide guidance on approaches for determining anthropogenic greenhouse gas emissions and removals associated with biomass of vegetation in managed coastal wetlands (IPCC, 2014). This guidance identifies three tiers of assessment that broadly reflect increasing accuracy from tier 1 assessment approaches to tier 3, recognising that it is 'good practice' for countries to improve inventory and reporting by using the highest possible tier of assessment. Tier 1 assessments are broad scale assessments that use IPCC default values of biomass in different forest biomes to estimate carbon storage (Table 2.4). These estimates have considerable variability and high uncertainty (Gibbs et al., 2007; Howard et al., 2014; Moomaw et al., 2018). Tier 2 assessments require carbon storage values to estimate regional variability for national carbon inventories (e.g. carbon storage estimates of mangrove forests in Indonesia; Alongi et al., 2015). Tier 3 assessments capture variability in carbon at the site level by stratification of vegetation types, ecological zones and salinity gradients. Tier 3 assessments provide the greatest

confidence in estimates and are encouraged where resources are available (Kauffman and Donato, 2012; Howard et al., 2014; IPCC, 2014). In order to meet the required confidence necessary for carbon off-setting initiatives such as REDD+, voluntary carbon markets and Australia's ERF, tier 3 assessments are required as stated in the Verified Carbon Standard (VCS, 2013, 2015).

Tier 3 assessments encourage the development and application of allometric equations to individual mangrove trees measured in quadrats for accurate estimates of mangrove above-ground biomass, and harvesting for saltmarsh above-ground biomass (VCS, 2013, 2015). For mangrove, these equations are developed for particular geographic areas by harvesting a subset of mangrove species and relating tree measured variables, such as height, DBH and crown area, to above-ground biomass (Komiya et al., 2008). Many mangrove allometric equations have been developed for tropical coasts (e.g. Day et al., 1987; Clough et al., 1997; Fromard et al., 1998; Ross et al., 2001; Sherman et al., 2003; Comley and McGuinness, 2005; Fu and Wu 2011; Estrada et al., 2014; Hossain et al., 2016), however fewer have been developed in temperate settings (e.g. Woodroffe, 1985; Osland et al., 2014; Bulmer et al., 2016a). Several 'common' allometric equations have been developed for application across different species and climatic regions (e.g. Chave et al., 2005; Komiya et al., 2005; Chave et al., 2014; Ray et al., 2011), however considerable discussion remains regarding their efficacy for broad application (Soares and Schaeffer-Novelli, 2005; Estrada et al., 2014). For saltmarsh vegetation, above-ground biomass is typically determined by harvesting a small area on the basis of replicate quadrats (Howard et al., 2014). A much smaller body of literature exists for saltmarsh above-ground biomass compared to mangrove above-ground biomass (e.g. da Cunha Lana et al., 1991; Garcia et al., 1993; Clarke and Jacoby, 1994; Ford and Grace, 1998; Craft et al., 1999; Connor and Chmura, 2000; Thursby et al., 2002; Castillo et al., 2008). This is likely due to the difficulty of accurately determining mangrove above-ground biomass, whereas saltmarsh can be determined accurately and directly with substantially less resources.

Typically replicate measures for both mangrove and saltmarsh at the site level are taken to estimate above-ground biomass and these are converted to carbon storage using a generalised conversion factor (45% C; IPCC, 2014). An average above-ground carbon

storage is often calculated for mangrove and saltmarsh and multiplied by vegetation extent to calculate total above-ground carbon storage (Howard et al., 2014). However, application of a standardised conversion factor does not provide the corresponding level of accuracy achieved when accounting for biomass variability associated with vegetation type, ecological zone and salinity gradients. Site-level estimates of mangrove and saltmarsh above-ground biomass should be paired with appropriate site level carbon conversion factors as mangrove and saltmarsh carbon content varies depending on species, location and biomass compartment (i.e. trunk, branches and leaves plus inflorescences) (Alongi et al., 2003; Bouillon et al., 2008; Rodrigues et al., 2015; Bulmer et al., 2016a). Furthermore vegetation extent is often only delineated to broad vegetation communities (i.e. mangrove and saltmarsh), which does not consider variation in species and vegetation structure associated with ecological zone and salinity gradients.

Carbon mitigation services provided by coastal wetlands are not spatially homogeneous (Kelleway et al., 2016; Yando et al., 2016; Macreadie et al., 2017b) and this has been recognised in IPCC advice, which indicates that a major source of uncertainty arises from dominant species-specific differences in carbon content and differences due to forest age, species composition, intertidal location, soil fertility and vegetation structure (IPCC, 2014). Mangrove and saltmarsh vegetation are structurally complex, varying in response to factors operating at different scales (Twilley et al., 1999; Estrada and Soares, 2017). This is particularly evident for the mangrove *Avicennia marina*, a common species throughout the Indo-Pacific having broad tolerance to salinity and inundation gradients, and a low temperature tolerance (Duke et al., 1998). Consequently, *Avicennia marina* commonly forms distinct zones and is co-dominant with other species throughout the tropics, while being the dominant mangrove throughout temperate Australia (Saintilan and Williams 1999; Morrissey et al., 2010). *Avicennia marina* in tropical settings are taller and have greater biomass than those in temperate settings (Komiya et al., 2008). However, considerable variability in height and biomass has been demonstrated for *Avicennia marina* in temperate settings such as southeast Australia (Saintilan, 1997b; Morrissey et al., 2010). As a result of structural variation many allometric equations have been produced for *Avicennia marina*. Application of allometric equations to estimate above-ground biomass is therefore difficult to ensure all variation in structure is being captured by the selected equation.

Similarly, saltmarsh vegetation structure also influences biomass, and should be considered when determining above-ground biomass and carbon storage of saltmarsh. Due to the generally lower stature of saltmarsh, it is often considered less complex in terms of biomass, but structural forms are variable ranging from tall (0.5 – 2 m; e.g. *Phragmites australis*) and short grasses (10 – 30 cm; e.g. *Sporobolus virginicus*), to rushes (e.g. *Juncus kraussii*), sedges (e.g. *Isolepis nodosa*), herbs (e.g. *Samolus repens*), and shrubs (e.g. *Suaeda australis*), some extending to heights of up to 2 m (e.g. *Tecticornia arbuscula*). Quantifying above-ground biomass of saltmarsh without recognising variability in structure may provide an indication of saltmarsh biomass, however estimates will have considerable uncertainty. Simpler approaches to biomass assessment based on destructive assessment over small areas and extrapolation of biomass to larger areas may be reasonable in situations where structural form is more homogeneous, such as extensive monospecific stands of *Spartina alterniflora* in parts of the USA (Craft et al., 1999; Adam, 2002), but less so where saltmarsh species diversity is high, distribution of species is in mosaics or zones, and structure of species is variable, such as in southeast Australia (Adam et al., 1988; Clarke and Jacoby, 1994; Saintilan, 2009a).

The aim of this study was to identify the spatial scale that optimises efficiency and accuracy of above-ground carbon storage assessment. The scale of assessment at which above-ground biomass and carbon content is measured will directly influence carbon storage estimates, whereby approaches that capture variation will be more accurate. Three spatial scales were tested in this study, the compartment scale, the structural scale and the regional scale. Above-ground biomass and carbon content were quantified at the compartment scale (trunk, branch, leaves plus inflorescences), structural scale (tall, shrub and dwarf mangrove), and regional scale (temperate southeast Australia). The hypothesis was that quantifying biomass and carbon content associated with vegetation structure will provide a better indication of above-ground carbon storage at both site and regional scale. The specific objectives of this study are to:

1. Establish the variation in biomass and carbon content within vegetation compartments of mangrove and saltmarsh by harvesting vegetation

2. Develop a range of allometric equations to estimate above-ground biomass at different spatial scales, including compartment-specific (trunk, branch, leaves plus inflorescences), structure-specific (tall, shrub, dwarf mangrove) and region-specific equations (temperate southeast Australia)
3. Apply allometric equations to mangroves measured in quadrats to determine variation in above-ground carbon storage at different scales for each study site
4. Extrapolate mangrove and saltmarsh biomass and carbon content to determine variation in above-ground carbon storage at different scales for each study site

As an outcome of this study, a tier 3 level assessment is developed that increases accuracy of above-ground carbon storage assessments, while optimising the efficiency of assessment. This is relevant for assessment over larger spatial extents, such as national scales, which can build upon higher accuracy assessments at regional scales.

4.2 Methods

4.2.1 Site locations

The coastline of southeast Australia is a wave-dominated coastline (Sloss et al., 2007). High energy conditions restrict coastal wetlands to estuaries where barrier development creates hydrodynamic conditions suitable for sediment deposition, and favourable for wetland vegetation establishment and growth (Roy et al., 2001). This coastline has a semi-diurnal tide regime, with a maximum tidal range of approximately 2 m. Southeast Australia has a temperate climate (Stern and de Hoedt, 2000) and supports mangrove and saltmarsh communities which co-occur along intertidal estuarine shorelines (Adam, 1990). Mangroves are commonly tropical and sub-tropical in distribution, however some species exhibit tolerance to cold temperatures and can extend into warm temperate regions (Saintilan et al., 2014). Mangroves typically occur lower within the tidal frame, while saltmarsh occupy higher intertidal areas (Saenger et al., 1977). The latitudinal range of this study is 32° S to 36° S. Four barrier estuaries were selected in the study region, Hunter River (151°42' E 32°51' S), Minnamurra River (150°50' E 34°38' S), Currambene Creek (150°40' E 35°01' S) and Caramba Inlet (150°46' E 34°59' S) (Figure 4.1). *Avicennia marina* is the dominant mangrove species in southeast Australia, however

Aegiceras corniculatum is also present in the region. Commonly present saltmarsh species are *Sporobolus virginicus*, *Samolus repens*, *Juncus kraussii* and *Sarcocornia quinqueflora* (Adam et al., 1988; Clarke, 1993; Sainty et al., 2012).

4.2.2 Vegetation structure

Mangrove and saltmarsh at study sites conform to one of several dominant structural forms in southeast Australia as previously identified in Chapter 3 (Figure 4.1). Three dominant structural forms were present for mangrove vegetation. Tall mangrove were typically 3 m to 8 m in height with a DBH greater than 15 cm. Shrub mangrove were typically 1.3 m to 3 m in height with a DBH less than 15 cm. Dwarf mangrove were typically less than 1.3 m in height (Table 3.2). The distribution and function of mangrove structural forms were similar to those described by Lugo and Snedaker (1974) and further by Woodroffe (1992). Tall mangrove had characteristics of fringe and river forests, shrub mangrove had similar characteristics to basin forests, and dwarf mangrove similar to dwarf forests, or scrub forests (Twilley et al., 1999). *Avicennia* were present in all three dominant structural forms, however *Aegiceras* typically have smaller stature with heights less than 3 m and were only present in dwarf mangrove structural form. Saltmarsh communities relevant to this study were previously classified as rush (*Juncus kraussii*), and herbs, grasses and sedges (HGS), inclusive of *Sporobolus virginicus*, *Samolus repens* and *Sarcocornia quinqueflora*. Distribution of structural forms for Minnamurra River, Currumbene Creek and Carama Inlet, delineated in Chapter 3, were used to extrapolate estimates of mangrove and saltmarsh above-ground biomass across the study site.

Figure 4.1 Location of selected study sites in southeast Australia and field photo examples of vegetation present in study region a) Tall mangrove b) Shrub mangrove c) Dwarf mangrove (*Avicennia*) d) Dwarf mangrove (*Aegiceras*) e) *Sporobolus virginicus* f) *Samolus repens* g) *Juncus kraussii* h) *Sarcocornia quinqueflora*.

4.2.3 Mangrove and saltmarsh harvesting

Harvesting of mangroves was undertaken at Hunter River and Minnamurra River. A total of 43 mangroves were harvested. Height, basal diameter, crown area and stem diameter were measured for each mangrove before felling. Stem diameter was measured at different heights on mangroves due to variation in vegetation structural form. The standardised height for DBH measurements of stems is 1.3 m, however measurements at this height were not possible for shrub and dwarf mangrove which do not have stems at 1.3 m. Tall mangrove stem diameter was measured at 1.3 m, corresponding to heights typical of measurements of DBH. Shrub mangrove stem diameter was measured at 30 cm, and dwarf at 10 cm. All harvested mangroves were selected to develop allometric relationships (tall mangrove $n = 13$, shrub mangrove $n = 9$, dwarf mangrove $n = 16$ *Avicennia* $n = 5$ *Aegiceras*). Once felled, mangroves were separated into three compartments; trunk, branches and leaves plus inflorescences. Trunk was defined as the main stem(s) of the mangrove originating from ground level. Branches were defined as

the woody compartment that extended from the bifurcation of the main stem(s) to leaves or inflorescences (Soares and Schaeffer-Novelli, 2005). Leaves plus inflorescences were the non-woody compartment of the mangrove (Bulmer et al., 2016a). Each compartment was weighed on site using a 50 kg spring balance (± 0.4 kg). Samples from each mangrove compartment were taken back to the laboratory. Samples were weighed then oven dried at 60°C to a constant mass and reweighed to determine dry weight. Total dry weight of each compartment was calculated by multiplying the wet weight by the wet to dry ratio of the sub-sample.

Harvesting of saltmarsh was undertaken at Minnamurra River. Saltmarsh species *Sporobolus virginicus*, *Samolus repens*, *Juncus kraussii* and *Sarcocornia quinqueflora* were harvested. Replicate quadrats (25 x 25 cm), nine in total, were randomly selected for each species. The selected quadrat size was considered to represent homogeneous units of saltmarsh vegetation density while minimising the degree of destructive harvesting. Previous research suggests no distinct seasonal trends occur in aboveground biomass of saltmarsh in southeast Australia, therefore repeat analysis to account for seasonal variation was not required (Clarke and Jacoby, 1994). All above-ground vegetation collected in each quadrat was taken back to the laboratory. Vegetation was rinsed to remove excess sediment, weighed, then oven dried at 60°C to a constant mass and reweighed.

4.2.4 Allometric equations

Allometric relationships for mangrove vegetation were evaluated using linear regression models. Allometric equations were developed at different spatial scales to compare above-ground biomass estimates. These included compartment-specific equations; trunk above-ground biomass, branch above-ground biomass, and leaves plus inflorescences above-ground biomass. The summation of biomass for each compartment was used to provide a biomass estimate for each mangrove individual. Structure-specific equations were also developed for tall, shrub and dwarf mangrove. A region-specific equation, which did not differentiate mangrove structural variability, was developed for mangroves in southeast Australia. Both structure-specific and region-specific equations provided biomass estimates for each mangrove individual. Independent variables were height, crown area, total stem diameter (i.e. summation of stem diameters on a mangrove if more

than one stem was present), and basal diameter. Independent variables were tested individually and in combination through simple and multiple linear regression analyses. All possible allometric relationships for variation in mangrove structural form and species were tested using independent variables. Response and independent variables were natural log (ln) transformed prior to analysis to meet assumptions of normality. The equations developed were back transformed from log transformations to facilitate calculating above-ground biomass. A correction factor (CF) was calculated for all equations as back transformations from log transformations are associated with underestimation of response variables (Sprugel, 1983). CF was calculated as $\exp(\text{RMSE}/2)$. Allometric equations were of the form:

$$\ln(y) = a + b \times \ln(x) \quad (4.1)$$

where: y is the above-ground biomass, and a and b are constants. To establish above-ground biomass and incorporate the correction factor, equation 4.1 becomes:

$$y = (\exp(a + b \times \ln(x))) \times CF \quad (4.2)$$

Statistical analysis for linear regression models, including coefficient of determination (r^2), root mean square error (RMSE) and statistical significance, was undertaken in JMP Version 11 (SAS Institute Inc., Cary, NC, USA). All statistical tests completed in this study were carried out using a 0.05 level of significance.

4.2.5 Above-ground biomass

Mangrove above-ground biomass was determined by measuring mangroves in quadrats at each site. Developed allometric equations were applied to each mangrove measured in the quadrat. The summation of mangrove biomass in each quadrat was standardised to provide an estimate of above-ground biomass in $\text{Mg ha}^{-1} \pm \text{SE}$. Sampling was stratified based on vegetation structural form. Appropriate quadrat size was selected to ensure adequate representation of each vegetation structural form, as mangrove vegetation density typically increases with diminishing vegetation height. Quadrats in tall mangrove vegetation were 20 m x 20 m, quadrats in shrub mangrove vegetation were 5 m x 5 m, and quadrats in dwarf mangrove vegetation were 3 m x 3 m, however some quadrats were

adjusted based on mangrove vegetation density (Appendix B). A total of 30 quadrats were measured, with three replicates of each structural form at Minnamurra River, Currumbene Creek and Cararma Inlet. Only three replicates of tall mangrove were measured at Hunter River due to the absence of homogenous zones of shrub and dwarf mangrove at this location.

Above-ground biomass of mangrove and saltmarsh was estimated for Minnamurra River, Currumbene Creek and Cararma Inlet using mapped areas of vegetation structural form (Chapter 3). Above-ground biomass of mangrove and saltmarsh at Hunter River was not estimated due to absence of vegetation structure mapping. Replicate mangrove quadrats were averaged to estimate above-ground biomass for each mangrove structural form ($\text{Mg ha}^{-1} \pm \text{SE}$) and then multiplied by the mapped areas at each site to provide an estimate of total mangrove above-ground biomass ($\text{Mg} \pm \text{SE}$). Total above-ground biomass estimates using the compartment-specific equations, structure-specific equations and region-specific equation were compared for each site. Above-ground biomass of each saltmarsh species was calculated by averaging replicate harvested quadrats and standardised to provide an estimate in $\text{Mg ha}^{-1} \pm \text{SE}$. Rush saltmarsh above-ground biomass was calculated using *Juncus kraussii*, and herbs, grasses and sedges saltmarsh was estimated using average above-ground biomass of *Sporobolus virginicus*, *Samolus repens*, and *Sarcocornia quinqueflora*.

Analysis of variance (ANOVA) was used to test for significant differences between mangrove and saltmarsh above-ground biomass and vegetation structural form. For mangrove, variables included height, vegetation density and differences in biomass between different mangrove structural forms. Similarly ANOVA was used on saltmarsh data to test for significant differences in biomass between species. Above-ground biomass estimates derived using compartment-specific, structure-specific and region-specific allometric equations were also tested to establish variability at different scales of assessment.

4.2.6 Above-ground carbon storage

Carbon content ($\% \text{ C} \pm \text{SE}$) of biomass was determined using samples from mangrove and saltmarsh harvest data. Samples (approximately 20g) were homogenised by grinding

to a fine power using a Retsch three-dimensional Vibrator Mill (Type-MM-2, Haan, Germany). Carbon content of samples was determined using an elemental analyser interfaced to a continuous flow isotope ratio mass spectrometer (CF-IRMS). Compartment carbon content was determined for six mangrove individuals (four *Avicennia*, two *Aegiceras*). Similarly, replicate sub-samples from each saltmarsh species were analysed for carbon content.

Above-ground carbon storage for each site ($\text{Mg C} \pm \text{SE}$) was subsequently estimated using above-ground biomass estimates ($\text{Mg} \pm \text{SE}$) and carbon content ($\% \text{ C} \pm \text{SE}$) of vegetation. Carbon content values for each compartment (trunk, branches, leaves plus inflorescences) were used for compartment-specific equations of each mangrove structural form. Structure-specific equations used an average carbon content for tall, shrub and dwarf mangrove. The region-specific equation used an average carbon content for mangroves in southeast Australia. Above-ground carbon storage ($\text{Mg C} \pm \text{SE}$) of saltmarsh was calculated by multiplying above-ground biomass ($\text{Mg} \pm \text{SE}$) of each species by its carbon content ($\% \text{ C} \pm \text{SE}$).

4.3 Results

4.3.1 Vegetation structure (harvested mangrove and saltmarsh)

Mangrove above-ground biomass varied with vegetation structural form. Harvested mangrove above-ground biomass of individual trees ranged from 35 g for dwarf mangrove to 121.96 kg for tall mangrove (Table 4.1). Average tall mangrove above-ground biomass ($32.54 \pm 9.19 \text{ kg}$) was significantly greater than shrub ($5.99 \pm 1.26 \text{ kg}$) and dwarf mangrove ($1.12 \pm 0.24 \text{ kg}$) ($p < 0.0001$). Above-ground biomass of dwarf mangrove was not significantly different for *Avicennia* ($0.98 \pm 0.26 \text{ kg}$) and *Aegiceras* ($1.51 \pm 0.58 \text{ kg}$) individuals ($p = 0.3508$). Mangrove compartment biomass, namely trunk, branch, leaves plus inflorescences, varied with mangrove structural form. Tall mangrove trunk biomass accounted for greater than 50% of the total above-ground biomass of individual tall mangroves (Figure 4.2a). For dwarf mangrove, branches contributed the largest proportion to total above-ground biomass of individuals, with greater than 40% for *Avicennia* and 50% for *Aegiceras*. As biomass contribution of the trunk decreased

from tall to dwarf mangrove individuals, leaves plus inflorescences biomass contribution increased inversely with height.

Saltmarsh above-ground biomass varied with species (Figure 4.2b). Harvested above-ground biomass of *Juncus kraussii* ($15.97 \pm 2.35 \text{ Mg ha}^{-1}$) was significantly greater than other saltmarsh species (*Sarcocornia quinqueflora* ($6.88 \pm 1.38 \text{ Mg ha}^{-1}$) $p = 0.0089$, *Samolus repens* ($5.51 \pm 0.80 \text{ Mg ha}^{-1}$) $p < 0.0001$, *Sporobolus virginicus* ($10.12 \pm 2.02 \text{ Mg ha}^{-1}$) $p = 0.0477$). However, *Sarcocornia quinqueflora*, *Sporobolus virginicus* and *Samolus repens* above-ground biomass were not significantly different from each other ($p = 0.2078$). Variation in vegetation density of saltmarsh samples resulted in a large range of above-ground biomass for each species (Figure 4.2b).

Table 4.1 Range of variables for harvested mangroves. AGB; Above-ground biomass. All mangrove harvest data provided in Appendix B.

Structural parameters	Tall mangrove			Shrub mangrove			Dwarf mangrove (<i>Avicennia</i>)			Dwarf mangrove (<i>Aegiceras</i>)		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Height (m)	3.1	4.6	5.5	1.6	2.5	3.4	0.6	1.0	1.4	0.6	0.9	1.4
Crown area (m ²)	1.1	4.2	11.7	0.6	1.8	4.1	0.1	0.7	1.7	0.1	0.9	1.8
Basal diameter (cm)	7.8	18.5	40	1.7	7.8	15.5	1.5	4.3	10	2.7	8.5	14
Total stem diameter (cm)	7.3	17.8	50.8	2.8	7.3	13.8	0.8	4.9	14.5	1.3	18.1	39.8
Compartment AGB	Tall mangrove			Shrub mangrove			Dwarf mangrove (<i>Avicennia</i>)			Dwarf mangrove (<i>Aegiceras</i>)		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Trunk biomass (g)	4031	20121	64325	721	2702	8103	17	354	1110	21.8	274	469
Branch biomass (g)	3691	11128	41417	625	2168	5500	10	408	1434	29	936	2078
Leaves plus inflorescences biomass (g)	1024	3986	16216	281	1123	3743	9	219	589	30	302	498
Total AGB (g)	8745	32539	121957	1639	5993	15277	35	982	3133	81	1511	2942

Figure 4.2 a) Compartment biomass allocation for mangrove harvest data for each mangrove structural form and species. Error bars represent standard deviation from the mean. b) Boxplots of saltmarsh above-ground biomass for harvested samples. Horizontal line inside box indicates median, cross indicates mean, the box indicates 25th and 75th percentiles, and whiskers indicate maxima and minima.

4.3.2 Allometric equations

Statistical analyses indicated that several allometric relationships were suitable for accurately determining a suite of above-ground biomass metrics at different scales (i.e. compartment, structural, regional) (Appendix B). When allometric equations were developed separately for *Avicennia* and *Aegiceras*, no significant differences (p-value

consistently > 0.05 , Appendix B) were identified between the biomass of the species. Therefore all equations reported here are inclusive of *Avicennia* and *Aegiceras*.

Allometric equations were developed for each compartment (trunk, branch and leaves plus inflorescences) of each mangrove structural form (tall, shrub and dwarf). Independent variables of height, total stem diameter and crown area used in combination consistently optimised r^2 and RMSE (Table 4.2). Allometric equations for above-ground biomass of each structural form were also developed, and indicated that height, total stem diameter and crown area were the optimal independent variables for determining above-ground biomass. Similarly, the region-specific equation generated using independent variables of height, total stem diameter and crown area in combination was the most robust. Equations generated using other independent variables individually or in combination performed well (Appendix B), however at a reduced accuracy with lower r^2 and RMSE not consistently optimised.

Table 4.2 Selected allometric equations for mangrove biomass compartments. Above-ground biomass (kg), height (cm), total stem diameter (cm), crown area (m²). Equations should be calculated as $y = (\exp(a + b \times \ln(x_1) + c \times \ln(x_2) + d \times \ln(x_3))) \times CF$. *SE* Standard error of variable, *CF* correction factor, *n* sample size. All tested equations provided in Appendix B.

	Above-ground Biomass	Predictors (x_1, x_2, x_3)	a (SE)	b (SE)	c (SE)	d (SE)	Adj-R ²	RMSE	CF	n
Tall mangrove	Trunk	Height, Total stem diameter,	-9.1738	1.5082	0.7829	0.4232	0.85	0.32	1.0531	13
		Crown area	(3.9923)	(0.6864)	(0.3171)	(0.2548)				
	Branch	Height, Total stem diameter,	-0.8993	0.01229	0.98218	0.2371	0.93	0.19	1.0183	13
		Crown area	(2.3640)	(0.4064)	(0.1877)	(0.1509)				
	Leaves plus inflorescences	Height, Total stem diameter,	-7.4608	0.9191	0.8898	0.3647	0.86	0.30	1.0463	13
		Crown area	(3.7339)	(0.6419)	(0.2965)	(0.2383)				
Shrub mangrove	Total (Structure-specific equation)	Height, Total stem diameter,	-5.3711	0.9652	0.8527	0.3481	0.91	0.23	1.0256	13
		Crown area	(2.7904)	(0.4797)	(0.2216)	(0.1781)				
	Trunk	Height, Total stem diameter,	-9.7830	1.6186	0.6883	0.6834	0.66	0.45	1.1075	11
		Crown area	(3.8750)	(0.6325)	(0.3885)	(0.2635)				
	Branch	Height, Total stem diameter,	-10.1200	1.5605	1.0501	0.2967	0.70	0.36	1.0653	11
		Crown area	(3.0508)	(0.4980)	(0.3059)	(0.2074)				
Dwarf mangrove	Leaves plus inflorescences	Height, Total stem diameter,	-7.0361	0.8453	0.9851	0.7341	0.72	0.43	1.0974	11
		Crown area	(3.6981)	(0.6036)	(0.3708)	(0.2514)				
	Total (Structure-specific equation)	Height, Total stem diameter,	-8.6707	1.5066	0.9014	0.5483	0.74	0.36	1.0673	11
		Crown area	(3.0941)	(0.5050)	(0.3102)	(0.2104)				
	Trunk	Height, Total stem diameter,	-11.7579	2.2117	0.1784	0.7750	0.90	0.45	1.1077	19
		Crown area	(1.9476)	(0.4028)	(0.1952)	(0.2448)				
Regional Total	Branch	Height, Total stem diameter,	-2.6645	0.2436	0.5009	1.0192	0.95	0.34	1.0585	19
		Crown area	(1.4521)	(0.3003)	(0.1455)	(0.1825)				
	Leaves plus inflorescences	Height, Total stem diameter,	-2.5089	0.1214	0.3623	0.9432	0.90	0.42	1.0915	19
		Crown area	(1.8015)	(0.3726)	(0.1805)	(0.2264)				
	Total (Structure-specific equation)	Height, Total stem diameter,	-3.7141	0.6959	0.3698	0.9578	0.95	0.30	1.0458	19
		Crown area	(1.2889)	(0.2666)	(0.1292)	(0.1620)				
(Region-specific equation)	Height, Total stem diameter,	-6.4908	1.2204	0.5280	0.7018	0.98	0.30	1.0475	43	
	Crown area	(0.5864)	(0.1008)	(0.0900)	(0.0995)					

4.3.3 Above-ground biomass

Mangrove above-ground biomass, derived from structure-specific allometric equations in Table 4.2 applied to mangroves measured in quadrats, increased in a positive relationship with height, whereby tall mangrove ($71.50 \pm 12.53 \text{ Mg ha}^{-1}$) had higher biomass than both shrub ($53.06 \pm 6.94 \text{ Mg ha}^{-1}$) and dwarf mangrove ($10.68 \pm 1.77 \text{ Mg ha}^{-1}$) ($p = 0.0004$) (Figure 4.3). However, this relationship was dominated by high biomass of tall mangrove at Hunter River where biomass at Hunter River ($132.05 \pm 28.31 \text{ Mg ha}^{-1}$) was significantly greater than tall mangrove at other study sites ($51.32 \pm 4.18 \text{ Mg ha}^{-1}$) ($p = 0.0006$). Vegetation structure, specifically height and vegetation density of mangroves measured in quadrats, indicated that tall mangrove at Hunter River were taller ($7.2 \pm 0.2 \text{ m}$) ($p < 0.001$) and had greater density (2617 ± 502 mangroves per ha^{-1}) ($p < 0.0001$) than tall mangrove elsewhere (height = $4.6 \pm 0.1 \text{ m}$, density = 469 ± 83 mangroves per ha^{-1}). When the mangrove biomass results from the Hunter River were excluded, above-ground biomass of tall mangrove ($51.32 \pm 4.18 \text{ Mg ha}^{-1}$) was not significantly different to shrub mangrove ($53.06 \pm 6.94 \text{ Mg ha}^{-1}$) ($p = 0.8333$), measurements in quadrats indicated that the vegetation density of shrub mangrove (9156 ± 2013 mangroves per ha^{-1}) was significantly greater than tall mangrove (469 ± 83 mangroves per ha^{-1}) ($p = 0.0005$). Furthermore, dwarf mangrove above-ground biomass ($10.68 \pm 1.77 \text{ Mg ha}^{-1}$) was significantly less than tall mangrove ($51.32 \pm 4.18 \text{ Mg ha}^{-1}$) and shrub mangrove ($53.06 \pm 6.94 \text{ Mg ha}^{-1}$) ($p < 0.0001$).

Average above-ground biomass of rush saltmarsh ($15.97 \pm 2.35 \text{ Mg ha}^{-1}$) was greater than herbs, grasses and sedges saltmarsh ($7.51 \pm 0.91 \text{ Mg ha}^{-1}$). Statistical analysis indicated no significant difference between the biomass of rush saltmarsh and dwarf mangrove ($p = 0.0909$), while herbs, grasses and sedges saltmarsh were significantly lower than rush saltmarsh ($p = 0.0002$).

Figure 4.3 Above-ground biomass of mangrove and saltmarsh for each vegetation structural form. Mangrove above-ground biomass derived using the structure-specific allometric equation for each quadrat measured at Hunter River, Minnamurra River, Currambene Creek and Cararma Inlet. All quadrat data in Appendix B. Saltmarsh above-ground biomass were derived from harvested samples at Minnamurra River.

Above-ground biomass estimates for mangroves measured in quadrats, derived using allometric equations at different spatial scales (i.e. compartment-specific, structure-specific, region-specific) indicated substantial differences between spatial scale. Tall mangrove estimates using the region-specific equation ($114.87 \pm 19.80 \text{ Mg ha}^{-1}$) were significantly greater than estimates using the compartment-specific equations ($77.93 \pm 14.68 \text{ Mg ha}^{-1}$) ($p = 0.0055$), while shrub mangrove estimates were lower (region-specific = $43.37 \pm 4.58 \text{ Mg ha}^{-1}$, compartment-specific = $52.63 \pm 6.71 \text{ Mg ha}^{-1}$), however this difference was not significant ($p = 0.2710$) (Figure 4.4a, b, c).

Estimates using the structure-specific equation for tall mangrove ($71.50 \pm 12.53 \text{ Mg ha}^{-1}$) were lower than estimates using compartment-specific equations ($77.93 \pm 14.68 \text{ Mg ha}^{-1}$), however this difference was not significant ($p = 0.7424$). Differences in biomass estimates derived from compartment-specific equations and structure-specific equations for shrub (compartment-specific = $52.63 \pm 6.71 \text{ Mg ha}^{-1}$, structure-specific = $53.06 \pm 6.94 \text{ Mg ha}^{-1}$) and dwarf mangrove (compartment-specific = $10.79 \pm 1.86 \text{ Mg ha}^{-1}$,

structure-specific = $10.68 \pm 1.77 \text{ Mg ha}^{-1}$) were not significant (shrub $p = 0.9653$, dwarf $p = 0.9652$) and this is reflected in the allometric equations (Figure 4.4d, e, f). These patterns were generally consistent between sites. High variability in estimates of dwarf mangrove was evident, demonstrating that the region-specific equation does not adequately describe the variation evident within the region.

When extrapolating quadrat derived estimates of above-ground biomass to the area of different vegetation structural forms, the effect of the scale of allometric equations (i.e. compartment-specific, structure-specific, region-specific) on biomass was mediated by the area of vegetation classes. This was particularly evident for tall mangrove, where the above-ground biomass estimate was markedly greater using the region-specific equation for all study sites (Table 4.3), but not as important for the shorter stature mangrove structural forms (i.e. shrub and dwarf). A similar pattern was observed for saltmarsh whereby spatial extent mediated quadrat derived above-ground biomass estimates. Rush saltmarsh extent at Currumbene Creek was small and offset the higher biomass associated with rush saltmarsh (Mg ha^{-1}), resulting in lower overall biomass compared to herbs, grasses and sedges.

Figure 4.4 Difference between mangrove biomass estimates derived from compartment-specific equations for individual measured quadrats a) tall, b) shrub, c) dwarf when compared to estimates derived from structure-specific equations (dark grey bars) and estimates derived from the region-specific equation (light grey bars). Difference calculated as percent difference from biomass estimates derived from compartment-specific equation. Comparison of allometric equation biomass estimates and observed biomass of harvested mangrove individuals d) tall, e) shrub, f) dwarf. Allometric equations are compared at different scales (i.e. compartment-specific, structure-specific, region-specific) for each mangrove structural form.

Table 4.3 Total above-ground biomass (AGB) estimates of mangrove and saltmarsh at different scales of assessment for Minnamurra River, Currumbene Creek and Cararma Inlet. Compartment, structure and region scale estimates for mangrove use compartment-specific, structure-specific and region-specific equations accordingly. Saltmarsh above-ground biomass estimates were not calculated at the compartment or regional scale due to harvest data and mapping units only corresponding to structural scale. Extent of vegetation structural form obtained from mapping in Chapter 3. HGS; herbs, grasses and sedges.

	Structure	Area (ha ⁻¹)	AGB estimates at the compartment scale (Mg ± SE)	AGB estimates at the structural scale (Mg ± SE)	AGB estimates at the regional scale (Mg ± SE)
Minnamurra River	Tall mangrove	14	733 ± 63	691 ± 55	1170 ± 83
	Shrub mangrove	17	783 ± 115	778 ± 133	680 ± 51
	Dwarf mangrove	11	170 ± 26	163 ± 20	253 ± 61
	Mangrove total	42	1686 ± 134	1632 ± 127	2103 ± 115
	HGS	7.5		56 ± 8	
	Rush	5.5		89 ± 11	
	Saltmarsh total	13		145 ± 13	
	Mangrove and saltmarsh total	55		1777 ± 146	
Currumbene Creek	Tall mangrove	16	1117 ± 85	1037 ± 77	1732 ± 216
	Shrub mangrove	6	545 ± 77	553 ± 85	448 ± 40
	Dwarf mangrove	7	33 ± 3	32 ± 3	34 ± 4
	Mangrove total	32	1694 ± 114	1622 ± 115	2214 ± 220
	HGS	5		36 ± 7	
	Rush	1		19 ± 2	
	Saltmarsh total	6		55 ± 7	
	Mangrove and saltmarsh total	38		1677 ± 115	
Cararma Inlet	Tall mangrove	10	448 ± 24	426 ± 23	687 ± 69
	Shrub mangrove	9	455 ± 129	460 ± 131	357 ± 98
	Dwarf mangrove	12	142 ± 20	146 ± 21	130 ± 23
	Mangrove total	31	1044 ± 133	1032 ± 134	1174 ± 122
	HGS	8.5		64 ± 12	
	Rush	9		147 ± 13	
	Saltmarsh total	17.5		211 ± 18	
	Mangrove and saltmarsh total	48.5		1243 ± 136	

4.3.4 Above-ground carbon storage

Carbon content varied between mangrove and saltmarsh vegetation. For mangrove, carbon content of biomass compartments was between 45% C and 50% C. Leaves plus inflorescences had the lowest carbon content of all mangrove compartments in all structural forms, with the exception of shrub mangrove. Branch carbon content was greater than leaves plus inflorescences, however trunk carbon content varied between structural form and species (Appendix B). The average carbon content for each vegetation structural form was $46.8 \pm 0.5\%$ C for tall, $47.6 \pm 0.5\%$ C for shrub and $47.5 \pm 0.9\%$ C for dwarf mangrove. For saltmarsh, carbon content for all four species was lower than all mangrove compartment carbon content. *Juncus kraussii* was highest ($42.9 \pm 1.7\%$ C) followed by *Samolus repens* ($42.5 \pm 0.1\%$ C), *Sporobolous virginicus* ($38.0 \pm 2.3\%$ C) and *Sarcocornia quinqueflora* ($34.4 \pm 0.8\%$ C). The average carbon content for herbs, grasses and sedges was estimated to be $38.3 \pm 2.5\%$ C.

Mangrove and saltmarsh above-ground carbon storage estimates were influenced by carbon content and above-ground biomass estimates. The mangrove regional scale estimate, using the region-specific allometric equation and an average carbon content value ($47.3 \pm 0.3\%$ C) was consistently higher at all study sites than other scales of assessment (Table 4.4). In contrast, the compartment and structural scales of assessment for mangrove, using the compartment-specific and structure-specific equations respectively, had similar carbon storage estimates, reflecting the pattern established in above-ground biomass estimates. Cararma Inlet which had the largest extent of rush saltmarsh, and highest carbon content, had the greatest carbon storage, whereas Currumbene Creek had the lowest estimate of saltmarsh carbon storage due to smaller extent of rush saltmarsh.

Table 4.4 Above-ground carbon storage estimates of mangrove and saltmarsh for Minnamurra River, Currumbene Creek and Cararma Inlet. Compartment, structure and region scale estimates for mangrove use compartment-specific, structure-specific and region-specific equations accordingly.

Site	Mangrove above-ground carbon storage (Mg C $\pm$ SE)			Saltmarsh above-ground carbon storage (Mg C $\pm$ SE)
	Compartment scale	Structural scale	Regional scale	
Minnamurra River	800 $\pm$ 64	771 $\pm$ 60	995 $\pm$ 54	60 $\pm$ 6
Currumbene Creek	802 $\pm$ 54	764 $\pm$ 54	1047 $\pm$ 104	22 $\pm$ 2
Cararma Inlet	495 $\pm$ 63	488 $\pm$ 64	555 $\pm$ 58	88 $\pm$ 14

4.4 Discussion

4.4.1 Synthesis of results

This study found that vegetation structure influenced biomass resulting in considerable variability in above-ground biomass estimates. For mangrove, this variation was related to height, stem diameter, crown area, and vegetation density, as demonstrated in other studies (Briggs, 1977; Fromard et al., 1998; Ross et al., 2001; Soares and Schaeffer-Novelli, 2005; Komiyama et al., 2008; Osland et al., 2014). Variation in saltmarsh biomass was associated with structural vegetation classes (rushes and herbs, grasses and sedges) related to height and density of vegetation in quadrats. It was also found that carbon content varied between species and biomass compartments within mangrove species, similar to results found elsewhere (Alongi et al., 2003; Saintilan et al., 2013; Bulmer et al., 2016a; Hossain et al., 2016). The variability in mangrove structure and its influence on biomass was accounted for in this study when developing allometric equations; these were developed at the compartment, structural and regional scale.

4.4.2 Accounting for scale in allometric equations

The pattern of scaling in allometric equations established in this study was consistent with other studies that apply similarly developed allometric equations for biomass compartments and total above-ground biomass (Clough et al., 1997; Ross et al., 2001; Ong et al., 2004; Comley and McGuinness, 2005; Osland et al., 2014; Hossain et al., 2016).

Developing allometric equations at different scales (i.e. compartment-specific, structure-specific, region-specific) to estimate mangrove above-ground biomass can increase confidence in estimates. A study of scaling of allometric equations suggests that variability increases when estimating biomass compartments compared to total above-ground biomass (Soares and Schaeffer-Novelli, 2005). In particular, branch and leaves plus inflorescences compartments were found to have highly variable biomass, likely due to variability in structural development. Similar results are found in this study and elsewhere (Estrada et al., 2014), suggesting that developing compartment-specific and structure-specific equations increases the capacity to capture variability that is overlooked using a region-specific equation.

Applying allometric equations at different scales influenced mangrove above-ground biomass estimates. The effect of spatial scale on mangrove ecosystems has been recognised for some time (Lugo and Snedaker, 1974; Duke 1998; Twilley et al., 1999; Schaeffer-Novelli et al., 2000), and discussed in the context of hierarchy theory (Twilley et al., 1999). In this regard, biomass allocation is compartmentalised at the smallest scale to biological cells which form roots, trunk, branches and leaves; the scale at which mangrove biomass was initially measured in this study. At the next spatial scale, biomass of individual mangroves was determined and equations at the structural and regional scale were developed. Hierarchy theory dictates that a process influencing any level of the hierarchy also influences higher and lower levels (Risser, 1987; Pickett et al., 1989). In this context, assimilation of biomass at smaller spatial scales, such as compartment scale, will influence higher spatial scales, such as structure and region spatial scales used in this study. To improve accuracy at larger spatial scales therefore requires consideration of variation at smaller spatial scales.

At the smallest spatial scale in this study, little difference in mangrove biomass was established when estimated using the compartment-specific or structure-specific allometric equations. This may relate to two factors. First, biomass variation at the structural scale based on measurements of height, stem diameter and crown area sufficiently described the variation in structure, and this was incorporated into the structure-specific allometric equation. These structural parameters were established in this study based on consistently optimising the r^2 and RMSE. They are also consistent

with parameters applied elsewhere with reasonable success (Ross et al., 2001; Soares and Schaeffer-Novelli, 2005; Osland et al., 2014; Bulmer et al., 2016a). Second, variation at the compartment scale was not adequately described and the variation was not recognised in the compartment-specific allometric equations developed in this study. Performance of allometric equations is therefore dependent on replication and sample size being adequate to describe variation in structure at different scales (Soares and Schaeffer-Novelli, 2005; Komiyama et al., 2008; Kauffman and Donato, 2012; Bonham, 2013).

The general pattern of performance of allometric equations at the compartment and structural scale was that r^2 was higher for structure-specific equations compared to compartment-specific equations, while RMSE generally decreased. Whether allometric equation performance should be evaluated on the basis of optimising r^2 or RMSE has been discussed for some time (Zar, 1968; Payandeh, 1981; Soares and Schaeffer-Novelli, 2005). Irrespective, little difference in biomass estimates for all mangrove vegetation structural forms (i.e. tall, shrub, dwarf) were found when using the compartment-specific or structure-specific allometric equations. Based on these results it is proposed that when determining mangrove above-ground biomass, efficiency is maximised using structure-specific allometric equations, and accuracy is approximately equivalent to that of the compartment-specific allometric equations.

Above-ground biomass derived using the region-specific allometric equation, where mangrove structural form was undifferentiated when developing the equation, produced greater overall mangrove biomass estimates at all study sites. This was primarily related to tall mangrove biomass being approximately 65% greater when estimated using the region-specific equation. Considerable variability also occurred for other vegetation structural forms. Sample size of harvested tall mangrove was considerably less ($n = 13$) than shorter height classes (shrub and dwarf mangrove $n = 30$) meaning that the trajectory of the region-specific allometric equation for mangrove biomass was dominated by the relationship between structural parameters of low stature mangroves. Removing the effect of shorter height classes on the mangrove biomass allometric equation by developing a tall mangrove structure-specific equation will improve accuracy, as demonstrated in this study.

4.4.3 Accounting for scale in carbon storage assessments

Variation was found in carbon content at the mangrove compartment scale as well as the structural scale of mangrove and saltmarsh. When determining carbon storage, the effect of this variation was compounded by variability in above-ground biomass estimates, as carbon storage is derived by multiplying carbon content and biomass. This is particularly important due to substantial variation in carbon content of saltmarsh species. Species typically distributed at higher elevations in southeast Australia, that is *Juncus kraussii* and *Samolus repens* (Adam et al., 1988; Clarke, 1993), have higher carbon content than other saltmarsh species. *Juncus kraussii* was found to have 25% more carbon in biomass than *Sarcocornia quinqueflora* which is substantially different and should be accounted for in carbon storage estimates. Little variation was identified in carbon content of different mangrove structural forms and this is likely to have little effect on carbon storage estimates when structural form is being accounted for (i.e. using structure-specific allometric equations).

Accurate quantification of carbon storage for a study site is dependent upon accurate assessment of biomass, carbon content and the extent of vegetation for which carbon storage is being assessed. This study demonstrated that above-ground biomass was best assessed when sampling is stratified at the structural scale, and that while there was variation in carbon content between compartments, the variation was small and less than the variation in carbon content of different species of mangrove and saltmarsh. Maintaining accuracy when assessing carbon storage requires mapping at units that correspond to the scale of biomass assessments. Not recognising the scale of biomass assessments when undertaking mapping allows additional error to be propagated. Typically carbon storage assessments are achieved by delineating mangrove and saltmarsh communities (Gibbs et al., 2007; Klemas, 2013; Patil et al., 2013; Manna et al., 2014). However results from this study suggest that overlooking the variation in biomass and carbon content of saltmarsh vegetation structure will provide incorrect estimates of carbon storage. For example, assuming similar carbon content of rush saltmarsh to herbs, grasses and sedges saltmarsh will result in underestimating carbon storage, particularly where rushes are extensive (i.e. Minnamurra River 22%, Currumbene Creek 37%, Carama Inlet 42%). The OBIA workflow presented in Chapter 3 delineates mangrove and saltmarsh at a scale suitable for structural scale carbon storage assessments and was

used as a basis for determining carbon storage in this study. Biomass estimates should be applied to mapping units that reflect the scale of assessment. This will improve accuracy and reliability of carbon storage assessments.

4.4.4 Determining above-ground biomass in temperate coastal wetlands

Structural complexity in temperate mangrove forests has been suggested to be greater than tropical mangrove stands, providing greater variability in height, stem diameter, crown area and vegetation density, and subsequently influencing above-ground biomass (see Morrissey et al., 2010). The variability in mangrove structural form and associated estimates of mangrove above-ground biomass was evident in previous above-ground biomass estimates in the region (southeast Australia). For example, mangrove measured at Lane Cove River (151°09' E 33°50' S) were reported to have an above-ground biomass of 112.3 – 114.5 Mg ha⁻¹ (Briggs, 1977), compared to mangrove measured at Hawkesbury River (151°30' E 33°30' S) that reportedly had an above-ground biomass of 52.1 – 60.1 Mg ha⁻¹ in hypersaline areas and approximately 400 Mg ha⁻¹ in areas of freshly accreted riverine flats (Saintilan, 1997b). The markedly different estimates from these studies and this study support the hypothesis that variation in vegetation structure and vegetation density profoundly influences biomass. Unlike equations developed in this study however, Briggs (1977) and Saintilan (1997b) used rudimentary equations that do not recognise variability in vegetation structure.

For saltmarsh vegetation, above-ground biomass estimates in this study were substantially higher compared with previously published estimates in the region (Clarke and Jacoby, 1994). *Sporobolus virginicus* was three times higher than previously reported (10.12 ± 2.02 Mg ha⁻¹ this study, 3.49 Mg ha⁻¹ Clarke and Jacoby, 1994), while *Juncus kraussii* (15.97 ± 2.35 Mg ha⁻¹ this study, 11.16 Mg ha⁻¹ Clarke and Jacoby, 1994) and *Sarcocornia quinqueflora* (6.88 ± 1.38 Mg ha⁻¹ this study, 3.17 Mg ha⁻¹ Clarke and Jacoby, 1994) were substantially higher. This variation in mean above-ground biomass of each species is likely a factor of variability in saltmarsh vegetation density, as demonstrated by replicate harvest quadrats by Clarke and Jacoby (1994) and results from this study.

4.4.5 Application of equations developed for global assessments

Previous research has attempted to quantify large scale mangrove above-ground biomass at the global and continental scale by extrapolating site scale measures (Twilley et al., 1992; Cohen et al., 2013; Hutchison et al., 2014; Rovai et al., 2016). Although larger scale estimates are useful for providing baseline estimates of above-ground biomass, these are yet to capture processes influencing variation of mangrove biomass at smaller scales (Estrada and Soares, 2017). Structural complexity of vegetation is not considered when extrapolating from site scale measurements of structure to larger spatial scales (Rovai et al., 2016), and is likely a function of averaging biomass estimates and subsequent extrapolation on the basis of low resolution mapping. This may be resolved to some degree by applying suitable mapping that reflects structural variation, as suggested by results in this study. Similar recommendations regarding mapping scale have been suggested to provide better national and global scale biomass estimates (Gibbs et al., 2007).

4.4.6 Implications of scale for carbon storage assessments

Results in this study demonstrate the importance of scale when reporting carbon storage estimates. Variation in vegetation structure, influencing biomass and carbon content of mangrove and saltmarsh vegetation, is important when estimating site level carbon storage. Using the region-specific allometric equation resulted in higher carbon storage estimates than both structure-specific and compartment-specific allometric equations across all sites for mangrove vegetation. Tier 1 and 2 assessments outlined by the IPCC (2014) are unable to provide the required confidence necessary to facilitate carbon credits through carbon off-setting initiatives such as REDD+, voluntary carbon markets and Australia's ERF. Only tier 3 assessments, where variability in mangrove and saltmarsh biomass and carbon content are described to a level that can provide the necessary confidence, are satisfactory for application to carbon markets (Kelleway et al., 2017c). Although high resolution assessments can be undertaken to improve accuracy, this is not feasible given the often limited resources (time and financial) to do so. There is a need to enhance assessment accuracy whilst optimising assessment effort, and this can be achieved by recognising the influence of structural variation in vegetation biomass. As demonstrated in the results, it is proposed that assessment of biomass and carbon content at the structural scale optimises accuracy and efficiency of tier 3 assessments required for

carbon off-setting initiatives. National carbon inventories should build upon higher accuracy assessments at regional scales to ensure confidence in carbon storage estimates.

4.5 Conclusions

This study developed a tier 3 level above-ground carbon storage assessment for study sites in southeast Australia. Accurate carbon storage assessment is dependent on three factors: accurate assessment of biomass, carbon content and vegetation extent. Mangrove and saltmarsh structure, biomass and carbon content are variable, and overlooking this variability will propagate error when estimating above-ground carbon storage. For mangrove, variability in above-ground biomass is best described by measuring height, stem diameter, crown area and vegetation density, whereas saltmarsh is best described by measurements of height, species and vegetation density. The scale of assessment at which above-ground biomass is measured will directly influence carbon storage estimates, whereby approaches that capture variation will be more accurate. While smaller scales are proposed to be more accurate, little variation in biomass was determined between the compartment and structural scale in this study. Assessments at the structural scale optimised efficiency and accuracy in above-ground biomass estimates. Maintaining this precision when quantifying above-ground carbon storage for a site requires mapping that corresponds to the scale of assessment. This study demonstrates that overall accuracy will be enhanced by mapping that delineates vegetation structural form. Application of average biomass and carbon content values extrapolated using coarse scale mapping, as proposed at tier 1 and 2 level assessments, will be inaccurate when accounting for carbon storage in coastal wetlands, and does not provide the necessary confidence for trading in carbon markets.