












Modeled approaches to estimating blue carbon accumulation with mangrove restoration to support a blue carbon accounting method for Australia

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Abstract

The development and refinement of methods for estimating organic carbon accumulation in biomass and soils during mangrove restoration and rehabilitation can encourage uptake of restoration projects for their ecosystem services, including those of climate change mitigation, or blue carbon. To support the development of a blue carbon method for Australia under the Emission Reduction Fund scheme we investigated; (1) whether carbon accumulation data from natural mangroves could be used to estimate carbon accumulation during restoration; (2) modeling mangrove biomass accumulation; and (3) how modeled carbon accumulation could be achieved over heterogeneous sites. First, we assessed carbon accumulation in soil and biomass pools from the global literature, finding that estimating carbon accumulation using data from natural mangroves provided similar estimates as those for restored or rehabilitated mangroves. We assessed mangrove biomass accumulation from global chronosequence studies, which we used to develop regional models for estimating biomass accumulation with restoration in Australia using values from local natural mangroves. Estimating biomass carbon accumulation using site-based means of stand biomass provided similar estimates as values estimated through use of regional means values stratified by elevation; and reduced overestimates of biomass carbon accumulation that were based on regional mean values. Modeling soil carbon accumulation over environmentally heterogeneous project sites can apply a similar approach, stratifying over variation in site elevation. Our analysis provides a strategy for modeling blue carbon pools for an Australian blue carbon method that accommodates regional differences and is based on data from natural mangroves.

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Additional Supporting Information may be found in the online version of this article.

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Efforts to restore mangroves are increasing to recover global mangrove cover, which has been reduced by 30–50% over the last century (Friess et al. 2019). Recovering global mangrove extent increases the resilience of coastlines because mangroves provide ecosystem functions and services for communities that include coastal protection, enhancement of water quality, support of biodiversity, fisheries, supply of forest and non-forest products and carbon sequestration, or blue carbon

(Barbier et al. 2011). Carbon sequestration in mangrove ecosystems in both biomass and soils contributes to climate change mitigation (McLeod et al. 2011), and thus these ecosystems have begun to be included in national policies and plans for reducing greenhouse gas emissions and climate change adaptation (e.g., Nationally Determined Contributions; NDCs) as well as within greenhouse gas inventories and in carbon markets (Herr and Landis 2016; Wylie et al. 2016).

Mangrove carbon stocks and accumulation rates vary at both regional and local spatial scales (Rovai et al. 2018; Sanderman et al. 2018; Simard et al. 2019). For example, mangroves of arid zones have lower stocks and accumulation rates compared to those in the wet tropics (Ezcurra et al. 2016; Kauffman et al. 2020), while at smaller scales carbon stocks and accumulation may vary with position in the intertidal zone and/or differences in vegetation structure (e.g., Lamont et al. 2020; Owers et al. 2020). Thus, the inclusion of mangroves into carbon markets and national carbon inventories requires science to develop appropriate methodologies that comprise nationally appropriate, regional, and local estimates of carbon stocks and accumulation (Kelleway et al. 2016; Needelman et al. 2018). Here we focus on developing accounting approaches that will contribute to estimating carbon credits under the Australian Governments Emissions Reduction Fund (ERF) scheme, which along with previous methods (e.g., Needelman et al. 2018) can inform method development in other nations and jurisdictions.

To register a blue carbon project under Australia's ERF scheme or other schemes, proponents must describe the range of management activities undertaken to increase carbon storage (e.g., conservation or restoration actions), and must estimate and verify how much carbon has been accumulated over time. For example, the requirements under the ERF scheme of Australia, are that all methods define the scope of eligible activities for proponents to be able to participate and estimate the carbon abatement quantity achieved as a result in the change in management. Carbon credit units generated under an ERF method can be sold or used as offsets for achieving carbon neutral certification. Under the ERF, estimates of changes in carbon pools over time consider the difference between carbon stocks and emissions under business-as-usual conditions, and carbon accumulated resulting from undertaking activities under the ERF method. Prior to project commencement, anticipated carbon accumulation may be modeled to assess the economic feasibility of commencing a project, and then as the project progresses, carbon accumulation can be measured and verified at prescribed intervals (e.g., up to 5 yr intervals for the ERF sequestration projects). Estimates of carbon accumulation can be achieved using robust models and on-ground monitoring methods over time, for example, forest inventory plots and changes in soil volume; remote-sensing approaches; and/or the use of proxies. For example, salinity as a proxy for methane emissions (Poffenbarger et al. 2011; Needelman

et al. 2018) or remote-sensing indices such as canopy fractional cover or Normalized Difference Vegetation Index (NDVI) as a proxy for aboveground biomass (Howard et al. 2014; Lymburner et al. 2020).

Approaches to modeling organic carbon accumulation in soil and biomass carbon pools of mangroves may use global mean rates of carbon accumulation from the IPCC Wetlands Supplement (2014), or national or regional mean values (e.g., Adame et al. 2018; Sasmito et al. 2019; Serrano et al. 2019). However, much of the data included in the calculation of global and regional mean values of carbon accumulation are derived from measurements in natural mangroves rather than managed mangroves that have been restored or rehabilitated, leading to uncertainty in using published mean estimates of carbon accumulation in carbon projects for mangrove restoration (IPCC 2014). Biomass accumulation in forests also varies over time (Odum 1960), which may not be well represented by mean carbon accumulation values from natural mangroves, leading to another source of uncertainty in estimates of carbon accumulation for mangrove restoration projects (Alongi 2012).

Finally, mangrove biomass and soil organic carbon accumulation vary over multiple spatial scales. While climate has a large influence over mangrove aboveground biomass (Hutchison et al. 2014; Serrano et al. 2019; Simard et al. 2019), at the scale of mangrove restoration projects (10s to 1000s of hectares, Bayraktarov et al. 2016) carbon accumulation in soils and biomass vary over steep intertidal gradients. For example, aboveground biomass and vertical accretion of sediments are often higher in low intertidal positions than in higher intertidal positions which are infrequently reached by tidal flows (Feller et al. 2010; Lovelock et al. 2010; Owers et al. 2018; Lamont et al. 2020). High levels of within-site variation in carbon accumulation could result in large errors in estimation of potential carbon accumulation in carbon projects (Oreska et al. 2017; Owers et al. 2020). A common approach to improve estimates of carbon accumulation is to stratify sites over environmental gradients, partitioning project sites into different strata (Howard et al. 2014; VCS 2020), which for mangroves could be linked to variation in tidal inundation with elevation as a proxy (VCS 2020). In seagrass meadows, stratification of sites over intertidal gradients was recommended to reduce uncertainty of estimates of carbon sequestered (Needelman et al. 2018), but the effectiveness of stratification in mangrove carbon projects for reducing uncertainty of estimated carbon accumulation has not been sufficiently evaluated.

Our objective was to facilitate modeling of aboveground biomass and soil organic carbon accumulation in a way that is robust, evidence-based, and conservative, to enhance the development of blue carbon projects. In view of the uncertainties described above that are associated with estimating carbon accumulation in mangrove restoration projects, we assess the following questions that address these uncertainties:

1. Can biomass and soil organic carbon accumulation data collected from natural mangroves adequately describe carbon accumulation in managed (restored, rehabilitated or plantation) mangroves?
2. At what rate do mangroves accumulate biomass over time, and are commonly used forest growth equations appropriate for estimating biomass accumulation?
3. How can carbon accumulation differences over differing intertidal zones be conservatively estimated to assist in simplifying carbon accounting approaches? For this component we used Australian case studies comprised of heterogenous vegetation types to assess the feasibility of estimating carbon accumulation using simplified modeled approaches.

Question 1: Can biomass and soil organic carbon accumulation data collected from natural mangrove adequately describe processes in managed (restored, rehabilitated or plantation) mangroves?

Growth rates of mangrove trees were recently reviewed (Xiong et al. 2019). These data comprised 475 observations of tree growth rates, expressed as increments in circumference of the tree stems (cm yr^{-1}) from natural mangroves (295 observations) and managed mangroves (90 observations). Managed mangroves included mangroves managed as plantations or restoration projects. The data set was global, spanning latitudes from the equator to 27.6° (both north and south). Australian mangroves were well represented with 78 observations from Australia included in the review, all from natural mangroves. Plot level data for biomass increments (tons of woody biomass per hectare per year) were also assessed. These comprised 184 observations, with 74 from natural mangroves and 110 from managed mangroves.

From this global data set, we found that stem circumference increments were higher in managed mangroves than natural mangroves (Table 1, see Supporting Information for description of statistical methods). Aboveground biomass increments measured using plot-based assessments (per hectare) indicate similar biomass increments in managed mangroves than in natural stands (Table 1). The biomass increment values were similar to the mean values of those presented in the IPCC Wetlands Supplement (IPCC 2014).

Managed mangroves, particularly plantations, may be thinned or otherwise managed to accelerate growth rates of trees (Saenger 2013). Additionally, rapidly growing species are often used in plantations and in restoration projects, which may result in faster growth in trees in managed mangroves (Chen et al. 2018; Feng et al. 2019). Higher stand biomass increments in managed mangrove compared to natural stands may also reflect variation in stand age (Phan et al. 2019). From this analysis we conclude that using biomass increment data (from stem circumference increments) from natural mangroves may underestimate biomass accumulation in restored and rehabilitated sites, and the use of plot-based biomass increments from natural mangroves will provide conservative estimates of biomass accumulation. For either growth measure, values from natural mangroves to estimate carbon accumulation in blue carbon restoration projects are likely conservative (and underestimated). Measurement of biomass accumulation, either using on-ground inventory plots or remote sensing techniques (e.g., Jones et al. 2020; Navarro et al. 2020) may provide more accurate estimates of carbon yields than those estimated from means derived from natural mangroves, although at higher cost.

To assess whether restored mangrove sites have soil organic carbon accumulation rates that were similar or different to those of natural sites we assessed the available literature, which is more limited compared to the data available for mangrove biomass accumulation. Assessment of nine studies from eight countries where soil carbon accumulation in natural sites was compared to restored or newly established mangrove habitat within the same study found no significant difference in soil carbon accumulation rates (Table 2, see Supporting Information Fig. S1 for a map of study sites and Table S1 for the references to the studies assessed). Using a larger data set where natural sites were not necessarily located at the same site as the restored mangroves, resulted in a similar conclusion (Supporting Information Fig. S1). Mean accumulated soil carbon in natural mangrove sites was slightly higher, but not statistically different to the rate of soil carbon accumulation in mangroves that are restored or were early in their development (Table 2). As soil carbon accumulation rates from managed mangroves were not significantly different from those from natural mangroves, we conclude that use of data from natural ecosystems is appropriate.

Our mean value of soil organic carbon sequestration ($1.94 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$) was slightly higher than that reported

Table 1. Rates of biomass accumulation in natural and managed mangroves. Data are mean \pm SE from Xiong et al. (2019). The significant differences between means of natural and managed mangroves for each row are indicated with different superscripts. Data were log transformed prior to analysis. See Supporting Information for further details of data analyses.

Growth parameter	Natural mangroves	Managed mangroves	Test
Stem growth rates increments in diameter, cm yr^{-1}	$0.33^a \pm 0.02$ ($N = 295$)	$0.77^b \pm 0.06$ ($N = 90$)	ANOVA $F_{1,378} = 81.0$, $p < 0.0001$
Stand biomass increments, $\text{Mg ha}^{-1} \text{ yr}^{-1}$	$6.83^a \pm 0.88$ ($N = 74$)	$7.80^a \pm 0.56$ ($N = 108$)	ANOVA $F_{1,180} = 3.00$, $p = 0.085$

Table 2. Comparison of soil organic carbon accumulation rates in restored and natural mangrove sites. Data were log transformed prior to analysis. See Supporting Information for further details of data analyses.

Data set	Soil organic carbon accumulation, Mg C ha ⁻¹ yr ⁻¹			Number of countries
	Restored	Reference/older	Test	
Global data where paired site was available	1.94 ± 0.89 (N = 10)	1.73 ± 0.48 (N = 10)	Paired <i>t</i> test <i>t</i> = 0.269, <i>p</i> = 0.794, df = 9	8
Global data (not paired)	2.44 ± 0.77 (N = 17)	1.94 ± 0.39 (N = 47)	ANOVA <i>F</i> _{1,58} = 0.025, <i>p</i> = 0.875	12

Table 3. Comparison of soil organic carbon accumulation rates among different methods used to estimate these values. Values for different methods were significantly different (ANOVA *F*_{1,60} = 5.16, *p* = 0.0085). Data are from sites within 12 countries. Significance differences between means are indicated with different superscripts. Data were log transformed prior to analysis. See Supporting Information for further details of data analyses.

Method	Soil organic carbon accumulation, Mg C ha ⁻¹ yr ⁻¹
Dated sediment cores	1.16 ^a ± 0.19 (N = 25)
Accumulation above a known horizon or baseline (including soil cores and marker horizons)	3.66 ^b ± 0.86 (N = 26)
Surface elevation tables	1.14 ^a ± 0.17 (N = 13)

in the 2013 Wetland Supplement (soil carbon accumulation for mangroves of 1.62 Mg C ha⁻¹ yr⁻¹, IPCC 2014). However, soil carbon accumulation estimates may be sensitive to the method used (Table 3). Mean values from dated sediment cores and surface elevation tables (~ 1.14–1.16 Mg C ha⁻¹ yr⁻¹) were lower than those reported in the 2013 Wetlands Supplement (IPCC 2014), while those assessed above a known baseline soil horizon were higher (3.66 Mg C ha⁻¹ yr⁻¹). Dated sediment cores usually comprise longer time periods than those for surface elevation tables (multiple decades compared to multiple years), but both methods incorporate processes of sediment compaction and decomposition (either over long time periods or deep in the soil profile), which may lead to similarly conservative soil organic carbon accumulation rates, compared to methods that evaluate short-term carbon accumulation above a baseline (Arias-Ortiz et al. 2018; Breithaupt et al. 2018). Given the high costs of dating sediment cores and installation and monitoring of surface elevation tables (Gerald et al. 2019), modeled soil carbon accumulation or measured data above a baseline may provide appropriate and equitable (among projects) methods to estimate soil carbon accumulation for mangrove restoration projects. However, there are higher levels of uncertainty in measurements of soil carbon accumulation above a known

horizon compared to other methods (Table 2). Higher levels of variability can result in inability to detect changes in soil carbon and thus impose substantial risks to projects (Viscarra Rossel and Brus 2018).

Alternative proxies to estimate soil organic carbon accumulation at scales appropriate for mangrove restoration projects may be developed that utilize the strong relationship observed between the sediment accommodation space and soil carbon accumulation in mangroves (Rogers et al. 2019) and the link between sediment availability and vertical accretion of soil volume (Lovelock et al. 2015). The accommodation space describes the space available to be filled with sediment in the intertidal zone (reflecting the volume of tidal inundation) which decreases with elevation and increases as sea level rises (Woodroffe et al. 2016). Thus, development of models that incorporate the concept of accommodation space have the potential to increase accuracy of modeled estimates and incorporate the effects of sea level rise on soil carbon accumulation over the lifetime of carbon projects, which are often 100 yr (Kelleway et al. 2016; Needelman et al. 2018).

In Australia, values for soil organic carbon accumulation in natural mangroves have been assembled and modeled regionally (Serrano et al. 2019), which can form the basis of modeled soil carbon accumulation with mangrove restoration in a blue carbon method, given the similarity in soil carbon accumulation rates in natural and restored sites (Table 2). However, using regional mean or median values from Serrano et al. (2019) may lead to overestimation of project level soil carbon accumulation as accommodation space varies over sites (e.g., from low to higher in the intertidal zone). Stratifying sites, based on variation in elevation provide a means to adjust soil carbon accumulation for variation in accommodation space over sites (Needelman et al. 2018). Furthermore, other models have recommended this approach (Rogers et al. 2019, Kirwan and Megonigal 2013). Additional site factors, for example soil fertility or species composition, may be incorporated into modeled estimates of soil organic carbon accumulation as data become available that could further reduce uncertainties in estimating soil carbon accumulation during restoration.

Question 2: At what rate do mangroves accumulate biomass over time and are commonly used forest growth equations useful for estimating biomass accumulation of mangroves?

Chronosequences of mangrove plots established at different times (i.e., plots of different ages) can provide a description of how mangroves develop over time. Data from nine sites with known ages of mangroves were retrieved from the literature, along with two unpublished studies from Australia (S. Dittmann and J. Kelleway unpubl. data). A typical growth curve used to describe forest biomass growth were fitted to the chronosequence studies (Table 4). Four sites were comprised of plantations of *Rhizophora apiculata*, which is the favored species used in plantations in South East Asia. One site was planted *R. apiculata* and one natural regeneration of *R. apiculata*. Four sites were comprised of species within the genus *Avicennia*, one of which were planted (*A. marina* in India, Kandasamy et al. 2021), and three which were natural forests (e.g., *A. germinans* in French Guiana, Marchand 2017, Walcker et al. 2018), or natural regeneration (*A. marina*, S. Dittmann and J. Kelleway unpubl. data).

Comparison of these mangrove chronosequences of development showed that they achieved different levels of mature standing biomass at between 20 and 40 yr of age (Fig. 1). The sites from which the data were extracted have varying climates and other environmental and management factors (nutrient availability, substrate type, disturbance regime, land-type) which influenced the mature biomass achieved. Biomass increments of mangroves have been described by standard growth equations used for terrestrial forests (Phan et al. 2019; Sasmito et al. 2019) and thus we modeled growth using functions that estimate tree yield (Waterworth and Richards 2008), which are used for estimating growth of terrestrial forests in the Australian Government's Full Carbon Accounting Model (FullCAM, <https://www.industry.gov.au/data-and-publications/full-carbon-accounting-model-fullcam>), that is used to estimate

the carbon stored and emitted from the land sector in Australia's annual greenhouse gas accounts. The tree yield curves for aboveground biomass (AGB) were of the form

$$AGB = a \times \left(\exp\left(-\frac{k}{age}\right) \right)$$

where “a” approximates the mature AGB and “k” the rate of AGB increase over time (Paul et al. 2015; Preece et al. 2017). Using the nine data sets, mean “k” was 29.6 with SD of 29.7. The lowest “k” values, indicating the most rapid growth to

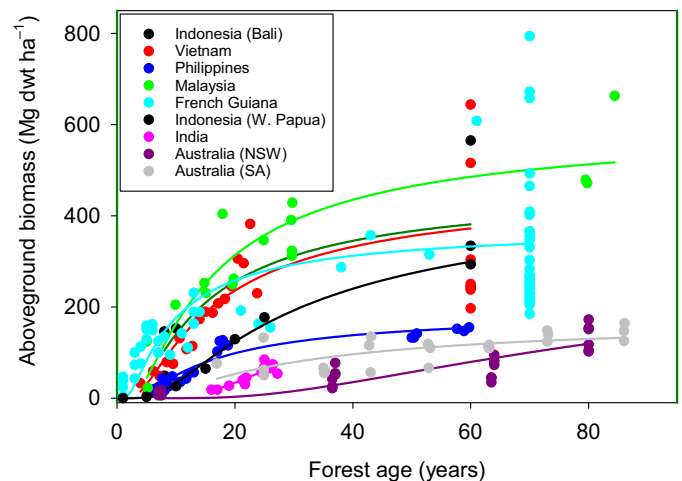


Fig. 1. Variation in mangrove aboveground biomass (Mg dry weight ha^{-1}) over stands of different ages. Data are from nine sites; Bali, Indonesia (dark green), Vietnam (red), Philippines (dark blue), Malaysia (light green), French Guiana (light blue), West Papua, Indonesia (black), India (pink), New South Wales, Australia (magenta) and South Australia (gray). Lines are fitted functions of the form $AGB (Mg dwt ha^{-1}) = a \times (\exp[-k/age])$, where “a” approximates the mature aboveground biomass and “k” the rate of biomass increase over time. Curve parameters are represented in Table 4.

Table 4. Parameters for growth curves of mangroves from mangroves. The curves are of the form $AGB (Mg dwt ha^{-1}) = a \times (\exp[-k/age])$, where “a” approximates the mature aboveground biomass and “k” the rate of biomass increase over time. Mean “k” was 29.6 with SD of 29.7 (SE 9.9).

Location	Species	Activity	a	k	R ²	Reference
Vietnam	<i>Rhizophora apiculata</i>	Plantation	467.6 ± 61.5	13.69 ± 3.09	0.632	Phan et al. 2019
Philippines	<i>Rhizophora apiculata</i>	Plantation	193.3 ± 11.9	13.49 ± 1.33	0.895	Salmo et al. 2013
Malaysia	<i>Rhizophora apiculata</i>	Plantation	604.4 ± 53.5	13.12 ± 2.36	0.817	Adame et al. 2018
Indonesia (Bali)	<i>Rhizophora apiculata</i>	Planted shrimp ponds	465.7 ± 111.6	11.99 ± 6.40	0.642	Sidik et al. 2019
French Guiana	<i>Avicennia germinans</i>	Natural regeneration	377.7 ± 27.7	7.61 ± 1.98	0.484	Walcker et al. 2018
India	<i>Avicennia marina</i>	Planting mud flats	621.5 ± 308*	58.1 ± 11.9	0.721	Kandasamy et al. 2021
Indonesia (Papua)	<i>Rhizophora apiculata</i>	Natural regeneration	464.6 ± 26.2	26.4 ± 1.74	0.990	Sillanpää et al. 2017
Australia (NSW)	<i>Avicennia marina</i>	Natural regeneration	405.7 ± 27.7	97.8 ± 25.6	0.696	J. Kelleway unpubl.
Australia (SA)	<i>Avicennia marina</i>	Natural regeneration	171.5 ± 24.9	23.9 ± 6.7	0.383	S. Dittmann unpubl.

*Data for older (> 27 yr) stands were not available.

maturity, were from the naturally occurring *A. germinans* stands in French Guiana and for *R. apiculata* in plantations. Higher “*k*” values were in naturally regenerating stands of *R. apiculata* and *A. marina*. The highest “*k*” (slowest growth to maturity) was for temperate mangroves comprised of *A. marina*.

Using the mean slope of the growth curves, but noting differences in the mature biomass estimated in mature mangroves, provides a general curve that could be used to develop estimates of biomass and therefore carbon (which is approximately 50% of biomass) accumulation in mangroves over time, if a local mature biomass is known. Mean mature aboveground biomass carbon for mangroves in different climatic regions in Australia were available in Serrano et al. (2019) (Table 5). These differing regional biomass carbon values incorporate variation in species composition over climate regions as well as difference in productivity.

From the mean parameter “*k*” from Table 4 and the mean aboveground biomass for each region as “*a*” the potential change in biomass over time in the different climatic regions can be modeled (Fig. 2). Further, SDs about the bioregional mean biomass can be used to determine an upper and lower range of biomass accumulation depending on local environmental factors (e.g., the level of tidal inundation). In Fig. 2b, the modeled curves for the subtropics in Australia are shown as an example, with the mean biomass and values that are one SD from the mean. We plot the modeled curves as well as observed plot-based biomass from a range of sites, including seaward fringing tall forests to high intertidal scrub forests (Fig. 2b).

This approach to modeling biomass accumulation over time indicates the potential to use growth curves that incorporate values of mature aboveground biomass that could be regional (e.g., Serrano et al. 2019), or derived from global or regional remote sensing (e.g., Simard et al. 2019; Hickey et al. 2018; Lucas et al. 2020), and from sensors on unmanned autonomous vehicles (UAVs) (Navarro et al. 2020; Jones et al. 2020). Regional or site-based allometric equations would increase the accuracy of remote sensing methods (e.g., Owers

et al. 2018; Jones et al. 2020). This approach also highlights the potential to consider additional environmental factors that vary within sites, through site stratification, to establish biomass accumulation for different “strata” with a site. Stratification of sites based on known variation in environmental factors can improve estimates of carbon accumulation that might occur when using regional mean values (Needelman et al. 2018; Oreska et al. 2017).

Question 3: How can carbon accumulation over different intertidal zones be conservatively estimated to assist in simplifying carbon accounting approaches?

Mangrove aboveground biomass varies among climatic regions, mainly due to variation in aridity (rainfall, humidity, river flows, groundwater) and temperature (Simard et al. 2019; Xiong et al. 2019). Within regions and within sites, local levels of porewater salinity, soil oxygen and nutrients largely determine mangrove growth and aboveground biomass, factors which are influenced by the level and duration of inundation by tidal waters as well as freshwater inputs (rivers, groundwater). Because of the overwhelming importance of levels of tidal inundation in determining mangrove soil conditions, and because levels of inundation are linked to elevation, elevation of coastal land has been used as a simple proxy for factors that directly influence plant growth and mangrove forest biomass development (Mogensen and Rogers 2018). However, elevation may not be an appropriate proxy in sites with complex hydrology. For example, elevation as a proxy for inundation frequency and intensity may be less appropriate where tidal inundation is attenuated by complex topographic and soil characteristics and vegetation, where tides fail to reach sites where it might be expected based on elevation alone (Hughes et al. 2019), or water is ponded for long periods at sites that are higher in elevation (e.g., behind levees) (Pérez-Ceballos et al. 2020). Additionally, groundwater seepage, which provides freshwater and/or nutrients that stimulate growth (Hayes et al. 2019), may also reduce the appropriateness of elevation as a proxy for inundation.

Despite the limitations of using elevation as an indication of tidal inundation and thus for stratifying projects for differences in potential mature mangrove biomass, elevation is an attractive proxy for tidal inundation because detailed elevation data of coastal lands are becoming increasingly available at finer scales. This is largely due to the development of Light Detection and Ranging (LiDAR) laser technology from which coastal digital elevation models (DEM) can be developed (Leon et al. 2014). For example, in Australia digital elevation models at 5 × 5 m grid resolution are available over much of the Australian coastline (Geoscience Australia, <http://www.ga.gov.au/scientific-topics/national-location-information/digital-elevation-data>). Additionally, even in sites where DEMs are not available, elevation profiles of sites can be estimated with

Table 5. Mean (± 1 SD) aboveground biomass carbon for mangroves in Australia in different climatic regions from Serrano et al. (2019, Supplementary table 3).

Climatic region	Mangrove aboveground biomass C stock, Mg C ha ⁻¹	Mangrove aboveground biomass, Mg dwt ha ⁻¹
Tropical (humid and monsoon)	167 \pm 101 (N = 15)	348 \pm 210 (N = 15)
Subtropical	101 \pm 78 (N = 5)	210 \pm 162 (N = 5)
Arid/semiarid	70.3 \pm 41 (N = 8)	146 \pm 85 (N = 8)
Temperate	70.4 \pm 41 (N = 9)	147 \pm 85 (N = 9)

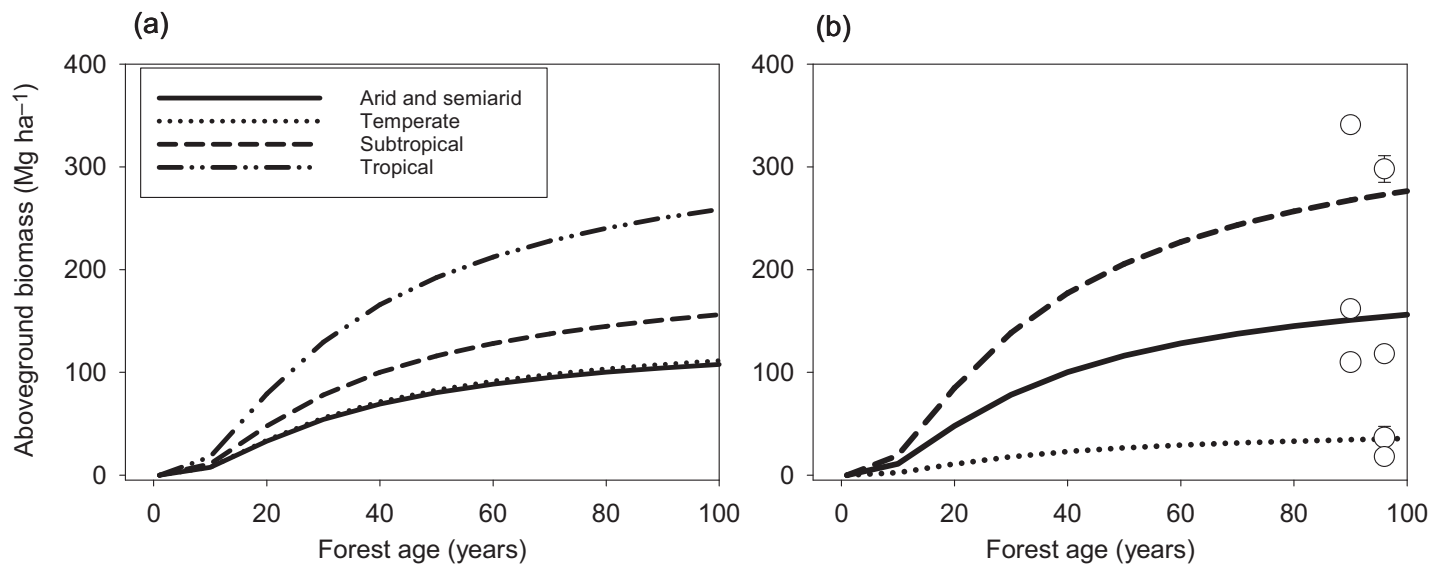


Fig. 2. Modeled mean aboveground biomass of mangroves over time in four climatic regions of Australia (a). Modeled accumulation of mangrove aboveground biomass carbon for subtropical regions in Australia using a range of values for “a,” including mean aboveground biomass (solid line) and values that represent one SD on the low (dotted) and high (long dash) range of aboveground biomass in the region (b). Mean biomass data (open symbols with SEs) from mature stands growing in different environmental settings in subtropical Australia are represented as circles and are from Mackey (1993) and Hill et al. (2021). For both panels the curves are of the form $AGB = a \times (\exp[-k/\text{age}])$ where “a” approximates the mature aboveground biomass (Table 5) and “k” the rate of biomass increase over time ($k = 29.6$).

a range of techniques, some of them at low-cost (Lewis and Brown 2014).

To evaluate the potential use of elevation to stratify sites to improve estimates of biomass accumulation for projects, aboveground biomass accumulation from a range of Australian case studies from different climatic regions were investigated. Case studies were identified as sites where aboveground biomass and elevation data were available. Elevation was expressed relative to the Australian Height Datum (AHD), but elevation ranges were also expressed as a proportion of the tidal range (from -1 (Lowest astronomical tide) to 0 (MSL) to $+1$ (Highest astronomical tide) to facilitate comparison among sites with different tidal ranges. The detailed description of the case studies is presented in the Supporting Information.

We used data from the case studies to estimate mangrove biomass in a simulated 100 ha site that had a similar distribution of elevation strata as occurred in the case study locations. For example, in the arid zone case study higher biomass trees occupied 11% of the intertidal zone while intertidal scrub trees occupied 33% of the intertidal zone (the remainder of the intertidal zone being unvegetated). Thus, for our 100 ha simulation we assume 11 ha occupied by higher biomass trees, and 33 ha occupied by lower biomass scrub trees. This analysis indicated that stratification of sites based on elevation (or the proportion of the tidal range occupied by different plant communities) resulted in small over- or underestimate (between $+3$ and -14%) of aboveground biomass compared to the use of a single site-based measured mean value of aboveground

biomass (Table 6). The use of mean values of mangrove biomass for climate regions (Serrano et al. 2019) to estimate aboveground biomass overestimated aboveground biomass by between 12% and 225%. This overestimation may reflect the selection of larger, seaward-fringing mangroves at lower elevations in historical surveys, rather than landscape assessments (as were considered in the case studies) which included lower biomass stands that occurred higher in the intertidal zone. The use of aboveground biomass values derived from the global mangrove height layer of Simard et al. (2019) provided estimates of aboveground biomass that were more similar to the estimates when sites were stratified and the estimates based on measured site values, compared to the estimates of aboveground biomass based on climatic regional values of Serrano et al. (2019), with a small underestimate (-9%) to overestimates (up to 112% in Darwin) of aboveground biomass. The similarity in biomass estimates when sites were stratified based on elevation and site-based assessment (obtained either from adjacent natural mangroves or using data from Simard et al. 2019) suggests that stratifying sites based on elevation, with biomass estimates of different strata linked to regional mean biomass, may provide a science-based, simple, and conservative method to estimate abatement.

The magnitude of over- and underestimates of aboveground biomass through use of the climate means of Serrano et al. (2019) were variable but larger in climate zones where tidal inundation, and sediment and nutrient availability over intertidal gradients result in strong gradients in aboveground biomass (Feller et al. 2010). The use of site-based mean values

Table 6. Summary of estimates of mangrove aboveground biomass accumulation in a range of case study sites using: (1) aboveground biomass values that are stratified across the project site using the area and biomass of plant communities associated with different elevation strata; (2) site-based mean value of aboveground biomass; (3) climatic mean values from Serrano et al. (2019); and (4) site-based mean value from global aboveground biomass from remote sensing data sourced from Simard et al. (2019). Project sites (within the case study area) were assumed to be 100 ha and comprised of the proportion of area for each elevation strata that is typical for the case study area. Detailed information on the case studies is available in the Supporting Information.

Region	Site	Estimated aboveground biomass accumulated (Mg per 100 ha)			
		(1) Stratified values (# of strata)	(2) Site-based mean value— measured (% difference from stratified estimate)	(3) Climatic regional mean (% difference from stratified estimate)	(4) Site-based mean value (% difference from stratified estimate)
Arid/semiarid	Exmouth Gulf	5255 (2)	5410 (+3%)	14,700 (+180%)	7000 (+33%)
Tropical (monsoon)	Darwin Harbor	6611 (4)	5670 (−14%)	14,700 (+122%)	14,000 (+112%)
Tropical (humid)	Daintree River	29,774 (2)	30,000 (+1%)	33,400 (+12%)	27,000 (−9%)
Subtropical	SE Queensland sand islands	6218 (3)	6220 (0%)	20,200 (+225%)	7000 (+13%)
Warm temperate	New South Wales	4765 (3)	4770 (0%)	14,000 (+194%)	7000 (+47%)

of aboveground biomass may provide the most appropriate values for the parameter “*a*” in tree yield formulations used to model aboveground biomass accumulation for carbon projects. Site values of aboveground biomass from global remotely sensed data (e.g., Simard et al. 2019) or acquired locally from the literature or from adjacent natural stands through new technologies such as UAV surveys using cameras and/or LiDAR methods (Owers et al. 2016; Navarro et al. 2020; Jones et al. 2020) could also be appropriate for estimating “*a*” at proposed blue carbon project sites. The use of LiDAR could also contribute to assessments of changes in soil elevation caused by sediment accretion in project sites to estimate soil carbon gains and losses (Pineux et al. 2017).

Conclusions

Our study focused on key areas of uncertainty in estimating abatement potential for carbon projects based on mangrove restoration. We conclude that estimating aboveground biomass and soil carbon accumulation in mangrove restoration or rehabilitation projects can use data from natural mangroves from the same types of locations (climatic and geomorphic). We also found that using parameters derived from growth curves from established global chronosequences of mangrove development could be used to conservatively estimate biomass accumulation over time. Growth curves can use varying values of mature biomass depending on climate regions and local site conditions, which may be derived from natural mangroves. Because of the large within-site variation in mangrove aboveground biomass over small spatial scales across the intertidal zone, we showed that stratifying project sites based on

elevation within the intertidal zone could lead to more robust estimates of aboveground biomass. While this type of stratification did not out-perform estimates from site-based mean values of aboveground biomass, whether measured or from proxies, the use of stratification improved the accuracy of estimates of biomass compared to those based on regional means. A similar approach for soil carbon accumulation could be used, and future work to verify estimates of soil carbon accumulation over heterogeneous sites, with approaches that consider accommodation space and incorporate sea level rise, being particularly promising. While other blue carbon accounting methods (e.g., Verified Carbon Standard VM0033, Needelman et al. 2018) have requirements for measuring accumulation of carbon stocks during restoration of coastal wetlands, our approach suggests models may also be appropriate which could reduce costs and increase uptake.

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Conflict of Interest

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