

**Bangor University**

## **MASTER OF PHILOSOPHY**

### **Sources of error in the estimation of aboveground biomass carbon stocks in mangrove ecosystems**

Greer, Bethan

*Award date:*  
2023

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# **Sources of error in the estimation of aboveground biomass carbon stocks in mangrove ecosystems**

**By Bethan Greer**

**Supervisors: Dr Nat Fenner and Prof Chris Freeman**



I hereby declare that this thesis is the results of my own investigations, except where otherwise stated. All other sources are acknowledged by bibliographic references. This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree unless, as agreed by the University, for approved dual awards.

I confirm that I am submitting this work with agreement of my supervisors.

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Yr wyf drwy hyn yn datgan mai canlyniad fy ymchwil fy hun yw'r thesis hwn, ac eithrio lle nodir yn wahanol. Caiff ffynonellau eraill eu cydnabod gan droednodiadau yn rhoi cyfeiriadau eglur. Nid yw sylwedd y gwaith hwn wedi cael ei dderbyn o'r blaen ar gyfer unrhyw radd, ac nid yw'n cael ei gyflwyno ar yr un pryd mewn ymgeisiaeth am unrhyw radd oni bai ei fod, fel y cytunwyd gan y Brifysgol, am gymwysterau deuol cymeradwy.

Rwy'n cadarnhau fy mod yn cyflwyno'r gwaith hwn gyda chytundeb fy Ngoruchwyliwr (Goruchwylwyr)

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## Summary

Mangrove forests are a type of wetland ecosystem found along subtropical and tropical coasts around the world. True mangrove species are specially adapted to the environments they grow in with a range of features such as salt glands for salt-excretion and aerial roots for respiration in the tidal systems. Whilst it has been known for many years that mangroves serve vital functions as nurseries for commercially important fish as well as providing protection from extreme weather events, in more recent decades focus has turned to the amount of carbon stored in these habitats, particularly as solid aboveground biomass (AGB). However, mangroves are difficult to work in and generalised allometric equations for AGB and carbon content values for aboveground biomass carbon (AGBC) have been developed to help produce estimates. But the accuracy of the estimates produced using generalised values when compared to site and species-specific data has been questioned, particularly where the values have been developed in different parts of the world. In chapter 1, a systematic evidence map was designed to assess whether there was geographical bias in the current literature on mangrove carbon and if helicopter research potentially influenced the locations of studies. It was found that only 51.6% of countries that contain mangrove ecosystems were represented in the map, however, 5 countries represented 53.6% of the total study locations showing that the current mangrove carbon research is skewed towards certain locations with African and Island countries noticeably less represented. But the map also showed that the current research has mostly been conducted by researchers based at institutions in the country they studied, suggested that helicopter research does not heavily influence the field. Chapter 2 reviewed the current literature about calculation of AGBC estimates using 13 generalised values found in the literature compared to site-specific data from 6 papers. It was found that the use of generalised values with site-specific AGB data created significant differences in the estimates of AGBC produced using site-specific carbon values, with the largest value of underestimation at 20.20% of the original AGBC estimate and the largest value of overestimation at 16.76%. In chapter 3, three generalised common equations for calculating mangrove AGB were tested against equations designed for use on 3 species in Florida where diameter at breast height (dbh) and tree height were measured at the Vester Field Station in South-West Florida. Tree height was measured using 2 different methods, a telescopic pole and a clinometer, to test for significant differences in height values produced. The use of the common equations for estimating AGB produced 2 significantly different estimates, although the last equation did not, potentially due to roughly equal distribution of individual tree AGB estimations. The site-specific AGB values were the smallest overall which suggests that the use of generalised equations results in overestimation of mangrove AGB. It was also found that the tree height measurements made using the clinometer were significantly different than those taken with

the telescopic pole. Chapter 4 used the site-specific AGB measurements from Florida combined with site-specific carbon content data, also collected from the Vester Field Station, to test the use of generalised carbon content values in situ, where it was found that all of the generalised carbon content values, apart from 49% (closest to the site-specific carbon value), produced significantly different estimates for AGBC. In Summary, the use of generalised AGB equations and carbon content values has been shown to produce significantly different AGBC estimates. This requires more testing, particularly in currently understudied regions, to assess whether there should be continued use of these equations and values in the production of AGBC estimates.

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## An introduction to mangroves and their potential in climate mitigation projects

### Abstract

Mangroves are coastal forests found across 147,359km<sup>2</sup> of the tropics and subtropics. Mangroves are highly specialised to their coastal environment with salt-exclusion mechanisms and aerial roots and pneumatophores for respiration in a saline tidal environment, propagules evolved for dispersal via water, and adaptations to their nutrient limited ecosystem that allow breakdown of insoluble nutrients as well as capturing sediment. Whilst many countries such as the USA are reducing the area of mangroves lost annually after historical deforestation and degradation, mangroves are still threatened from destruction for construction, altered hydrology due to changes in drainage and extreme weather events such as hurricanes which are expected to increase in frequency and severity due to climate change. Carbon emissions reduction schemes include work such as reforestation, with mangroves being considered for improving long-term carbon sequestration in degraded coastal environments. However, mangroves are complex ecosystems requiring thorough consideration of factors such as hydrology, tidal frequency, inundation period and location of the site. Many mangrove carbon sequestration projects focus on the aboveground biomass carbon (AGBC) and soil carbon, but much of the current research fails to acknowledge the potential variations in aboveground biomass (AGB) and AGBC, using generic allometric equations to calculate AGB followed by generalised carbon content values to estimate AGBC. The aim of this project was to evaluate whether the current literature on mangrove carbon exhibits geographical bias that could impact the reliability of data applied to mangroves worldwide, whilst investigating if use of generalised biomass equations or carbon content values create error in AGBC estimates when compared to site-specific data.

### Mangroves

Mangrove forests are coastal tropical and subtropical wetland forest systems found almost exclusively between the latitudes of 40°N and 40°S, located in 2 main areas referred to as the Indo-West Pacific (the IWP) and the Atlantic-East Pacific (the AEP), covering 124 countries around the world (FAO, 2007; Tomlinson, 2016). It is estimated that worldwide mangroves cover an area of 147,359km<sup>2</sup> as of 2020 (Bunting et al, 2022). Mangroves can be defined as a group of dicotyledonous vascular plants within tropical intertidal forest communities characterized by their presence in ecotones influenced by tidal action and are 1 of 3 types of salt-water wetland systems, with the other 2 being sea grass beds and saltmarshes respectively (Tomlinson 1986; Hogarth 2015). It is estimated that there are between 54 and 67 species of true mangroves, along with many mangrove associates

that also grow in these wetland forests (Hogarth, 2015; Tomlinson, 2016; Quadros and Zimmer, 2017). However, in the last few decades work has continued to identify species previously considered hybrids or variations of other true species (Sheue et al, 2003; Tomlinson, 2016; Quadros and Zimmer, 2017).

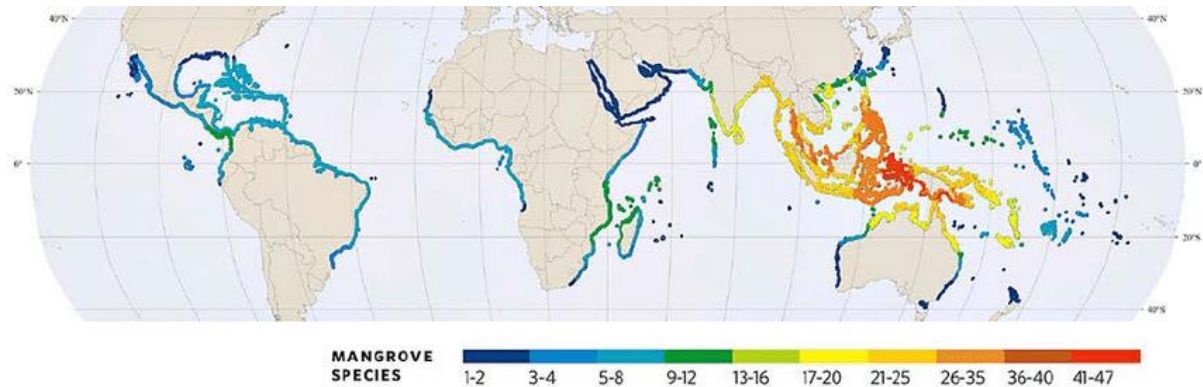


Figure 1: The distribution of mangroves globally, showing the tropical and subtropical latitudes mangroves ecosystems are found in, with the highest species density in the IWP zone. Image taken from Hoff et al (2002).

True mangrove species are defined by several criteria. In Tomlinson (1986) true mangroves are defined by 4 major factors:

1. The species only occurs in mangrove habitat and does not expand to further terrestrial ecosystems.
2. They must possess some feature or mechanism designed for exclusion or excretion of salt.
3. The species must also possess other morphological features such as pneumatophores or aerial roots that adapt them to the mangrove ecosystem.
4. True mangroves should be taxonomically separated from non-mangrove terrestrial relatives at a minimum at the level of genera.

Major and minor species of a mangrove community can then be further separated by their ability to form pure stands of just one species, which only major elements of mangrove communities can do. Other work by researchers such as Duke et al (1998) suggested vivipary as another factor for determining whether a species would be considered a true mangrove. More recently Quadros and Zimmer (2017) presented a dataset including 125 traits that could be used to identify the species they described as true mangroves including features such as type of germination, tolerance to environmental changes, root structure, leaf lifespan and wood density.

Mangroves are found on all continents that have land in the tropics or subtropics, with the extended parts of their range including Florida in the USA, Japan, South Africa, and New Zealand (Tomlinson,

1986; Spalding, 1992; Hogarth, 2015). Mangroves can tolerate a range of temperatures which allows them to survive temperatures as low as 5°C in countries such as Japan or New Zealand (Hogarth, 2015). But mangroves are unable to tolerate frosts and die-offs of mangrove forests have occurred where temperatures have gone below their temperature threshold (Osland et al, 2015). Sea-surface temperature (SST) is another significant factor for explaining the distribution of mangrove forests as all mangrove forests are in areas where SST does not reach below 20°C for extended periods of time (Tomlinson, 1986; Hogarth, 2015). The forests on the edges of mangrove habitat range are all supplied with warm water and provided a source of propagules for continued seedling establishment in these regions from currents that run from tropical regions (Tomlinson, 1986; Hogarth, 2015).

### The challenges and adaptations of mangroves

As with many tropical forests, mangroves are nutrient limited due to low availability of nutrients including nitrogen and phosphorous which are essential for plant growth (Tomlinson, 1986). Most nutrients that mangroves can use are transported either in freshwater rivers or underground seepage, or by tidal action from the sea, however some may come from other sources such as rainfall, guano from bird colonies or microbial activity in the soil (Hogarth, 2015). But mangroves are also able to unlock nutrients that would be unavailable in aerobic terrestrial soils. Due to the waterlogged nature of many mangrove soils, anoxic sediments allow redox reactions that reduce insoluble ferric salts to ferrous salts that can be taken up by plants as soluble iron and phosphate (Hogarth, 2015; Lodge, 2017). It has also been found that some bacteria and fungi may also break down insoluble phosphorous into a soluble form, contributing to the role of micro-organisms in the nutrient cycle. Oxygen release from photosynthetic process also impacts the structure of the microbial community, allowing small areas around the roots where aerobic microbes may survive and contribute to processes such as nitrification as part of the further nitrogen cycle, increasing the amount of nitrogen available to the mangroves (Hogarth, 2015).

While tidal action brings nutrients into the mangroves, the inundation presents another challenge for the plants. The waterlogging of the soils reduces the amount of oxygen available for respiration, so mangroves have developed a variety of root structures adapted to the changing water levels.

Pneumatophores are structures that grow up from the underground roots of a mangrove tree to allow greater respiration and increase the volume of air the roots are exposed to (Tomlinson, 1986; Hogarth, 2015; Lodge, 2017). These pneumatophores can vary in height, with the highest recorded being 3m, and with this height the time roots are exposed to the air and not underwater increases, extending the period the trees can respire for (Hogarth, 2015). Other mangrove species from families

such as *Rhizophorae* may also have aerial roots that branch out from the main trunk to increase the reach of the roots and increase the overall surface area of the tree (Tomlinson 1986, Hogarth 2015; Lodge, 2017). Under the soil, mangrove root biomass is often comprised of aerenchyma tissue, which has a structure not dissimilar to honeycomb with many air spaces that run along the length of root (Hogarth, 2015). The air enters these spaces in the roots through specialised pores called lenticels. The lenticels facilitate oxygen entering the root system of mangroves, and as the water level rises with tidal action, the hydrophobic nature of the lenticels forces them shut which prevents water entering through these pores (Hogarth, 2015).

Pneumatophores and aerial roots also serve another function. When tidal action brings silt and organic matter into the root system it can become trapped there due to the presence of aboveground roots like pneumatophores (Hogarth, 2015; Lodge, 2017). These structures slow the movement of water around them, resulting in the increased settling of sediment brought into the mangroves, resulting in a build-up of layers of sediment. Over time this can result in an increase of land around a mangrove community, but also a deep layer of peat that can build over millennia (Ezcurra et al, 2016). In some countries, the layer of peat underneath mangrove forests can be over 2000 years old (Ezcurra et al, 2016).

Mangroves presence in tidal zones also brings the challenge of salinity. For many plant species including important crop plants, salinity can only be tolerated up to 100mM NaCl (Tuteja, 2007). Halophytes such as mangroves can however survive in much more saline conditions of up to 250mM NaCl, with mangroves able to survive in conditions where the salt concentrations result in osmotic potential of as low as -2.5MPa (Tuteja, 2007; Hogarth, 2015). This allows them to form ecosystems in estuaries and directly on coastlines, as well as further upstream where the water is brackish (Tomlinson, 1986). This is due to several features. Some mangroves have salt secretion glands on the leaves that excrete the salt which crystalizes before being blown or washed off the leaf's surface (Tomlinson, 1986; Hogarth 2015). Others generate negative osmotic pressure within the plant that allow water to be drawn into the plant without bringing the salt inside the plant with it (Hogarth 2015). It has been found that in some species of mangroves that between 90 and 99% of salt can be excluded from uptake at the root level (Hogarth, 2015). Whilst much of the exclusion of salt is done before it can impact cells that are less salt-tolerant, different cellular structures including the cell walls have also been found to compartmentalize Na and Cl ions away from the cell cytoplasm (Hogarth, 2015).

Whilst there are other halophytic species that can tolerate environmental salinities similar to mangroves, and other tropical plants living in swamp ecosystems that grow aerial roots, the only



halophytic trees that exhibit the trait of true vivipary are mangroves as one of several reproductive adaptations (Tomlinson, 1986; Das et al, 2022). There are 4 genera of mangroves (*Rhizophora*, *Bruguiera*, *Kandelia*, *Ceriops*) that show true vivipary; where the embryo of the mangrove grows out of its seed coat and the surrounding fruit before it has detached from the parent plant (Tomlinson, 1986, Das et al, 2022). 3 other genera (*Aegiceras*, *Aegilitis*, *Avicennia*) show a version of this known as crypto-vivipary where the embryo only emerges from the seed coat before it is separated from the parent plant (Tomlinson, 1986, Das et al, 2022). Mangroves are pollinated by a range of insect and bird species (E.g., *Trigona* bees, *Heliophorus epicles* butterflies, *Meliphaga gracilis* honeyeater etc.) as well as through wind-born pollination and in some hermaphroditic species such as *Ceriops decandra*, through self-pollination (Solomon Raju and Henry, 2008). Once pollination takes place and the propagules have grown on the parent tree, they are then released for dispersal via water as tidal action and currents move the propagules to new areas (Lodge, 2017; Das et al, 2022). Mangrove propagules do not appear to become “dormant” as they are transported and it is hypothesised that physio-chemical changes within the seedling allow it to adjust to the salinity of the surrounding water, as well as changing its buoyancy (Wang et al, 2019). Establishment of the propagules appears to revolve around several biotic and abiotic factors (Yando et al, 2021). Biotic factors that could impact the survival of mangrove propagules include propagule size, period on the parent plant and risk of predation from animals such as crabs, whereas the abiotic factors include elevation of the land, tidal inundation frequency and height, environmental salinity, sea surface temperature and air temperature and the physio-chemical characteristics of the soil (Wang et al, 2019; Yando et al, 2021).

These adaptations make mangroves highly specialised to the tropical and subtropical regions they grow in, from the coast right into areas of brackish water and fresh water further up estuaries (Hogarth, 2015). But the adaptations that make mangroves so successful in these areas also put limits on their range. As mangroves get closer to their environmental limits, net primary productivity (NPP) begins to reduce as environmental factors such as average air temperatures, daylengths and growing seasons reduce due to latitudinal restrictions (Hogarth, 2015). This is predominant around the edges of mangroves geographical distribution such as in Florida.

### Mangroves in Florida

Historically, in countries such as the United States (USA) mangroves have been regarded as dangerous, unpleasant environments with few uses to the people who live in close proximity to them (Lugo and Snedaker, 1974). Said to release a potentially deadly “swamp gas” (most likely hydrogen sulphide) and containing many feared animals such as alligators, for years the goal in many countries

was to remove these wetlands to gain land for commercial uses or building homes in coastal areas (Lugo and Snedaker, 1974). Between 1985 and 2001 Florida lost 60,000 ha of mangrove forests, roughly 23% of the total previous area (Lewis et al, 2000). But perceptions of these environments have changed particularly in recent years with increased understanding of mangrove adaptations to the ecological niche they fill and their importance to many industries and the residential areas neighbouring these forests.

There are 3 species of true mangrove in the USA, *Rhizophora mangle*, *Avicennia germinans* and *Laguncularia racemosa* (FAO, 2007; Lodge, 2017; FDEP, 2022). *Rhizophora mangle* is part of one of the largest family of true mangroves and is known as a red mangrove due to the red colour under the top layer of bark (Tomlinson, 2016). *R. mangle* is a pantropical species that is easily identifiable by large prop roots that spread away from the trunk of the tree (FDEP, 2022). Then there is *Avicennia germinans*, a black mangrove that is widespread through North and Central America, the Caribbean and extending to the Pacific coast of South America as well as the Galapagos is identifiable most easily by the texture and colour of the bark which is a grey brown (Tomlinson, 1986; FDEP, 2022). The white mangrove species, *Laguncularia racemosa*, has a rounded leaf edge that is distinct from the other 2 species, as well as no visible aerial roots. These 3 species are commonly found growing in mixed forests, with mangrove associates such as *Conocarpus erectus* (the buttonwood tree), but with increase in latitude *A. germinans* becomes dominant as it is the most tolerant to cold temperatures (Lodge, 2017; FDEP, 2022).

There are a few major threats to the mangrove ecosystems of Florida. Deforestation of mangroves is common worldwide in order to allow expansion of settlements and the USA is no exception. In the last 30 years the population of Florida has grown at a rate over double that of the US general population, with an increase from around 13.5million residents in 1992 to 21.6million at the time of the 2022 census (Carrillo et al, 2022). This population increase is found primarily in coastal communities and with that comes more home construction as well as a need for businesses and services such as schools (Oliver-Smith, 2020). Florida is also a hub for tourism, and even though there are a large number of tourist attractions based around mangrove forests, tourism still requires infrastructure such as roads as well as accommodation to stay in which only creates high demand for land (Spalding and Parrett, 2019; Carrillo et al, 2022).

The expansion of coastal communities and the need to secure the water supply for those areas has historically led to issues with drainage in Florida. In the previous century 1/3 of the wetland area in the Florida Everglades was drained (Mitsch, 2019; Lagomasino et al, 2021). Water flow and drainage were altered using canals, dikes and ditches, which then altered the hydrology of many of the

surrounding wetland ecosystems such as the mangrove forests (Simon and Travis, 2011; Kendall et al, 2022; Lennon and Sealey, 2022). Changes to the surface flow and the hydrology of the mangrove ecosystems coupled with the building of structures such as sea walls can have major impacts on nutrient exchange which leads to degradation of the mangroves (Marois and Mitsch, 2017; Lagomasino et al, 2021; Lennon and Sealey, 2022). Mangroves in Florida have shown negative reactions after long-term altering of the water shed has led to issues from agricultural run-off causing eutrophication, and increased salinity and pulses of freshwater and sediment coming from water sources further up the canal system resulting in the degradation of mangrove habitat (Lennon and Sealey, 2022).

But not all causes of mangrove degradation and mortality are directly tied to anthropogenic causes. Between 1922 and Summer 2022 Florida was hit by 28 hurricanes of category 3 or higher (Carrillo et al, 2022). Mangroves as coastal ecosystems are susceptible to damage when hit by a hurricane particularly from 2 sources: storm surges and high winds (Doyle et al, 1995; Smith et al, 2009; Marios and Mitsch, 2015). Wind damage affects the branches and leaves of the mangroves the most, snapping branches and stripping leaves off the tree, but occasionally whole trees are blown down, particularly *Rhizophora mangle* which is unable to resprout after major stem damage (Lagomasino et al, 2021). Previous work by Doyle et al (1995) has also suggested that *Laguncularia racemosa* may also be susceptible to wind damage after study plots were analysed in South Florida following Hurricane Andrew in 1992. When a storm surge hits the mangroves, the aerial roots and pneumatophores help to dissipate the energy of the waves, but this can result in large volumes of sediment being dropped onto the mangroves and potentially suffocating the root system (Smith et al, 2009; Menéndez et al, 2020).

This issue can also be compounded when combined with human-made barriers, such as roads or drainage ditches, which prevent adequate flushing of the mangroves after storm surge events, increasing the risk of die-off within the forests even months after the hurricane (Lagomasino et al, 2021). The damage to ecosystems and communities from hurricanes is predicted to increase as SSTs increase due to climate change (IPCC, 2012; Trenberth et al, 2018). With that it is expected that there will be more frequent hurricanes of category 3 or higher which is a major problem for low-lying and coastal states with large populations (IPCC, 2012; Dinan, 2017). With mangrove habitat already fractured through destruction for construction and the drainage of wetlands altering hydrology, there may not be adequate conditions for mangroves to recover from the tree mortality that hurricanes often cause.

### Mangroves in emissions reduction projects

With predictions of extreme weather events increasing in frequency and rising SST and sea level, many countries are now looking into ways to lower their emissions and limit the potential impacts of climate change (IPCC, 2012; Marsooli et al, 2019). Reforestation and afforestation using different temperate and tropical forest species has been used by many countries following the UNFCCC guidelines to reduce carbon emissions lost to the atmosphere and in more recent years it has been suggested that mangroves could be used in a similar manner (Basuki et al, 2022; Lovelock et al, 2022a; Andres et al, 2023). The UNFCCC defines reforestation as “the planting of trees on land which previously supported tree-dominated ecosystems” and afforestation as “the planting of trees on land which previously supported non-tree-dominated ecosystems” and combined with REDD+ protocols allow countries to earn money using a rewards-based payment system for reductions in emissions from deforestation and degradation of their forests (Basuki et al, 2022; UNFCCC, 2022).

It has been suggested that mangroves be used for replanting projects in many coastal countries and the Global Mangrove Alliance has announced their aim for mangrove area to be increased from reforestation, afforestation and restoration by 20% by 2030 (Lee et al, 2019). As Florida addresses issues with water drainage and changes to sheet flow from the 1900’s, the hydrology of the state may alter to provide better conditions for mangrove growth, providing an opportunity to replant in historically degraded areas (McLeod et al, 2011; Mitsch, 2019). But mangrove replanting projects are often plagued with problems.

Whilst countries such as Indonesia, Australia, the Philippines and the USA are replanting areas of mangroves to sequester carbon, many of these projects end in failure (Lewis III, 2005; Lee et al, 2019; Lovelock et al, 2022a). With many of the previous projects that have failed, there was a lack of understanding of factors such as hydrology at the chosen site as strategies for terrestrial environments are often applied without factoring the coastal side of the ecosystems (O’Connor et al, 2019). Planning often overemphasises tidal patterns and frequency when looking at potential sites but fails to consider other factors such as inundation period or average rainfall and its frequency (Lewis III, 2005). Site selection often leads to failure as areas such as mudflats and seagrass beds are chosen to be replaced because they are easier to reach and work on than locations such as abandoned shrimp ponds, despite the fact the mudflats and seagrass may not be suitable and the project would remove a different but also important coastal ecosystem (Lee et al, 2019; Lovelock et al, 2022a). A lack of consideration for the complexity of these ecosystems and an understanding of factors such as critical habitat area to the participation of local groups and communities have so far left large numbers of mangrove planting projects as failures to launch (Lovelock et al, 2022a).

### Current knowledge gaps in mangrove carbon

Despite covering roughly 0.7% of total land area and 1% of tropical forest area, mangroves could sequester up to 20PgC (Rao et al, 2021; Zhu and Yan, 2022). Whilst much of the carbon in the cycle is released from the mangroves as dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), or particulate organic carbon (POC), much of it is also buried in the sediment or stored in the trees as biomass (Zhu and Yan, 2022). But many research projects on long-term mangrove carbon storage focus on the variability in soil C stocks in mangroves without reference to the potential variation in the carbon storage potential of the aboveground biomass (AGB) (Rao et al, 2021; Lovelock et al, 2022b). AGB may be calculated using broad allometric equations designed to estimate the amount of biomass in a site whilst the carbon stocks in AGB (AGBC) are often calculated using generalised carbon content values that may be based on a small volume of data from one country or region (Thomas and Martin, 2012; Chave et al, 2019; Lovelock et al, 2022b).

Currently there are no reviews looking into whether there is a potential source of geographical bias in the literature on mangrove research, either on account of choice of study site or by lack of local researchers in underrepresented countries, or research into whether the use of broad use allometric equations for AGB and generalised carbon content values introduce a significant level of error to the estimation of AGBC, using the mangroves of South Florida as a study area.

The research aims of this project are:

1. Is the distribution of mangrove carbon studies reflective of geographical and species distributions of mangroves? (Chapter 1)
2. Is the current literature on mangrove carbon research reflective of authors from low- and high-income countries? (Chapter 1)
3. Does the use of generalised carbon values result in significant overestimation or underestimation when compared to site-specific values? (Chapter 2)
4. Does the use of general aboveground biomass equations result in significantly different AGB estimates than species-specific equations? (Chapter 3)

5. Does the use of generalised carbon values produce significantly different AGBC estimates than site-specific values? (Chapter 4)

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## A Systematic Evidence Map of the current scope of naturally occurring mangrove carbon research: assessing the risk of geographical bias and helicopter research

### Abstract

Predicted shifts in climatic patterns are expected to cause declines in the aerial coverage of wetlands. Wetlands are important for many ecosystem services such as blue carbon storage in salt marshes, seagrass beds and mangrove forests. Mangroves are highly productive environments, storing 11.2PgC globally. However, due to the difficulties of working in mangrove environments, gaps in the evidence base may have appeared, allowing geographical bias and 'helicopter research', defined as researchers from higher income countries conducting research of little local benefit in lower income countries, to influence understanding of these ecosystems and future policy making. Here a systematic evidence map was designed to identify in a collection of mangrove carbon research: year published, study location, species included and the location of the first authors institute (n=859). The study showed that there was geographical bias as the 5 most studied countries represented over 50% of total study locations and only 51.6% of countries containing mangroves were represented, with Africa and many island nations underrepresented in the literature. Helicopter research did not appear as a prevalent issue as the first authors of 619 studies were based at institutes within the same country as their study. Species data was influenced by the bias in geographical locations, resulting in species from the most frequently studied countries being most represented. It is concluded that gaps in the current literature must be addressed in ways that encourages scientific development in underrepresented areas and protects mangroves as important ecosystems for future blue carbon policy and climate action.

### Shifting climates and wetland environments

The 2021 IPCC report on climate change stated that the current concentrations of atmospheric CO<sub>2</sub> and other greenhouse gases have reached levels not experienced for at least 2 million years (Arias et al, 2021). As global surface temperatures and mean sea level rise at historic rates, the effects of human-induced climate change are already occurring around the world as more extreme heat events, droughts and sea level rises are observed. Changes in precipitation patterns and increases in extreme weather events such as cyclones have been observed in the last 40 years and whilst future climate change models from the IPCC report with lowered CO<sub>2</sub> emissions project that natural carbon sinks will be able to keep pace and store the carbon released, models with higher projected emissions show a smaller amount of take up relative to emissions released (Arias et al, 2021). The

Table 1: The identified types of wetlands categorised into inland, coastal and human-made types based off data from The Global Wetland Outlook 2018 (Ramsar Convention on Wetlands, 2018). Coastal wetlands considered blue carbon habitats are indicated by light blue shading of the box.

Inland Wetlands	Coastal Wetlands	Human-made wetlands
Rivers and Streams	Estuaries:	Water Storage bodies:
Natural lakes	-Unvegetated Tidal Flats	-Reservoirs
Natural ponds	-Saltmarshes	-Small (e.g., Farms) ponds
Peatlands:	-Coastal Delta	Agricultural Wetlands
-Forested Peatlands	Mangroves	Rice Paddy
-Non-forested Peatlands	Seagrass Beds	Palm Oil Plantations
-Tropical Peatlands	Coral Reefs (warm water systems)	Wet Grasslands
-Temperate/Boreal Peatlands	Shellfish Reefs	Wastewater Treatment/ Constructed Wetlands
Marshes and Swamps	Coastal Lagoons	Saltpans (Salines/Salinas)
Tropical Freshwater Swamps	Kelp Forests	Aquaculture Ponds
Forested Wetlands	Shallow Subtidal marine systems	Human-made Karst and Caves
Groundwater-dependent Wetlands:	Sand Dunes/Beaches/Rocky Shores	
-Karst and Cave systems	Coastal Karst and Caves	
-Springs and Oases		
-Other Groundwater-dependent Wetlands		
Tidal freshwater marshes		

shift in climatic patterns is predicted to cause a decline in several different ecosystems including wetlands.

Wetlands are often-underappreciated systems as demonstrated by the continued degradation and destruction of many types of natural wetlands worldwide leading to a 35% reduction in their extent,

compared to ones seen as ‘useful’ such as paddy fields, shrimp farms and artificial salt pans which increased by 233% in the same timeframe (Junk et al, 2013; Tomlinson, 2016; Convention on Wetlands, 2021a). Wetlands are important for many ecosystem services that they provide including coastal stabilization and natural barriers from storm events and surges, habitat for a range of endemic species, as well as supply of drinking and irrigation water for crops (Barbier, 2006; Convention on Wetlands, 2021a). But the impacts of human activity combined with climate change have led to variations in acidification, rainfall and temperatures of the sea surface, leading to the drying out and desertification of wetlands whilst increased pollution has created dead zones in over 700 coastal systems from eutrophication and higher plant mortality in mangrove wetlands where oil spills cover plant surfaces and pollute the soils (Duke, 2014; Convention on Wetlands, 2021a). Recently however, more research is being done on whether the ability of wetlands to store carbon could be used in climate mitigation plans, with many looking at ‘blue carbon’ environments such as salt marshes, seagrass meadows and mangrove forests (Taillardat et al, 2018; Convention on Wetlands, 2021a).

#### Blue carbon in mangroves

Blue carbon is defined by the Convention of Wetlands as ‘carbon captured by living organisms in coastal and marine ecosystems and stored in biomass and sediments’ (Convention on Wetlands, 2021b). Ecosystems that store blue carbon can keep much of it in a stable form for millennia, with sequestration rates up to 55 times higher than those of tropical rainforests. They are often characterised by disproportionate carbon sequestration capabilities for the global area they cover, with the majority of carbon stored in the sediments (McLeod et al, 2011; Taillardat et al, 2018; Convention on Wetlands, 2021b). Worldwide, blue carbon systems only cover 0.4% of land but represent around 1.3% of carbon sequestration on land (Taillardat et al, 2018).

Table 2: The sequestration rates of blue carbon environments according to The Global Wetland Outlook (Convention on Wetlands, 2021a)

Blue carbon habitat	Carbon sequestered (tonnes per hectare)
Seagrass Beds	512
Saltmarshes	917
Mangroves	1028

Out of the types of blue carbon ecosystems, mangroves have been found to be particularly productive environments storing up to 11.2PgC globally (Sanders et al, 2016). These systems are located along tropical and subtropical coastlines starting in the intertidal zones and continuing inland where saline water becomes brackish (Singh et al, 2005; Prasad and Ramanathan, 2008). Mangrove forests, also referred to as mangals, are forests comprised of plants suited to the intertidal community that are distinctive due to their morphological and physiological adaptations to the brackish environment such as salt-secretion mechanisms, aerial roots and vivipary (Tomlinson, 2016; Duke 2016). Whilst there is still some debate about what are included as 'true' mangrove species, the number of species is estimated at around 54-55, divided into major and minor components, whilst many more species are considered mangrove associates (Tomlinson, 2016; Quadros and Zimmer, 2017). Mangroves tend to be most abundant along estuaries and coastlines with extensive sedimentation. This due to deposits high in nutrients, minerals and organic matter that become accumulate in their root systems, building up the sediment and reducing erosion of the shoreline (Prasad and Ramanathan, 2008; Tomlinson, 2016; Willemsen et al, 2016). The anoxic conditions linked to tidal inundation creates an environment where carbon burial can take place whilst the nutrient rich substrate allows growth of belowground and aboveground biomass with some mangrove forests reaching heights of over 60 metres (Singh et al ,2005; Prasad and Ramanathan, 2008; Simard et al, 2019). These processes result in disproportionate carbon storage even in mature forests with average carbon sequestration estimated at  $168 \pm 36 \text{gCm}^{-2} \text{yr}^{-1}$  and net primary production globally estimated as  $218 \pm 72 \text{TgC yr}^{-1}$  (Bouillon et al, 2008; Fuentes and Barr, 2015; Taillardat et al, 2018). However, when mangroves are disturbed or destroyed, they can release large amounts of sequestered carbon in the form of the greenhouse gases  $\text{CO}_2$ ,  $\text{CH}_4$  and  $\text{N}_2\text{O}$  that are a by-product of microbial processes in the anoxic soils, which would contribute to further global warming and atmospheric  $\text{CO}_2$  and greenhouse gas concentrations (Gilman et al, 2008; Duke, 2016; Castillo et al, 2017). This threat to mangal ecosystems is only going to increase as deforestation, relative sea level rises and extreme weather events increase worldwide (Gilman et al, 2008; Arias et al, 2021).

To understand how these systems could be used in blue carbon mitigation policies it is important to have data for as many representative global locations and species as possible. But mangrove forests can be difficult to access, and studies can become expensive, leading to potential issues with information produced not reflecting biogeographical factors such as climate variables and spatial patterns or inadequate sample size. A potential issue with geographical bias is that the locations that are studied may not reflect mangal habitats globally as particular countries are excluded from the data pools. Researchers from lower income countries may not have the funding to set up these

studies, leading to research from these areas being “helicopter research” done by scientists from higher income countries that provides no local benefit or cannot be used practically (Rovai et al, 2015; Li et al, 2019; Lagomasino et al; 2019; Minasny et al, 2020; Hsu et al, 2021).

Mangroves also often grow in monospecific stands which may lead to issues where rarer species of mangrove are not adequately covered in the current literature and therefore not considered in carbon or replanting projects against more studied species (Tomlinson, 2016; Feng et al; 2019). Despite these apparent risks for bias and error in this field there has not been any large sample study or review so far looking at the current distribution of mangrove research and whether the global distribution and species range of mangroves is reflected in the literature. And whilst studies have shown a trend of researchers in lower income countries being omitted in fields such as soil science and genomics it is currently unclear if this is an issue that the field of mangrove carbon research also faces (Minasny et al, 2020; Hsu et al, 2021). Here we use a systematic evidence map (SEM) to investigate these issues

An SEM is a type of literature review used to map out potential knowledge gaps and areas of research that could benefit from further investigation (Hetrick et al, 2010). Using an explicit research question with key components defined, such as population and outcome, a systematic evidence map attempts to identify all relevant literature to provide an overview of the subject, showing what has been investigated and any areas lacking studies (Miake-Lye et al, 2016). Further review of the evidence can also be done to produce a systematic review (SR) by studying the scientific rigor of the evidence gathered to investigate limitations of the current literature in answer to a particular question (Rytwinski et al, 2021). A systematic evidence map was chosen for the research question as a broad analysis of the literature was considered more appropriate for looking at a larger set of data and its variables.

The questions investigated in this SEM are:

1. Do the study locations in the current literature on carbon in mangroves proportionately reflect the distribution and area of mangrove wetlands and the number of countries they are present in?
2. Are the currently accepted species of mangrove reflected proportionally in the current mangrove literature?
3. Is there adequate representation of local authors and authors from developing countries in the current literature on carbon in mangroves?

## Methods

The objective of this systematic evidence map was to provide a clear overview of the geographical range of primary research involving carbon in mangrove systems, with further synthesis of the species included and the country where the first authors of each paper were based. The papers for the evidence map was collected initially in May 2020 from the open access databases ProQuest and Web of Science and then updated in August 2020 to include any published on those databases before the start of analysis. ProQuest originally produced over 12000 results but would not allow

Table 3: The search strings for each database used and the number of results for each search.

Database/source	Search String	Number of results
ProQuest	("mangrove" AND "carbon*") NOT (at.exact("Commentary" OR "Editorial" OR "News" OR "Front Matter" OR "Table Of Contents" OR "Undefined" OR "Evidence Based Healthcare" OR "Back Matter" OR "Interview" OR "Obituary" OR "Recipe") NOT stype.exact("Magazines") NOT la.exact("CHI" OR "RUS" OR "FRE" OR "POL" OR "CZE" OR "GER" OR "IND" OR "TUR") NOT subt.exact("genes" OR "fisheries" OR "gene expression") AND PEER(yes)) NOT (at.exact("Correspondence" OR "Correction/Retraction" OR "Biography" OR "Conference Proceeding" OR "Statistics/Data Report" OR "Conference") NOT subt.exact("abundance" OR "taxonomy" OR "contaminated sediments")) NOT (at.exact("Working Paper/Pre-Print" OR "Report" OR "Case Study" OR "Correspondence" OR "Correction/Retraction" OR "Biography" OR "Conference Proceeding" OR "Statistics/Data Report" OR "Conference") AND stype.exact("Scholarly Journals") NOT subt.exact("lead" OR "proteins" OR "zinc" OR "lakes" OR "soil erosion") AND PEER(yes)) AND FULL TEXT	9836
Web of Science	TOPIC: ("mangrove*") AND TOPIC: ("carbon*")	3062



more than 10000 to be downloaded, so additional filters were added to bring the number down to 9836. On the other hand, when more refined filters were used for Web of Science the number of papers was reduced without any noticeable increase in accuracy to the search terms, so filters were kept broader. CADIMA, a piece of software published by the Julius Kühn-Institut that the Collaboration for Environmental Evidence encourages use of for systematic evidence maps and reviews, was used to build the evidence map. A total of 12898 papers were included in the dataset before 660 duplicates were removed. The titles and abstracts were screened with the criteria for exclusion being no mention of mangroves or carbon and no evidence of the research including primary data. If there was ambiguous or unclear language the papers were retained to prevent qualifying studies being excluded unnecessarily. After this level there were 2005 papers studied at full text level. For screening the full articles additional exclusion criteria were added. The included studies on mangroves had to include primary data, a study aim including carbon analysis, and also must include the country or countries the study sites were located in. The list of countries and regions followed the lists given in the FAO Forestry Paper 153 (FAO, 2007). Data was then extracted from the 857 studies that met all criteria. All the papers that remained included were of primary research that had been peer-reviewed with full text available, with greenhouse studies and manipulated plots excluded as they would not accurately reflect conditions in non-manipulated mangrove forests. For the first author comparison variable of political/historical ties this was defined here as previous colonial ties, current trade agreements or other funding and foreign campuses for universities or research, between the country of the lead author and the country the study was located in.

Table 4: The key elements of the systematic evidence map questions broken down into populations, interventions, comparators, and outcomes. These were used to then inform the search strings created for the evidence map.

Population	Intervention	Comparator	Outcome
Mangroves, Mangals, Mangrove wetlands	Carbon measurement (including soil, AGBC, BGBC, POC, DIC, DOC, TOC, TIC, SOC, SC, SIC, DWC, LC, LWC, TEOC, WSOC, POXC, MOC, C)	Geographical location, location of first authors institution, mangrove species	Locations of mangrove carbon studies, species included in mangrove carbon research, location of the first authors institution

## Results

The studies included in the final dataset were found to have all been published in the last 40 years, with the earliest paper published in 1985. The number of papers on mangrove carbon increased over this time period with the majority (59.5%) of studies produced between 2015-2020. Many of the studies investigated multiple forms of environmental carbon, however, the most frequently studied were forms of soil carbon (Soil organic carbon, inorganic carbon, soil carbon, total organic carbon of soil, etc.).

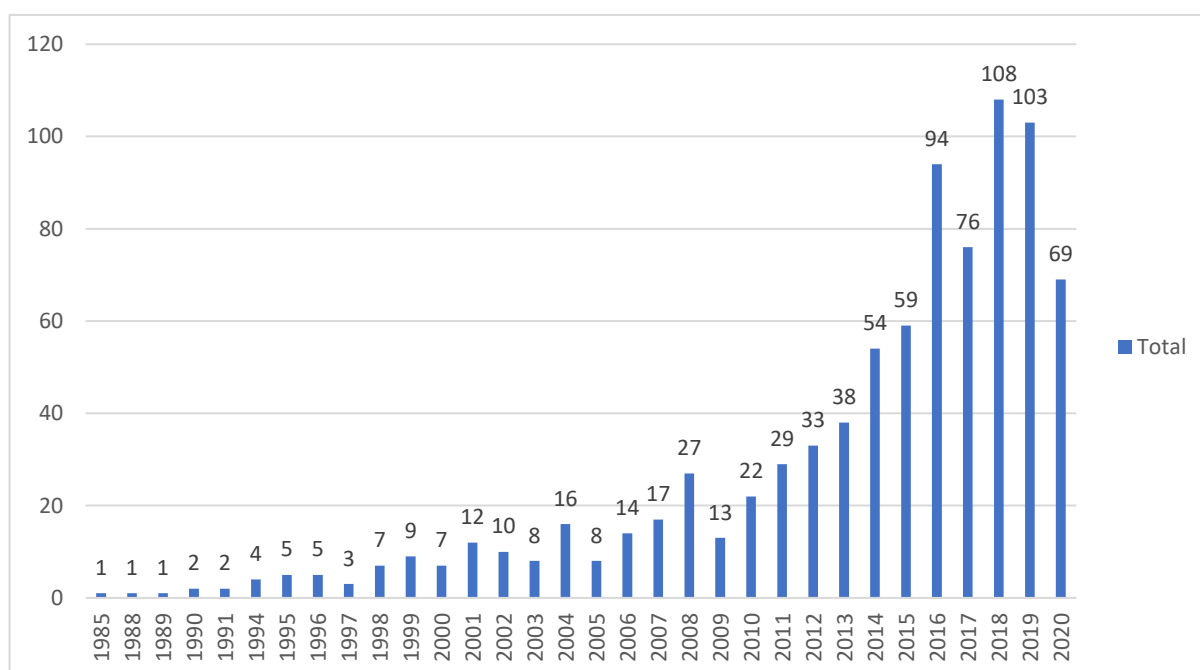


Figure 1: Year of publication of the mangrove carbon studies included and the number of papers from the evidence map dataset published in each year.

The evidence map of the geographical locations of each study showed 923 sites over 64 countries, representing just over half of the countries where mangroves are found. The 5 most common study locations were India (140), China (127), Brazil (80), the USA (78) and Australia (70), which when combined represented over 50% of the total study sites. South and South-East Asia had the largest proportion of studies between the 12 countries represented in this region, whilst Africa had the smallest proportion of sites despite 20 countries being represented, including Nigeria which has one of the largest areas of mangroves worldwide. The dataset was made up of papers from 61 countries and out of the 857 studies, 617 were done with lead authors who were based at institutions in the same country as the study location. Out of the remaining 240, there were 39 where the country the study was in was within 1000km but 208 had political or historical ties. From the dataset there were

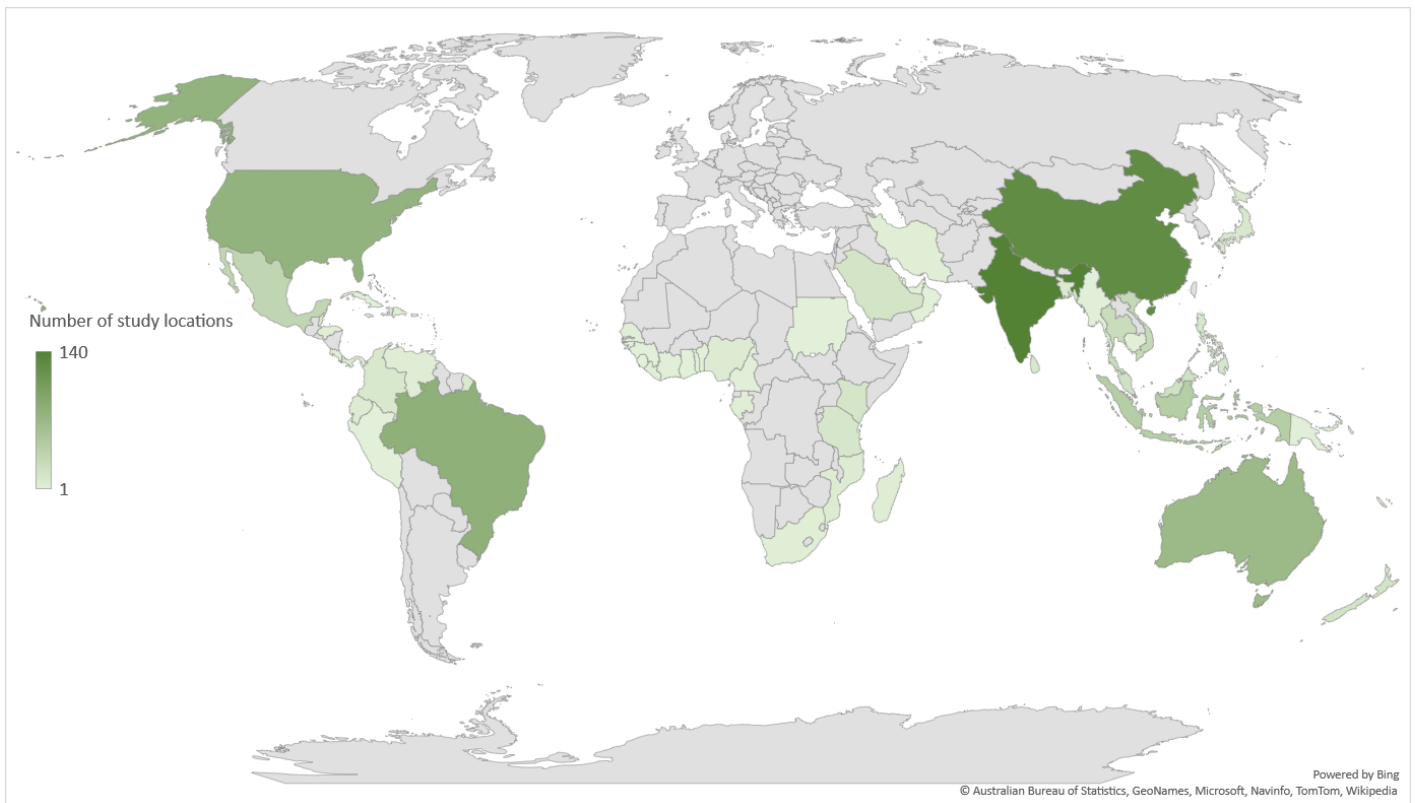


Figure 2: A map showing the number of study locations per country included in the dataset. The 5 most frequently appearing countries came from 4 different regions and totalled 495 of the 923 study locations.

30 studies where there were no apparent geographical, historical, or political ties between the country of the lead author's institutions and the study location suggesting instead a personal affinity or connections between researchers and their study sites. The 5 countries that were responsible for the most studies of mangrove carbon were the same countries that had the most study sites, although this did not correspond exactly, with China having the highest number of lead author studies. 51 species of true mangrove were found in the dataset with 2225 datapoints. The most common species were *Avicennia marina* (265), *Rhizophora mangle* (176), *Rhizophora mucronata* (139), *Avicennia germinans* (136) and *Laguncularia racemosa* (131).

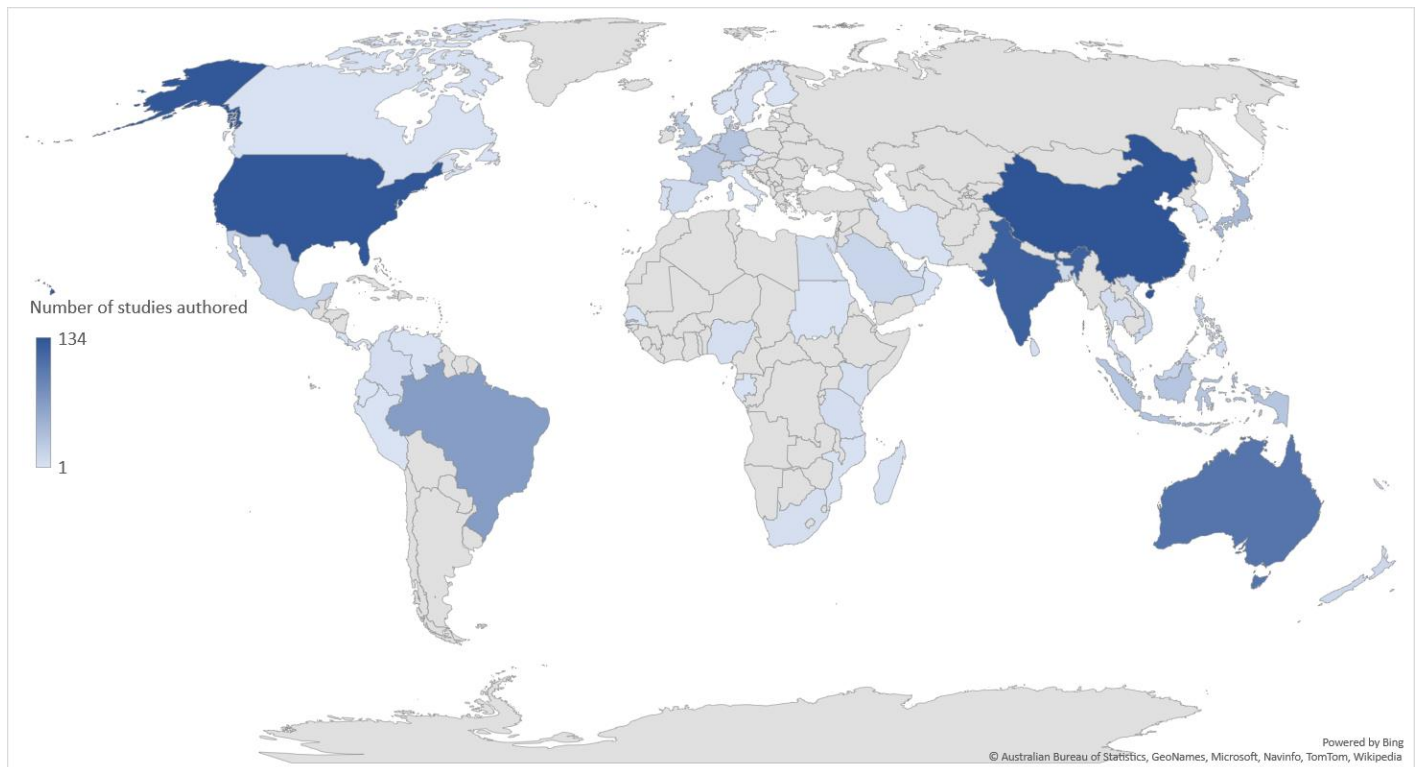


Figure 3: A map showing the number of studies published with the first author's institute based within that country. China (which is combined with Hong Kong and Taiwan) had the highest number at 134 studies making up 15.6% of studies included. The next highest were the USA (131), India (122), Australia (104) and Brazil (64).

### Geographical distribution of the studies and their authors

The papers collected reflected 64 of the 124 countries (51.6%) that contain areas of mangrove forests, leaving almost half unrepresented. This combined with the bias towards a small number of countries dominating the research, namely India, China, Brazil, the USA, and Australia, indicates that geographical bias is a factor that impacts the current literature of mangrove carbon research. A Spearman's rank correlation showed that total mangrove area of a country did correlate to the number of studies located in each country ( $p < 0.001$ ), however data was not normally distributed with a value for skewness of 1.943.

All regions were found to have countries missing from the dataset. Whilst Asia combined with the Middle East were the most commonly occurring regions with 465 study locations (50.3%) over 19 countries, 6 countries centred mostly around the Middle East were missing from the data. South America only lacked study locations in 2 countries, Guyana and Suriname. Oceania was missing 17 countries out of 23 from the region with mangroves, the majority of which are island nations. This is similar to the regional data for North and Central America which lacks information on 19 countries, mostly islands in the Caribbean. Whilst all regions lacked data from at least a few countries, the

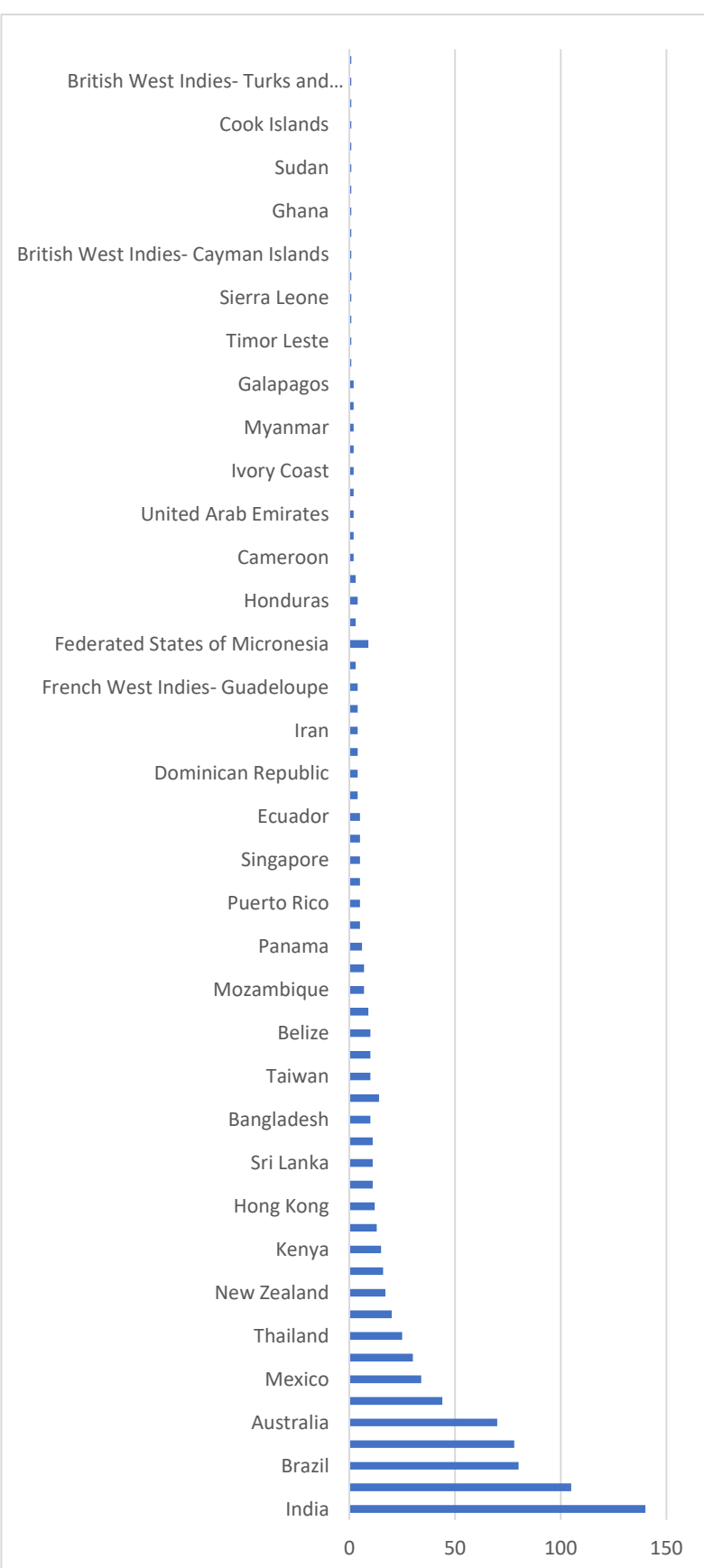


Figure 4: Bar chart showing the frequency of each country used as a study location in the dataset with a positive skew of 1.943 with the majority of data points represented by 5 countries.

continent of Africa was only represented by 55.9% of the countries that have mangrove forests and the 19 countries present out of 34 were only included as study locations 77 times out of 923 (8.3%), even though Africa contains over 20% of the worlds mangrove coverage and has 4 out of 15 of the countries with the largest mangrove area, including Nigeria which ranks at 3<sup>rd</sup> (FAO, 2007; Giri et al, 2010). Similar gaps in the geographical range of research have been found to occur in tropical biology and soil carbon stocks with the continent of Africa producing little research compared to South Asia and the Americas (Stocks et al, 2008; Powers et al, 2011).

One suggestion from Stocks et al (2008) was that population size could be used to predict research output. Using the most recent figures found it was determined through a Spearman’s rank correlation that there was a significant positive correlation between the number of studies located in a country and the population of that country ( $p<0.001$ ). This reflects the trends found in the authors of papers accepted in tropical biology journals by Stocks et al (2008) who also found a positive correlation of papers produced per country related to population size ( $p<0.0012$ ). GDP was also identified as another potential predictor of chosen geographical location as an indicator for a country’s investment in science and research. With figures taken from the World Bank (2022) using GDP per capita in US\$, it was found that the locations

data from this evidence map that there was no correlation between the GDP of a country and how frequently it was used as the location of mangrove carbon studies (Spearman's rank correlation  $p > 0.05$ ). Whilst this evidence map can be used to investigate future paths for further analysis on factors that impact the scientific output of a country, it is limited as to what can be assumed as it is very difficult solely from the literature to assess how the presence of institutional partnerships and legacy effects, the researcher's nationality and personal connections or the desired methodology may impact choices of location and study species (Reboredo Segovia et al, 2020).

One consideration researchers must take into account when doing fieldwork is the safety of themselves and anyone they are working with. Mangroves are a difficult environment to collect data in influenced by the tides, with root systems above ground that are difficult to navigate. Paired with the fact that some of the countries that contain mangroves have areas marked as unsafe for outside travel due to disease or political unrest, this may lead many researchers to choose regions with fewer warnings and more infrastructure (Stocks et al, 2008; Powers et al, 2011; Bahn, 2012). This perception of risk would be enough to discourage teams from travelling to certain countries and regions including areas of Africa and Central America where data is lacking (Reboredo Segovia et al, 2020).

Another consideration is that many of the countries that are not found in the dataset are islands in either the Caribbean or in the Pacific Ocean which have higher travel costs associated with them, which may contribute to the lack of research as people assign more of their funding to equipment and other expenses in the design of their studies, despite many of these countries facing the most immediate threats of sea level rise, biodiversity loss and increasing storm activity (Iftekhar, 2008; Courchamp et al, 2014; Reboredo Segovia et al, 2020). This may link to the data on authors location as the majority included were completed within the country of the authors institute, which would have reduced costs compared to international travel, particularly in locations where little money from the government is put into scientific research (Tandon, 2021).

As well as travel costs, lack of funding can result in fewer studies from lower income countries for several other reasons. In some developing countries, researchers may not have the same access to resources such as unmanned aerial vehicles (UAVs) used for work such as remote sensing which has become widely used in mangrove research to assess forest extent, due to regional laws and regulations. This combined with differences in government regulations means that scientists from lower income countries are less able to train new researchers, conduct long-term studies and produce data that can be included in global inventories (Stocks et al, 2008; Hsu et al, 2021). Countries in the global south often have less access to funding for scientific research which can lead

to researchers from higher income countries taking part in what is known as “helicopter research”. This is where researchers from countries with increased funding or research opportunities enter lower income countries and complete studies with little to no benefit for local scientists or people in terms of aims or opportunities for participation (Haelewaters et al, 2021; Tandon, 2021). As 73% of the studies in the dataset were completed with first authors from institutes within the study countries it can be assumed that helicopter research is not as urgent a problem in mangrove carbon research as the geographical bias observed. Although, it cannot be precluded that the 2 problems are not inextricably linked, as a large part the data collected by countries that are not part of the global south comes from mangrove systems growing in their own countries (USA, Australia, Mexico), meaning that the funding they would use to potentially conduct helicopter research is kept within their own countries and institutes, rather than being used in underdeveloped locations. However, just because it does not appear prevalently in this dataset does not mean helicopter research is not a problem in mangrove research as it can be difficult from the literature to find all the people involved but not named in a project (Gómez-Pompa, 2004; Adame, 2021).

Findings from fieldwork must be published to be viewed internationally and this can add another layer of difficulty for researchers from lower income countries. Many journals and articles must be bought by institutes in order for researchers to gain access and where there are limited funds there will be less access to the current literature which would impede scientists from lower income countries from accessing up to date information from international sources (Gómez-Pompa, 2004). Researchers may prefer to publish in local journals where their work is more relevant to the readers and could be published in more local languages as international journals often publish only in English (Pettorelli et al, 2020; Haelewaters et al, 2021). It has been found that there can be bias towards English language papers receiving more citations, which can push researchers with English as a second language to pay for expensive translation services to improve their chances of having their manuscripts approved (Di Bitetti and Ferreras, 2017, Tandon, 2021). One of the acknowledged shortcomings of this study is that due to the exporting limit on papers from the ProQuest database, several languages had to be removed to from the search terms which, which removed several papers from possible inclusion in the final dataset, although it was not enough studies to cause significant changes to the results of the evidence map.

#### Mangrove species in the dataset and literature

A total of 2225 datapoints were collected for species included in mangrove carbon research, but the species included and their frequency in the data were highly dependent on their geographical range,

with number of species in a country found to correlate directly with the total mangrove area and the number of studies completed in a country (Spearman's rank  $p < 0.001$  and  $p < 0.001$  respectively). In the literature it was found that the most studied species all had large geographical ranges. The most common species named, *Avicennia marina*, has a range that spans 44 countries from East Africa and the Red Sea through Asia down to New Zealand and was present in 8 of the 10 most studied countries in this dataset, resulting in a higher probability of its inclusion in the dataset. The Atlantic-Eastern Pacific (AEP) zone has lower diversity of mangrove species compared to the Indo-Western Pacific (IWP) area. In the AEP zone the 3 most common species are *Rhizophora mangle*, *Avicennia germinans* and *Laguncularia racemosa* are present in 52, 61 and 54 countries respectively including Brazil and the USA which contribute to 160 of the study location between them. Whilst the influence of the geographical location data makes it difficult to find patterns between mangrove carbon data and choice of study species, several factors in the literature were identified as potential areas for problems to emerge.

One problem highlighted from the literature is that in studies where there is a wide variety of flora or the focus is on soil carbon or gas emissions, the most common taxa or those most important to the study are often the only ones listed with brief reference given to the presence of others in the area, or in other cases no species are listed at all (Dehairs et al, 2000; Mandal et al, 2009; Borges et al, 2018). This means that species may be underrepresented in review studies like this, so research conclusions can only be drawn about the most included species. This can have negative impacts on future project planning where the most included and studied species may not be the most appropriate for the aims of the project. In the case of (Chen et al, 2012) a comparison of the introduced quick growing species *Sonneratia apetala* and the native *Sonneratia caseolaris* were compared in China for carbon sequestration potential and it was found that although less studied for projects replanting mangroves for carbon storage, the native *S. caseolaris* had significantly higher total carbon content in the biomass and soil after 25 months than the introduced *S. apetala*.

The next most common issue was related to the definition of true mangrove species. Though mangrove forests are well defined, the definition of a true mangrove species is more problematic as there are a range of traits, both qualitative and quantitative, that are debated for inclusion (Tomlinson, 2016; Quadros and Zimmer, 2017). But not all the literature agrees with each other on what those traits are. Tomlinson (2016) lists true mangrove species split into major and minor components, revised from the previous edition published in 1986, covering 54 species. They were identified as true mangroves, of which 45 were found in this study, as well as listing many species of mangrove associate that also grow in these ecosystems. On the other hand, Quadros and Zimmer (2017) published a list of 125 traits used to identify 55 true mangrove species of which 46 were



included in the dataset. Each list varies by several species, and this could cause true mangrove species not to be listed even as new research methods support a species being identified as a true mangrove.

As molecular techniques have improved in recent years the lists of mangrove species have also changed to include subspecies, hybrids and those different species identified as one originally. One example from 2003 was the identification of *Kandelia obovata* as a separate species from *Kandelia candel* (Sheue et al, 2003). On the other hand, in 2010 two new species of the genus *Ceriops* were described as *Ceriops zippeliana* and *Ceriops pseudodecandra*, but neither were included as an accepted true mangrove species in the more recent species guides (Sheue et al, 2010). The reason these would not be included is unclear; it may be that the authors of the true mangrove lists were unaware of these newer identifications due to the current size and scope of the literature, or further confirmation of the results may have been needed.

There can also be issues with the distribution of such resources, as one problem of the Tomlinson (2016) book is that whilst the table states 11 minor genera and their 19 species are listed, only 10 genera and 16 species are listed. From reading the 1<sup>st</sup> edition the missing genus can be identified as *Heritiera* with *Heritiera fomes*, *Heritiera littoralis* and *Heritiera minor* as the species, but this error could be easily missed whilst gathering background information (Tomlinson, 1986). Along with the differences between these guides and possible errors, there are the issues of species identification and synonyms. Synonyms of true mangrove species may also create confusion when included in the literature. Whilst many species are known primarily by their latin name, some species such as *Avicennia germinans* have as many as 26 synonyms such as *Avicennia africana*, *Avicennia floridana*, *Bontia germinans* and *Hilairanthus tomentosus* (The World Flora Online, 2022). This may be due to the geographical ranges of these species giving more opportunity for changes in nomenclature as well as attempts to reorder different taxa or rename species (Cornejo, 2020). Whilst some of these are still easily identifiable as the correct species, others may cause confusion as to what is a new species, a hybrid, a local name or a misidentification that may then continue to occur through the literature due to lack of correction. All of these factors together suggest that geographical bias, lack of resources and a lack of universal agreement on what a true mangrove is have created substantial gaps in the knowledge of mangrove carbon globally.

## Conclusions

For future climate change action, it is important to understand the way the planet and its ecoregions are responding to changes in the environment. If we are to support smaller and developing countries in a way that encourages economic growth and green policy making decisions whilst working to reduce the negative impacts of climate change, we must be able to provide the relevant data for their local mangrove ecosystems and how their protection can benefit human populations on both small and large scales. While vitally important ecosystems, mangroves are greatly threatened by deforestation and degradation which will only be exacerbated by increasing human populations and environmental changes in sea level and changes in climatic patterns. The lack of data for particular regions and countries results in gaps in our knowledge of these forests health and productivity, both important for assessing countries carbon sequestration and the forests carbon storage potential when green policies such as carbon taxes or cap and trade are considered as future economic incentives in a world moving towards carbon neutrality. By understanding where the gaps in our knowledge are, we will be able to build better blue carbon projects and policies suited to the regions being targeted and support local researchers in previously underdeveloped locations.

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## A review of the effects of generalised carbon content values on the accuracy of mangrove aboveground carbon stock estimation

### Abstract

The function of forests as important stores of carbon is increasingly recognised as a potential tool for climate change mitigation, with the potential for blue carbon environments such as mangrove forests, seagrass beds and saltmarshes to be included. Many carbon stocks for aboveground biomass (AGB) are calculated using generic carbon conversion factors rather than ones designed for specific species, regions, or sites significantly impair our ability to calculate carbon stocks. Therefore, the aim of this review was to compare the results of generalised C% conversion factors used to estimate aboveground biomass carbon with site-specific carbon data using a meta-analysis approach. 177 papers were screened, 13 generic carbon factors compared against 6 papers that used site specific data to produce aboveground biomass carbon estimates (AGBC.) A significant variation from site-specific AGBC estimates was found resulting in overestimation for some regions and underestimation in others. Many of the generic values lacked accessible unpinning evidence for their use and several were designed to be used on all types of tropical forests producing both over and underestimation in the mangrove AGBC. These results highlight the need for more work on the variation of AGB carbon content between mangrove species, plant biomass types and where environmental or climatic conditions such as hydrology, vegetation structure and elevation vary.

### Forest carbon stock estimation

Forest carbon stock is defined by Mukul et al (2020) as “the amount of carbon sequestered from the atmosphere and stored in a forest ecosystem, mainly within living biomass and soil and, to a lesser extent, in deadwood and litter”. Forest carbon stocks are the largest terrestrial carbon stocks on earth with previous estimates of  $2.4 \pm 0.4$  Pg of carbon being sequestered per year resulting in global carbon stocks of  $861 \pm 66$  Pg C in the world’s forests (Pan et al, 2011). These stocks are divided evenly between the soil (44%) and living biomass (42%), with most of the remaining carbon stored in forms of dead biomass (13%) (Pan et al, 2011). This function of forests has been recognised by the United Nations as a potential mitigation tool of climate change by managing emissions of CO<sub>2</sub> and CH<sub>4</sub> through reducing degradation and deforestation around the world and replanting trees. This would mean more carbon could be removed from the atmosphere though forests acting as a ‘carbon sink’ (Patenaude et al, 2005; Domke et al, 2012; Mukul et al, 2020). The most carbon rich of forest types according to previous forest carbon inventories are tropical forests containing up to 45% of the total terrestrial carbon, which can range environmentally from rainforests to coastal forests such as mangroves (Pan et al 2011; Friess, 2013; Mukul et al, 2020). Mangrove forests are wetland



ecosystems of salt-tolerant species adapted to the coastal environments between the latitudes of 30°N and 30°S, mostly in tropical regions of the world although some stretch further into temperate areas (Siikamäki et al, 2013; Bulmer et al, 2016; Sanders et al, 2016). For coastal wetland systems, there has been growing interest in the storage of 'blue carbon' in mangroves, along with tidally influenced cypress forests, seagrasses and saltmarshes and how it could potentially be incorporated into programs such as REDD+ in the future, with some carbon payment schemes already set up to potentially include mangroves in existing frameworks for forests (Friess, 2013; Owers et al, 2018; Lovelock and Duarte, 2019).

Forest carbon stocks can be estimated using several methods that are often split into "top-down" and "bottom-up" approaches. Top-down approaches usually address atmospheric emissions of carbon over a large-scale using technology such as remote sensing and computer modelling. Bottom-up approaches rely on local data collection such as biomass sampling (Nisbet and Weiss, 2010). For large scale investigations into carbon stocks and emissions both methods are used in combination, as the top-down models and remote sensing need local data for calibrations, whilst the uncertainty of bottom-up approaches can be improved with the addition of data provided by top-down approaches (Saunois et al, 2020; Chen et al, 2021). In mangrove forests methods of estimating the carbon stocks in aboveground biomass often start with methods of biomass estimation such as study plots through removal, finding the means of the trees or using remote sensing techniques like LiDAR (Komiya et al, 2008; Castillo et al, 2017; Salum et al, 2020). Destructive methods of measuring AGB can be done by removing and partitioning trees into biomass types and measuring the carbon using CHN analysers, but these are impractical for large scale studies and difficult to conduct on mature forests due to conservation concerns, equipment needs, and both the amount of time and people needed for such work (Komiya et al 2008; Ray et al, 2011). Sampling biomass from mangrove forests can be difficult due to tree structure, height and the logistics of bringing equipment in amongst the prop roots and mud so the use of generalised carbon conversion factors reduces the number of problems in the field and simplifies the calculation of carbon (Bulmer et al, 2016; Owers et al, 2018).

A popular method for use studying mangrove wetlands, using allometric equations reduces the time and number of people required to access and study these coastal forests (Komiya et al, 2008; Bulmer et al, 2016; Salum et al, 2020). Allometric equations use measurements taken from a subsample of trees or forest plots including diameter at breast height, tree height, wood density and crown depth, which are then entered into allometric models designed for the specific species or sites being studied to produce an estimate of aboveground biomass (Chave et al, 2005; Komiya et

al, 2008). These equations can then be used in conjunction with carbon content data to produce an estimate of aboveground carbon present in the mangrove ecosystem being studied.

However, general carbon values are commonly used in mangrove research in order to achieve this (Gifford, 2000; Kauffman and Donato, 2012; Rodrigues et al, 2014; Howard et al, 2014). These values usually generated through previous reports or studies and are applied to any mangrove system in the world as a set percentage of the AGB, e.g., if mangrove AGB is found to be 45% carbon from a study in India, 45% of the total AGB found for any mangrove ecosystem, irrespective of differences in environmental conditions or species present, is assumed to be the total AGB carbon value (Ewe et al, 2006; Bouillon et al, 2008; Kauffman and Donato, 2012). In the current literature these generalised values range between 40% and 50% based on data taken from a range of regions, countries, species of mangroves and other forest types. But, over the last decade there has been some exploration in the literature of how accurate carbon stocks produced using these generalised carbon conversion factors which showed significant differences when compared to carbon stock data generated using carbon data from the specific sites or species studied (Rodrigues et al, 2014; Bulmer et al, 2016; Owers et al, 2018).

There appears to be little consensus on whether such values are appropriate for continued use in carbon inventories. This potentially could lead to problems of over or underestimation of aboveground carbon stocks, leading to incorrect data for forest carbon inventories and any initial pricing estimates for mangrove forests if they were to be included in carbon markets in the future. The aim of this literature review is to evaluate whether there is a significant difference found where generalised C% conversion factors are used to estimate aboveground biomass carbon compared to site-specific carbon data and the implications of this for conservation, carbon inventories and the carbon markets.

## Methods

A search of the current literature was conducted using ProQuest, Web of Science and Google Scholar using the terms “mangrove carbon”, “mangrove carbon storage/sequestration” and “mangrove carbon conversion factors”. This yielded 177 papers that were entered into a dataset, then sorted into continent the research took place on, and the carbon conversion factors used to calculate AGBC. The source of the carbon conversion factor was recorded, whether it was site-specific or taken from the literature, as well as data on aboveground biomass before it was converted to AGBC. Sixty papers collected site-specific AGB data and of these 9 papers used site-specific carbon

conversion factors i.e., carbon contents taken with the corresponding AGB estimates (Table 1). 3 were excluded due to small sample sizes. The remaining 6 studies were conducted at sites in Australia, India, Malaysia, and New Zealand, and covered 13 species that are all considered 'true mangroves' by at least one source (Tomlinson, 2016; Quadros and Zimmer, 2017). Each of the final 6 papers collected were produced within the last 15 years with the earliest being published in 2011.

Table 1: Papers using site or species-specific research to estimate AGBC from 4 countries and 6 different groups of authors, with estimates of site-specific C% ranging from 41.63%-48.07% as reported in the

Authors	Mangrove carbon content estimates (%)	Country of study origin
Mitra et al (2011)	41.63	India
	43	
	44.59	
	44.83	
	45.42	
	46.45	
Rozainah et al (2018)	44.9	Malaysia
	48.07	
Ray et al (2011)	42.245	India
	42.775	
Kathiresan et al (2013)	42	India
Owers et al (2018)	47.3	Australia
Bulmer et al (2016)	43.1	New Zealand

From these papers, the aboveground biomass was taken and multiplied against the corresponding carbon conversion percentage to produce a carbon estimate in  $\text{MgCha}^{-1}$  (i.e.  $1 \times 10^6 \times \text{g}$ ) that was site-specific, as well as 13 generalised carbon conversion factors produced from 23 papers and reports published between 1992 and 2014, that were cited multiple times in the remaining literature ranging from 40-50% (Table 2). The difference between the carbon estimates taken from the studies and the carbon estimates made using the generalised values were then statistically tested in SPSS (version

27). If the data produced was parametric a paired t-test was used, whereas if the data was non-parametric using Wilcoxon Signed tests.

Table 2: This table shows the 13 generalised carbon content values found in the literature review and the sources that were given by the papers citing them for these values. There were 17 sources for the values ranging between 40%-50%.

Source of the generalised carbon content value	Generalised carbon content (%)
Schlesinger (1997)	40
Bouillon et al (2008)	41.5
Rodrigues et al (2014)	42.6
Ewe et al (2006)/Bouillon et al (2008)	44
Rodrigues et al (2014)	44.1
Kauffman and Donato (2012)/ Houghton et al (1983)/ Howard et al (2014)/ Lasco et al (2001)	45
Hiraishi et al (2013)	45.1
Kauffman and Donato (2012)	46
Kauffman et al (2011)	46.4
IPCC (2006)/ Kauffman and Donato (2012)/ Abino et al (2014)	47
Kauffman and Donato (2012)	48
Kauffman and Donato (2012)	49
IPCC (1996)/ Komiyama et al (2008)/ Gifford (2000)/ Birdsey (1992)/ Brown (1997)/ Kauffman and Donato (2012)	50

## Results

From the 6 papers analysed, a total of 117 estimates of AGB were used to produce AGBC estimates for each site, using either the 13 generalised carbon conversion factors or the corresponding site-specific estimates, producing 1778 carbon estimates in measured in tonnes of carbon per hectare ( $\text{tCha}^{-1}$ ). In these estimates, carbon stored in the AGB of the mangroves was found to be significantly different when generalised carbon conversion factors were used compared to site-specific carbon data ( $p < 0.05$  for all general carbon content value estimates). Therefore, the null hypothesis that use of generalised carbon conversion factors does not cause significant differences in AGBC from values where the site-specific carbon estimates are used can be rejected. For the use of the generalised factors the results of the Wilcoxon Signed tests were a statistically significant from the site-specific values with  $p < 0.05$  and Z values ranging between -2.810 to -6.031. For Rozainah et al (2018), the only normally distributed dataset, the p value varied between 0.002 and 0.003 for the generalised 45% carbon value, with the t-value ranging between -4.735 and 4.764. The greatest differences between the carbon estimates made from the author's data and the generalised factors were produced for larger volumes of biomass per hectare.

The largest example of overestimation came from Kathiresan et al (2013) where a plot with  $350.5\text{tha}^{-1}$  converted to  $147.21\text{tCha}^{-1}$  using the site-specific carbon value of 42%. When multiplied by the generalised 50% taken from a few sources including the 1996 IPCC report, the value produced was  $175.25\text{tCha}^{-1}$ , resulting in overestimation of 16% or  $28.04\text{tCha}^{-1}$  (Table 3). Where the biomass of a plot was low to begin with the error found was less prominent but for larger AGB values the under and overestimation would result in much larger variation from the true carbon estimates.

Underestimation was found to be less of an issue in the papers sampled as most of the site-specific values measured from 40-45.5%, however the highest site-specific carbon value found (48.07%), produced by Rozainah et al (2018), led to underestimation of up to  $12.62\text{tCha}^{-1}$  when a generalised value of 40% was used.

Table 3: The highest values underestimation and overestimation produced when AGBC estimates were produced using generalised carbon content values with AGB data from the studies compared to the site-specific carbon values collected at the study sites.

Study source	Site-specific carbon content (%)	Largest underestimation of AGBC (%)	Largest overestimation of AGBC (%)
Mitra et al (2011)	41.63	4.15	16.76
	43	7.52	14.02
	44.59	11.52	10.84
	44.83	12.11	10.38
	45.42	13.58	9.19
	46.45	16.16	7.17
Rozainah et al (2018)	44.90	12.27	10.21
	48.07	20.20	3.88
Ray et al (2011)	42.25	5.61	15.51
	42.78	6.94	14.45
Kathiresan et al (2013)	42	5	16
Owers et al (2018)	47.30	18.25	5.40
Bulmer et al (2016)	43.10	7.75	13.80

## Discussion

Whilst the 6 studies included for AGB analysis featured 13 out of roughly 50 mangrove species, the study sites were only based in 4 countries out of the 124 that contain mangrove ecosystems (FAO, 2007; Tomlinson, 2016; Quadros and Zimmer, 2017). These countries were also all based within the Indo-Western Pacific (IWP) zone which is known to have higher biodiversity of species in mangrove

forests than the Atlantic-Eastern Pacific (AEP) zone, but any variation between these zones from environmental conditions, species composition or anthropogenic impacts would not be reflected in this review of the literature due to the lack of applicable data (Tomlinson, 2016). Potentially this could be due to differences in research priorities focusing on the need for site-specific carbon data, as Malaysia has submitted reference levels for participation in REDD+ results-based payments (Ministry of Natural Resources and Environment, 2015). The concentration of studies in the IWP zone may also be due to the concentration of mangroves studies based in Asia as shown in Chapter 1, increasing the probability that these countries would be best represented in the literature search as 100 of the papers pulled in the initial data search were from Asian study sites.

Out of the papers and reports that were cited to produce the range of 13 generalised carbon conversion factors in the literature, only 3 used corresponding site-specific sampling and of those 2 contained species-specific carbon content as well (Kauffman et al, 2011; Abino et al, 2014; Rodrigues et al, 2014). The species included in Kauffman et al (2011) and Rodrigues et al (2014) were all native to the countries these studies took place in (Federated States of Micronesia and Brazil) and included *Bruguiera gymnorrhiza*, *Rhizophora apiculata*, *Sonneratia alba*, *Avicennia schaueriana*, *Rhizophora mangle* and *Laguncularia racemosa*.

However, several studies use estimates for general mangrove carbon conversion factors that are sourced incorrectly either from other types of forest or from incorrectly cited studies. The report by Gifford (2000) stated that there could be variation in carbon content of tree species that would make 50% inappropriate and whilst this value was found to work as an average for a selection of native Australian tree species, none of the species analysed were mangroves. Houghton et al (1983), Brown (1997) and each of the IPCC reports cited as sources (1997, 2006 and 2013) also do not include mangroves in the lists of species studied or used to produce the general carbon values that were found used to calculate AGBC for mangrove forests. Another paper cited as a source was Kauffman and Cole (2010), but this paper does not include any carbon analysis as it is about structural damage mangroves suffered after a typhoon. It is likely that this citation was meant to be for the Kauffman et al (2011) paper listed above due to an identical carbon conversion factor provided in the data (46.4%). Another example comes from the 2014 IPCC reports that are cited with a general biomass carbon conversion factor of 47% similar to the one included in the 2006 reports (IPCC, 2006; Hiraishi et al, 2013). But the IPCC 2014 reports do not contain the carbon conversion factor as it is contained in a 2013 supplement to the 2006 Guidelines for National Greenhouse Gas Inventories to add information for wetlands. In addition to this citation error, the 2013 guidelines report a general carbon factor of 45.1% which, compared to the 47% from the 2006 reports, does lead to a significant difference in AGBC calculated in this analysis ( $p < 0.05$ ). Other sources that are

cited with incorrect values include Birdsey (1992), which cited 50% as sourced from an unpublished report by Koch (1989), but this report continues on to say that other research suggests 52.1% for softwoods and 49.1% for hardwood species. Schlesinger (1997) is cited as 40% for carbon but the book states that plant carbon varies between 45 and 50%. In Komiyama et al (2008), the author uses AGB data cited from Golley et al (1962) to calculate net ecosystem productivity with an example carbon content of 50%. However, a few papers have since used this example as their source of the 50% carbon content they used in their own studies (Dharmawan, 2018; Vinod et al, 2018). The same issue occurs in Lasco et al (2001) where a value of 45% is cited by other papers but the research gives that value as part of a range from 39-45% for biomass carbon and none of the species studied were mangrove species (Gevana et al, 2008; Gevana and Pampolina, 2009).

An issue found with several of the cited carbon factors was that rather than incorrect sources of information, there was no source explaining the values origin. In the Kauffman and Donato (2012) working paper outlining a potential methodology for measuring total carbon in mangrove ecosystems a range from 46-50% is proposed as a carbon conversion factor, if there are no site-specific or species values available. But many papers that cite this report do not provide evidence for why a number from this range was chosen, besides that the range has been used before, which goes against the recommendations of the authors. In both Twilley et al (1992) and Howard et al (2014) use 45% as the recommended carbon conversion factor for mangrove systems, however there is no discernible source of this value which would be valuable for further analysis. 2 other papers by Ewe et al (2006) and Bouillon et al (2008) stated that their general carbon conversion values came from their own unpublished data and the results of an unpublished literature which, if published, would provide important base data for building scientific understanding of mangrove carbon content. In the Bouillon et al (2008) paper the results of the literature result produce a carbon content value of 41.5% whilst the value produced from their own collected mangrove litter data is 44%. These values are used interchangeably in the literature with both used for AGBC in the literature sampled for this review, only cited as Bouillon et al (2008) with no reasoning behind the choice of either number from the study (Siikamäki et al, 2013; Yando et al, 2016; Krauss et al, 2018; Radabaugh et al, 2018; Dontis et al, 2020).

Several of the sources of these generalised carbon conversion factors come from values considered to be generic for all types of tropical forest (IPCC, 2006; Hiraishi et al, 2013; Houghton et al 1983; Birdsey 1992). But this assumption may also be a fallacy. Martin and Thomas (2011) sampled wood biomass from 59 species found in a Panamanian lowland tropical moist forest and found that the average carbon content was 47.35% with species specific values ranging between 41.87% to 51.57%. This was found to produce significantly lower estimates of AGBC than the generalised value of 50%



taken from the 2006 IPCC report for tropical and subtropical woods. Similar differences in many species tested by Thomas and Martin (2012) and Ma et al (2018), where it was found that carbon content in other tree species varies significantly based on plant organ, latitude and climatic factors. Owers et al (2018) found in their study that changes in vegetation structure also influenced carbon content of the biomass whilst Rao et al (2021) found a positive correlation between wood density and carbon content in 12 mangrove species, but many studies looking at the effects of climatic or environmental factors on biomass carbon focus only on changes in the AGB with carbon estimates calculated with the generic values, rather than on whether carbon content is affected in the same ways that biomass is (Rahman et al, 2015; Sasmito et al, 2020; Harishma et al, 2020).

Mangroves are threatened in a number of ways both due to anthropogenic interference and naturally occurring threats such as typhoons and wildfires, and to establish any conservation or replanting work focused on carbon sequestration we need to have accurate figures to work with. Using general values designed for use on all types of forests ignores any environmental or species-specific differences and is not reflective of real forest systems, introducing a source of error into carbon assessments and inventories (Thomas and Martin, 2012; Owers et al, 2018; Gillerot et al, 2018). And where these general carbon factors have been used instead of more specific ones, whole estimates of previous carbon emissions and forest carbon storage could be wrong leading to incorrect baseline data being used for current global carbon emissions estimates. As it stands, the use of general carbon conversion factors is one of the reasons that some carbon credit programs exclude mangrove forests as the estimates do not account for variability in the carbon stocks which could lead to significant errors in the accuracy of the carbon stocks inventoried and therefore the financial costs and benefits of such projects (Owers et al, 2018; Gillerot et al, 2018). Having site-specific and species-specific values of carbon for mangroves would increase the accuracy of monitoring these ecosystems for inclusion in emission reduction payment schemes as it would more accurately show any changes in biomass carbon that may result from management practices. For more credible estimates of carbon stored in a system and therefore better rates of carbon credits, projects such as REDD+ (Reducing Emissions from Deforestation and forest Degradation) prefer what the IPCC defines as Tier 2 and above assessments of carbon which require country-specific data (Kauffman and Donato, 2012). This means that many current estimates from the literature would be ineligible due to the use of the common values if the projects moved forward for carbon financing. For future inventories and assessments of potential carbon sequestration in many environments, including mangroves forests it is vital that more research is done to investigate differences in AGB carbon content between plant organs, species and sites with differing environmental conditions to reduce the error created through general conversion factors use.

## Conclusion

The use of generalised values to calculate aboveground biomass carbon produces significant differences compared to site-specific or species-specific values in not just mangrove ecosystems, but likely in other forest systems as well. The results of this literature review suggests that there needs to be a wide-scale review of the sources of general carbon content values in mangrove research with ground-truthing in as many locations as possible in order to constrain the uncertainties surrounding carbon stocks, as many estimates used for climate policy and calculations of forest inventories may not reflect the actual quantities of carbon stored in plant biomass or potentially released from these systems as carbon dioxide or methane. Implications for national emissions inventories and climate change mitigation plans that rely on accurate data suggest this is an important area for future research.

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## Observations of error generated through use of common allometric equations to calculate mangrove aboveground biomass

### Abstract

The measurement of aboveground biomass (AGB) is key to many forest inventories and estimates of global carbon sequestration. But for many ecosystems, conducting the required studies is physically taxing and expensive in time and resources. As a result, many common allometric equations have been designed to estimate AGB using factors such as wood density and diameter at breast height (dbh=1.3m), but there is concern that these generalised equations may result in over- or underestimation of AGB and increase error in the estimates. This study tested 3 common allometric equations for mangroves against a site- and species-specific equation for Southwest Florida using data from Bonita Springs, Florida and found that 2 of the common equations from Komiyama et al (2005) and Chave et al (2006) produced significantly different AGB values than the specific equation (both  $p < 0.001$ ). The incorrectly cited Chave et al (2006) equation from Komiyama et al (2008), whilst not statistically significant, did still overestimate the AGB (51.65%). The range of estimates produced was 168.36 tha-410.29 tha with the specific equation producing the lowest estimate. Including height as a measurement reduced the difference between the estimates however, the 2 methods tested produced significantly different height measurements. Inconsistency with dbh measurements and the criteria of inclusion within a study will also have an impact on accuracy of models and equations built using the data, as well as the lack of accounting for differences in wood density. There are many factors that can impact the accuracy of common allometric equations and until further research can be done on a local level quantifying the impact of both biological and geographical factors on carbon storage potential, it is recommended that researchers should produce AGB estimates using local data and specific allometric equations.

### Introduction

One of the major components of terrestrial carbon storage and sequestration is forest biomass (Chave et al, 2019; Luo et al, 2020). Globally, forests occupy roughly 30% of the world's surface and make up between 70 and 90% of terrestrial biomass, creating vast stores of carbon (Fatoyinbo and Simard, 2013; Duncanson et al, 2015; Luo et al, 2020). Potentially up to 1030Gt of carbon is stored in forests, with up to 4Gt of atmospheric carbon sequestered annually (Duncanson et al, 2015; Timothy et al, 2016). Between the potential carbon sequestration for climate change mitigation, needing to understand the implications of land-use change and fuel loads, and commercial uses of wood and

tree products, it is vital for many reasons that estimates of the forest biomass are accurate, particularly for aboveground biomass (AGB) (Henry et al, 2011; Chojnacky et al, 2014; Yuen et al, 2016). Any countries who are part of the United Nations Framework Convention on Climate Change (UNFCCC) have to provide regular reports of forest resources and those who wish to qualify for REDD+ must provide carbon data collected from forest biomass that has been accurately monitored over time (Henry et al, 2011; Yuen et al, 2016)

Aboveground biomass is defined by Cintron and Novelli (1984) as “the amount of standing organic matter per unit at a given time, which is related to a function of system productivity, stand age, and organic allocation, and exportation strategies”. It is made up primarily of leaves, branches, stem tissue, reproductive parts and in the cases of ecosystems such as cypress swamps and mangroves, cypress knees and prop roots. There are several different methods for estimating AGB in forests. In the last few decades, the use of remote sensing technology such as Landsat and LiDAR to measure the volume of aboveground biomass has increased in use across a range of forest types from boreal to tropical (Timothy et al, 2016). But it does require some ground-proofing to test the equations used to calibrate the data (Chave et al, 2019; Réjou-Méchain et al, 2019). This information is either collected using destructive or non-destructive methods. Destructive sampling involves harvesting a small number of trees and weighing each biomass component to produce estimates of AGB (Henry et al, 2011). But due to the time-consuming and costly nature of this work, and the fact conservationists are reluctant to log trees in areas they are trying to protect, most researchers use non-destructive methods including the use of forest plots and allometric equations (Duncanson et al, 2015; Yuen et al, 2016).

Forest plots are set up in areas ranging in size from 10x10m<sup>2</sup>squares or circles to plots measuring several hectares. Researchers will then log information about the site including species composition and tree density. They may also collect data that will allow aboveground biomass to be estimated using allometric equations. Allometric equations for AGB are created using statistical models that rely on power-laws between related variable, often using a normalization constant as well, and using data collected from either a low level of destructive sampling or using field measurements of tree components such as height, wood density and stem diameter at breast height (dbh= 1.3m) (Duncanson et al, 2015; Yuen et al 2016). These equations are designed provide a standard protocol and to reduce the time, money and physical work needed for destructive sampling and provide baseline data for remote sensing technology and can be designed for use with specific species and locations or for general use for a particular ecosystem (Duncanson et al, 2015; Timothy et al, 2016; Réjou-Méchain et al, 2019).

Mangroves are of great research interest as an important ecosystem for biodiversity, fishery enhancement, coastal protection and as a 'blue carbon' ecosystem, storing organic carbon of both marine and coastal origin (Macreadie et al, 2017; Radabaugh et al, 2018; Passos et al, 2021; Agaton and Collera, 2022). Mangroves are estimated to cover only 1% of the earth's surface but are believed to sequester up to 4.4PgC globally (Fatoyinbo and Simard, 2013; Atwood et al, 2017). But for potential inclusion in forest carbon sequestration projects measurements of AGB are needed. Whilst all forest plots can be difficult to survey, mangrove forests in the tropics and subtropics have a host of problems such as deep mud, tangled branches, prop roots and overlapping tree canopies that create problematic conditions for producing AGB estimates using plots or remote sensing, resulting in a number of allometric equations being produced (Komiyama et al, 2008; Fatoyinbo and Simard, 2013). At present remote sensing contends with several issues that make using it for mangrove estimation difficult, including problems operating with cloud cover, issues differentiating mangroves from other coastal wetland systems and a lack of data for creating the necessary models and regressions due to the ground conditions and remoteness of some mangrove forests (Fatoyinbo and Simard, 2013). This means that fieldwork is necessary and with the field conditions of mangroves many researchers instead rely on the allometric equations made for general use or specific species. Belowground biomass for mangroves is also often based in allometric equations relying on aboveground biomass estimates created by equations as well (Komiyama et al, 2008).

But in many forest systems there is concern that use of generalised allometric equations could be causing errors in AGB estimation as they fail to take local variation in species, wood density and other environmental factors such as frequency of disturbance events or local climate (Henry et al, 2010; Réjou-Méchain et al, 2019; Xing et al, 2019). Even with equations based on the results of destructive sampling, the data often comes from a very small sample of trees and species or from a specific region that may not be representative of the system as a whole (Muukkonen, 2007; Duncanson et al, 2015; Timothy et al, 2016). The aim of this project therefore, is to test whether the use of generalised allometric equations will result in significantly different estimates of AGB than the use of species-specific allometric equations designed in the area of study.

## Methods

The biomass plots were part of a permanent set of 10x10m<sup>2</sup> experimental plots created by Florida Gulf Coast University at the Vester field station in Bonita Springs Florida (DD:26.330713551985273, -81.83721754256217 (Figure 1).

Measurements for the plots included in this work began at the end of March 2022 and ran until the end of April 2022. The dominant species in the plots was *Rhizophora mangle*, with *Avicennia germinans* and *Laguncularia racemosa* scattered through the site and no



Figure 1: Vester Field Station (highlighted in yellow above) with direct access to mangrove forest by boat, the location of the mangrove plots is highlighted in red

visible mangrove-associate vegetation. The study site is located in an area of mangrove locally allocated for conservation as the Imperial River Preserve that is fed by the Imperial River draining into Little Hickory Bay and Estero Bay and surrounded by residential properties built along the waterways. The mangroves in the area of Vester Field station are difficult to classify into the classic 6 habitat types characterised by Lugo and Snedaker (1974) due to the hydromorphology and topography of the site, therefore this identification has been excluded from the results.

The plots are set in a grid running from A1 in the South of the plots to A10 at the top (Figure 2) separated out by marked boundaries along the edges of the grids. For the purposes of this study plots A6-A10 were chosen for inclusion for their location and additional researchers working there due to time and resource limitations. In each plot trees with a diameter at breast height (dbh) or 1.3m, of over 3cm had their species, health status, dbh, plot position and height recorded. Species diversity was also calculated using the Shannon-Wiener index for the study area. Height was recorded in 2022 using a telescopic pole, operated by 2 people to improve accuracy, and dbh was measured using dbh tapes whilst health status was noted from observations of any live biomass or visible damage. This data was then put into a series of allometric equations to calculate the AGB of the plots. At the same plots in 2023, the same trees were measured again with a clinometer to test if the use of a clinometer would result in significantly different height measurements that may decrease the accuracy of AGB estimates produced. The

A10
A9
A8
A7
A6

↓ Plots A1-  
A5 and  
shoreline

Figure 2: The layout of the 5 plots sampled and their position compared to the shoreline and the other plots

measurements taken included distance from the trunk to the person measuring, distance from the person's eyeline to the ground and the angle to the treetop.

Smith and Whelan (2006) published a series of species-specific allometric equations for the 3 most common species of mangrove found in Florida. The equations for total biomass for each species shown below were chosen over those for separate biomass compartments as reported in Pevenna-Reed et al (2021) due to the reporting of the equations in this paper:

$$\textit{Avicennia germinans}: B(\text{total}) = 10^{(1.934 * \log_{10}(D) - 0.395)}$$

$$\textit{Rhizophora mangle}: B(\text{total}) = 10^{(1.731 * \log_{10}(D) - 0.112)}$$

$$\textit{Laguncularia racemosa}: B(\text{total}) = 10^{(1.930 * \log_{10}(D) - 0.441)}$$

With  $B(\text{total}) = \text{AGB}$  and  $D = \text{dbh (cm)}$

For the common allometric equations Chave et al (2005) and Komiyama et al (2005) were selected as mangrove specific equations used in the literature and designed for use globally with no specific species stated. The common allometric equation designed for mangroves from Chave et al (2005) was based on regression models using information collected from 27 datasets of tropical forests:

$$(\text{AGB})_{\text{est}} = 0.0509 \times \rho D^2 H$$

With  $\text{AGB}$  in kg,  $\rho = \text{wood density}$ ,  $D = \text{dbh (cm)}$  and  $H = \text{height (cm)}$

The equation produced by Komiyama et al (2005) is based on an equation designed using the pipe model theory, where indirectly measuring tree crown biomass and using the distribution of leaves is used to determine the relationship between mass of photosynthetic and non-photosynthetic biomass. This was then tested using fieldwork in Thailand and Indonesia representing 10 mangrove species over 5 sites:

$$W_{\text{top}} = 0.251 \rho D^{2.46}$$

With  $W_{\text{top}} = \text{AGB (kg)}$ ,  $\rho = \text{wood density}$  and  $D = \text{dbh (cm)}$

However, in the Komiyama et al (2008) review paper that features a table of allometric equations for mangroves, the equation from Chave et al (2005) is instead reported as:

$$W_{\text{top}} = 0.168 \rho DBH^{2.47}$$

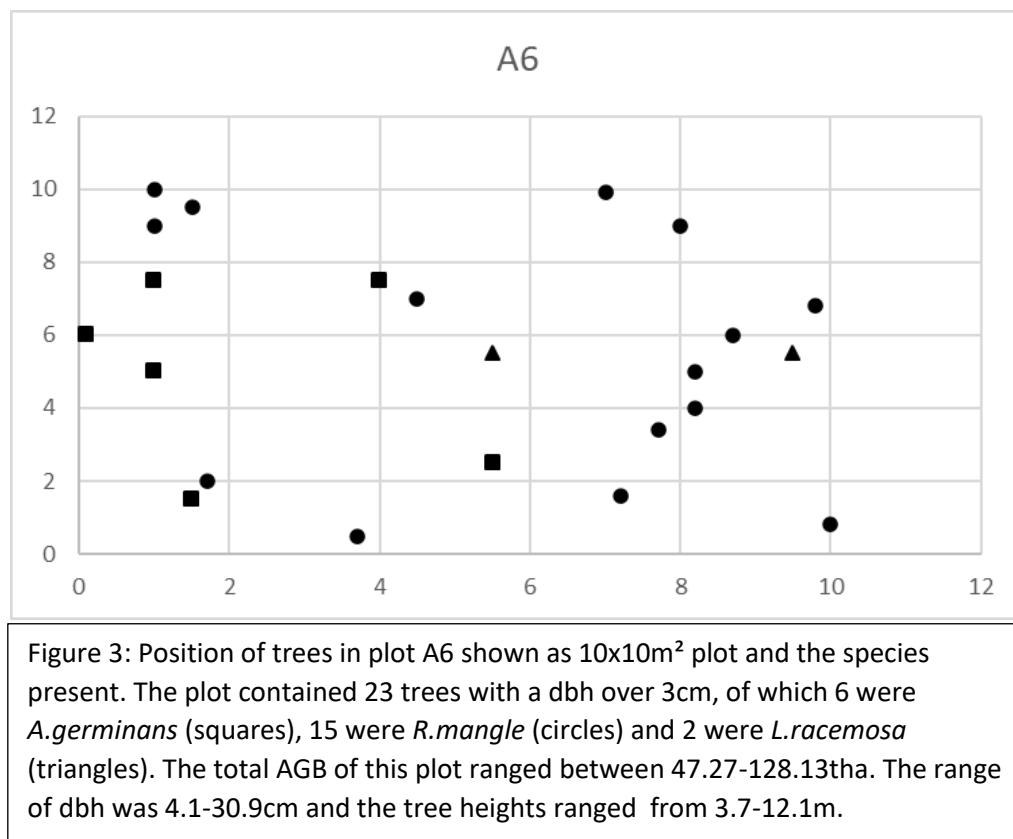
With  $W_{\text{top}} = \text{AGB (kg)}$  and  $\rho = \text{wood density}$

It was decided that in addition to testing the common equations against site- and species-specific equations, the original version of the Chave et al (2005) equation should be tested against the

incorrectly reported equation from Komiyama et al (2008) to test whether the results are also statistically significant from each other. Wilcoxon-Signed Ranks test was used to test for significant differences between the equations whilst a Spearman's Rank correlation was used to test if there was a correlation between the dbh of each tree and its height.

## Results

A total of 129 trees were sampled with 98 *R.mangle*, 19 *A.germinans*, 9 *L.racemosa* and 3 that could not be identified due to lack of bark and leaves. Due to the appearance of the remaining biomass, it was suggested that 2 of the unknown individuals were *R.mangle* and the other was *A.germinans* but this could not be confirmed in the field. Using the Shannon-Wiener equation the diversity index was calculated at 0.672, reflecting the low species diversity and the dominance of *R.mangle* in the research plots.



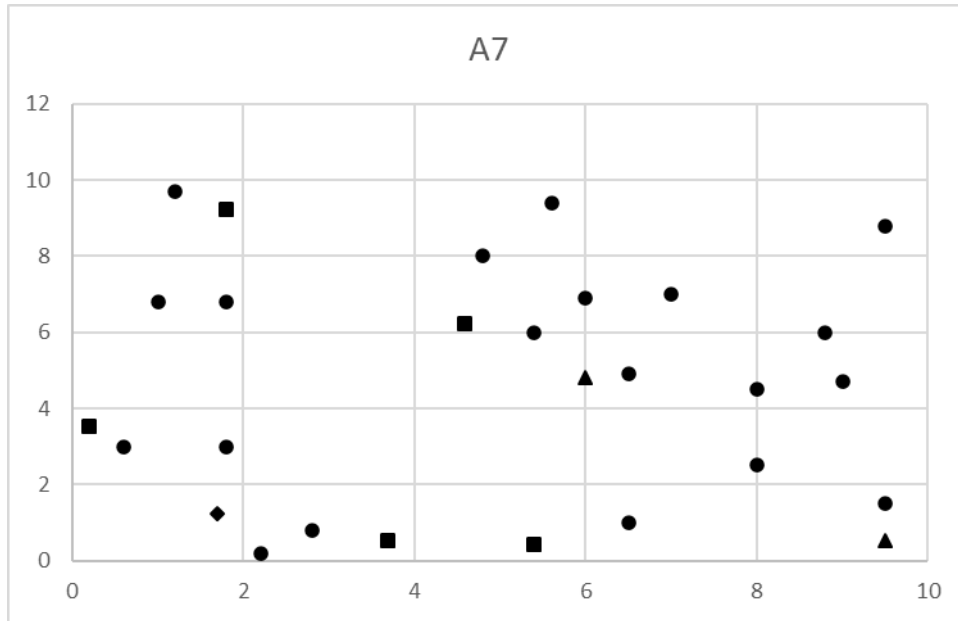


Figure 4: The position of trees in A7 and the species present. The plot contained 28 trees with a dbh over 3cm, of which 5 were *A.germinans*, 20 were *R.mangle*, 2 were *L.racemosa* and 1 was unknown. The total AGB of this plot ranged between 27.69-61.97tha. The range of dbhs was 4.2-35.3cm and the heights ranged from 0.8-12.2m.

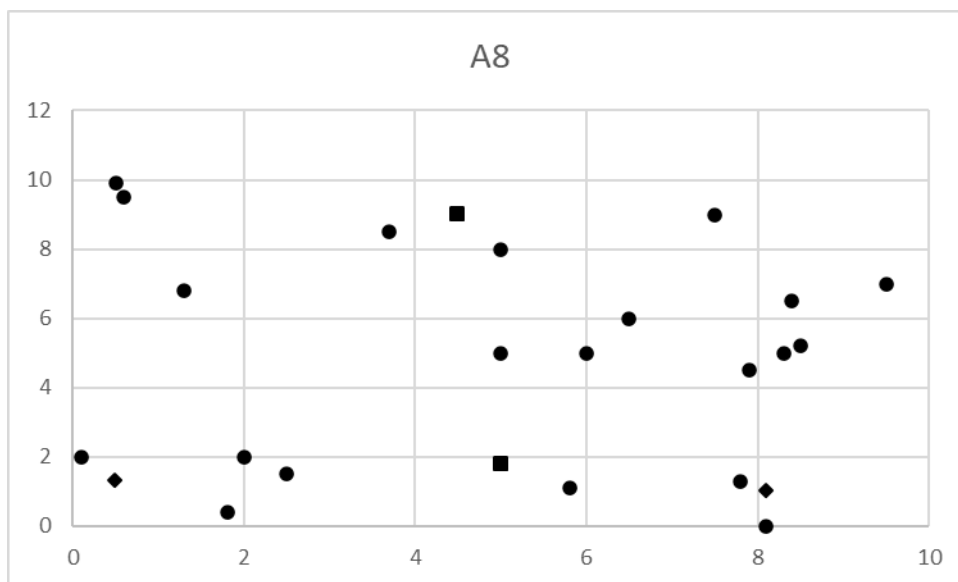


Figure 5: Position of trees in A8 and the species present. The plot contained 25 trees with a dbh over 3cm, of which 2 were *A.germinans*, 21 were *R.mangle* and 2 were not identifiable. The total AGB of this plot ranged between 14.02-37.75tha. The heights of the trees ranged from 1.8-9.1m and the dbh ranged between 3.6-27.2cm.

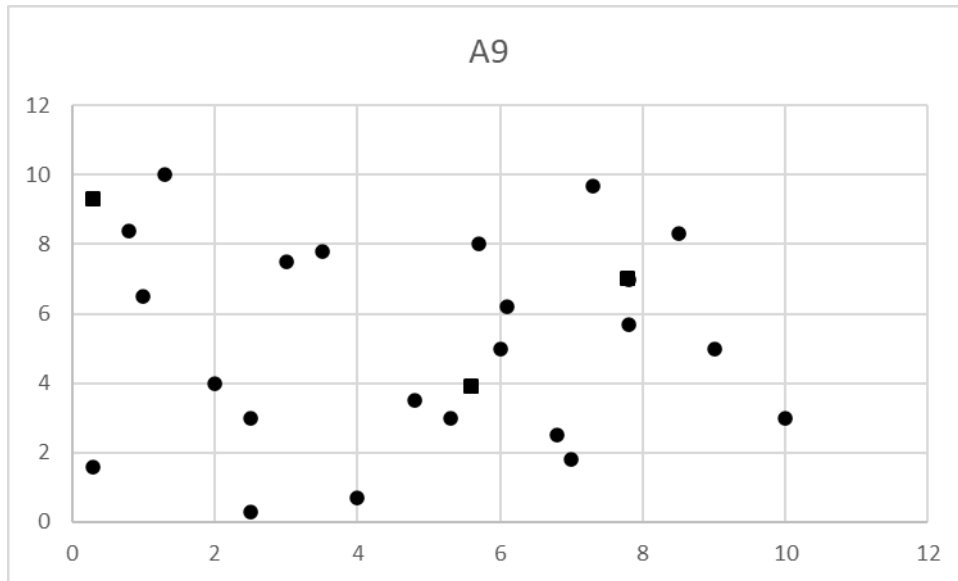


Figure 6: The position of trees in A9 and the species present. The plot contained 26 trees with a dbh over 3cm, with 2 being part of a dual-stemmed individual, of which 4 were *A.germinans* and 22 were *R.mangle*. The total AGB of this plot ranged between 31.49-65.4166tha. The dbh of the mangroves ranged from 4.7-31.2cm and the heights ranged between 2.9-11.4m.

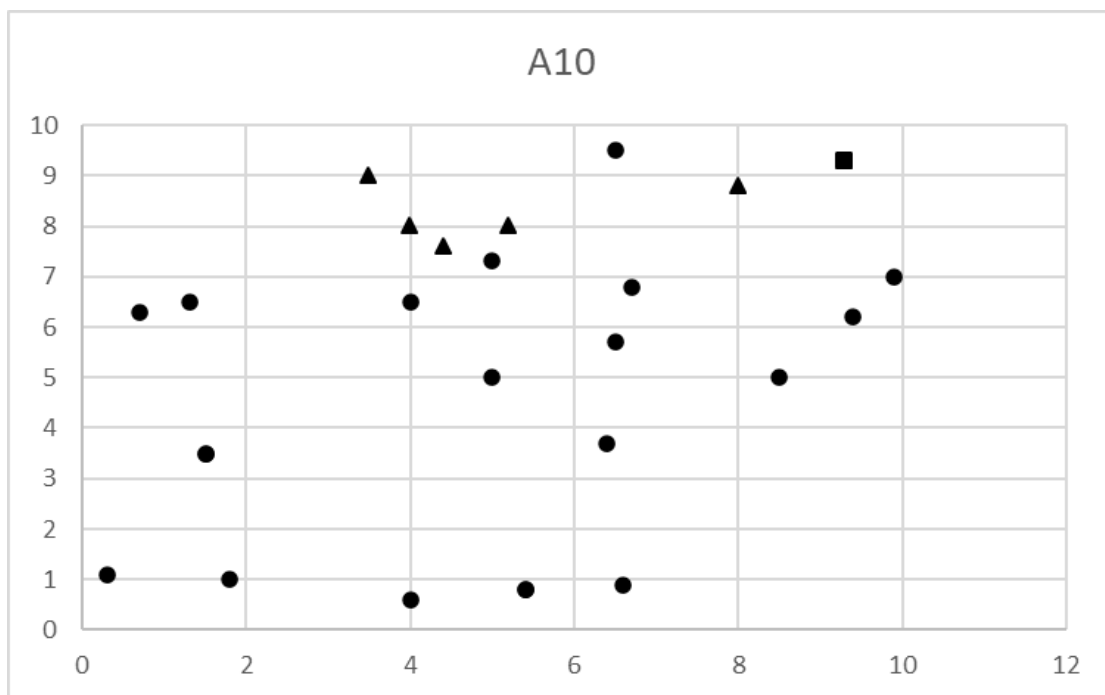


Figure 7: A plot of the species present and the position of trees in A10. The plot contained 24 trees with a dbh over 3cm, of which 1 was *A.germinans*, 18 were *R.mangle* and 5 were *L.racemosa*. The total AGB of this plot ranged between 38.19-117.03tha. The dbh of trees in this plot ranged between 4-63.6cm and the heights measured between 2.6-12.6m.



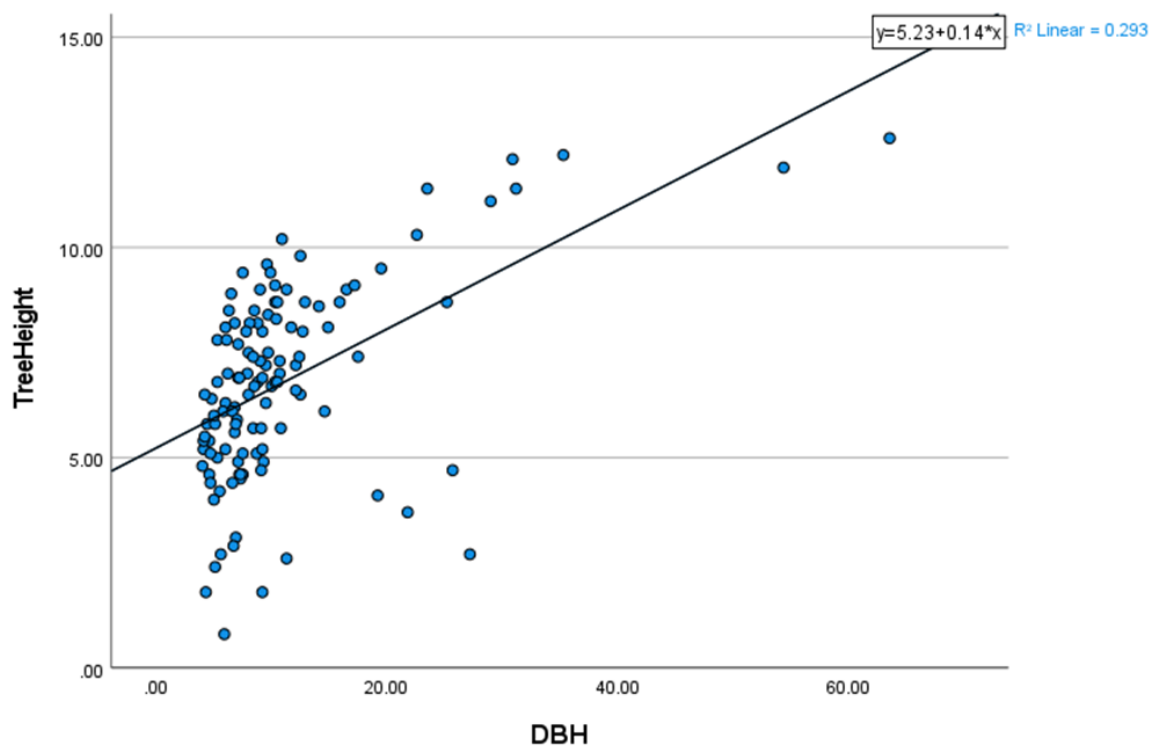


Figure 8: Significant correlation between the height of the mangroves and their diameter at breast height (dbh). The total range of dbh for the mangroves was 3.6-63.6cm and the range of heights was 0.8-12.6m.

Whilst *R.mangle* remained dominant in all plots sampled, the number of *A.germinans* individuals reduced from 6 individuals to 1 going through A6 to A10 whereas *L.racemosa* was found in low numbers in A6, A7 and A10 (Figures 1-5) Tree height varied between 0.8-12.6m and dbh varied between 3.6-63.6cm. The species with the largest dbh range was *A.germinans* and for height range was *R.mangle*. The results of the Spearman's Rank correlation showed a significant correlation between the dbh of the trees and their heights ( $y=5.23+0.14*x$ ,  $R^2$  linear= 0.293,  $p=0.00$ ) (figure 6). When the height data collected with a clinometer was compared to the data collected with the telescopic pole, it was found that the use of the clinometer produced significantly different measurements to those from the telescopic pole data (paired t-test,  $p<0.05$ ,  $t$ -value=6.190). This also resulted in significantly different AGB estimates (Wilcoxon-Signed ranks test  $p<0.05$ ,  $Z$ -value= -5.697).

The 4 estimates of total ABG ranged from 168.36 tha-410.29 tha, with the Smith and Whelan (2006) equations producing the lowest estimate and the Komiyama et al (2005) common equation producing the highest. The incorrect Chave et al (2005) equation created an estimate of 285.61 tha whilst the equation directly from Chave et al (2005) produced as AGB estimate of 171.97tha. Using the separate species allometric equations from Smith and Whelan (2006) the *A.germinans*

contributed 101.1tha, the *R. mangle* 60.44tha, the *L. racemosa* 1.47tha, the unknown species roughly 5.36tha. There was a significant difference between the species- and site-specific equations and the 2 correctly reported common equations (Z value=-8.259 for Komiyama et al (2008) and -7.157 for Chave et al (2005) respectively,  $p < 0.05$  for both estimates), but the incorrectly reported equation showed no significant difference in results (Z value=-0.72 and  $p = 0.943$ ). There was also found to be a significant result between the correct and incorrect versions of the Chave et al (2005) with a Z value of -9.535 and  $p < 0.05$ . When the equation for Chave et al (2005) was used with the clinometer height data, the estimate of AGB produced was significantly different from the estimate produced using the telescopic pole data at 112.924tha.

## Discussion

The estimate of aboveground biomass created through use of the Smith and Whelan (2006) equation of 168.36tha is slightly higher than previous estimates of mangrove AGB produced by Lugo and Snedaker (1974) from several sites in Florida. Their estimates of AGB ranged between 7.9-12.5tha in the dwarf mangrove habitats and between 57.8-135.5tha in other mangrove systems. The highest estimate of aboveground woody biomass produced by Castañeda-Moya et al (2013) from Shark River at 162.2 tha, in line with the value generated by the site-specific equations. Other estimates for mangroves in Florida included many dwarf mangrove habitats dominated by *Rhizophora mangle* such as that in Coronado-Molina et al (2004) where AGB ranged from 7.9-21.2tha. Out of the 3 species present in the plots *Rhizophora mangle* made up 76% of the trees present but only 36% of the AGB so the low AGB of dwarf mangrove ecosystems comprising of only *R. mangle* is expected. This pattern of lower AGB in *Rhizophora* dominated plots is seen in other countries such as Micronesia where the mean of the *Rhizophora* dominated site measured was 254tha which was 37.4% lower than the *Sonneratia* dominated site where the mean was 406tha (Kauffman et al, 2011).

The differences in the estimates of aboveground biomass show that there is significant variation caused by using the 2 common allometric equations from estimates produced using equations designed for use with the specific species included, and in the region the sampling for the models was completed in. The estimate of 410.29tha for AGB produced using the Komiyama et al (2005) equation was 243% over the estimate created using the Smith and Whelan (2006) equations. The reason for this may partially lie within the theory that this equation is based on. The pipe model theory by (Shinozaki et al, 1964a and b) is based on the relationship between stem diameter and tree crown biomass and distribution, but the models were originally designed for use at the scale of

the individual plant without clear definitions of what is included as photosynthetic or non-photosynthetic tissue. This leaves these factors to be determined by the researcher. The original paper also lacks several experimental parameters for evaluating how stem growth would be estimated such as wood volume (Lehnebach et al, 2018). This creates a source of error when producing estimates of AGB using the equation based on this theory.

The common equation for moist mangrove forests taken from Chave et al (2005) produced an estimate of 171.97tha which is only 3.61tha on the specific equations value, though the result was still significantly different ( $p < 0.001$ ). This equation was developed using 27 databases of either published or unpublished tree harvest studies from tropical forests and a selection of linear regression models based on tree dbh, height and wood specific gravity. The addition of height as a variable accounted for in the equation appears to be the factor responsible for producing a closer AGB estimate to observed values, which has also been shown in other forests through the ground truthing of the models (Chave et al, 2005). However, there were only 2 databases built from mangrove data, with one based in Guadeloupe and the other from French Guiana, with 84 trees measured between them. The authors also pointed out that each model tested did result in overestimation of AGB and in models that did not take forest type into account the error could be over 50% (Chave et al, 2005). So, even though the AGB value produced was very close to the specific equations value, it would be beneficial for this equation to be further tested using any new tree harvest datasets for mangroves to potentially improve the accuracy.

The only estimate of AGB that was not significantly different ( $p = 0.943$ ) from the estimates produced using the specific equations was the incorrectly cited Chave et al (2005) equation as printed in Komiyama et al (2008), which estimated AGB at the site as 285.61tha. It was originally unclear why this result is not significant as it is roughly 1.7 times higher than the specific equations AGB value and there was clear overestimation of biomass when AGB value was over 0.72tha for an individual. However, the sum of ranks values showed that the number of positive ranks (49) and negative ranks (80) are similar so the lack of statistical significance could be a result of the datasets having similar median values, with the sum of ranks coming out as 4223 for positive ranks and 4162 for negative ranks. In comparison, the Komiyama et al (2005) equation had 100 positive ranks and 29 negative ranks, with the sum of ranks as 7706 positive ranks and 679 negative ranks. The source of the equation error is unclear as there is no equation stated in the Chave et al (2005) paper that resembles the one shown above, or in the cited literature from the research. Potentially, the error may have come from the misinterpreting of information taken from Brown et al (1989) with a sample size of 168 and a residual standard error value of 0.247 which are similar to sections of the

given equation. But the equations from Brown et al (1989) for moist forests (shown below) are also not a match for the incorrect equation:

$$Y = 38.4908 - 11.7883 (D) + 1.1926 D^2$$

$$Y = \exp\{-3.1141 + 0.9719 \ln (D^2 H)\}$$

With Y= AGB, D= dbh (cm) and H= height (m)

Therefore, the conclusion drawn from this equation is that although the result may not be statistically significant, the variation from the specific equations and the lack of a traceable source for this equation should encourage researchers to be more careful about sourcing their information as to avoid an obvious source of error.

The primary measurement used in all allometric equations for AGB is the dbh of the trees. For most studies dbh is set at 1.3 metres from the ground or above any buttresses, but some researchers use dbh at 1.4 metres (e.g., Smith and Whelan, 2006; Proudman et al, 2021). This creates variation where ideally a standard methodology would be used to reduce potential introduction of bias. However, it is unclear from the literature if anyone has quantified if there is a significant effect on accuracy. Problems with dbh may also occur at the minimum and maximum boundaries of the data collected. When collecting the data there will always be a largest and smallest value collected but when using allometry this can then cause issues if the data the equations are used on includes trees with larger dbh values than tested against. Whilst for Komiyama et al (2005), the maximum dbh recorded and used to design the equation was 85.6cm, in the mangrove study by Imbert and Rollet (1989) and Fromard et al (1998) that provide the mangrove data for Chave et al (2005), the largest dbh values recorded were 40.7cm and 30.1cm. The maximum dbh for the site-specific equations from Smith and Whelan (2006) was even lower at 20cm for *R.mangle*, 21.5cm for *A.germinans* and 18cm for *L.racemosa* which potentially reduces the accuracy of the estimates created despite their specificity. This means that for estimates calculated using equations with lower maximum dbh values than found at the research sites there is room for error, most commonly through overestimation. In the data from Vester the largest dbh recorded was 63.6cm, over 20cm larger than the highest dbh values used in the Chave equation.

On the other hand, minimum dbh is also a problem. Currently there is little agreement of what the lowest dbh measured in a plot should be. For the 2 mangrove papers used for the Chave equation the minimum reported values were a mean of 2.1cm for Fromard et al (1998) and 6.6cm for Imbert and Rollet (1989) who also stated that no trees with a dbh of below 5cm were measured which was the same rule as Komiyama et al (2005). Meanwhile for Smith and Whelan (2006) the minimum dbh

ranged from 0.5-0.7 cm between the different species. The researchers who created the forest plots at Vester used a rule of 3cm minimum for measuring dbh which eliminates many young trees and saplings from the data pool. For many other estimates there is a failure to report the minimum dbh so it unclear when choosing an equation whether the data will be representative of the full range of dbh that may be in forest plots (Komiya et al, 2008; Kauffman and Donato, 2012). Dbh as a factor also fails to consider the way hollows form in some larger trees where the diameter measurement of the tree fails to represent the lack of biomass present in the trunk where these form (Henry et al, 2010).

There are a few methods of measuring tree height from the ground. Telescopic poles can be used to reach the treetops but can be limited in their reach and require at least 2 people to operate them and verify the result. Other researchers use clinometers which measure tree height through the use of angles. However, in this study it was found that the two methods produced significantly different results. In plot A6, an *A.germinans* tree previously measured at 12.1m using the height pole only measured at 4.2m using the clinometer, whilst a nearby *R.mangle* tree previously measured at 4.2m was measured at 10.5m using the clinometer. There are multiple methods of taking these measurements including the tangent and sine methods, which respectively measure the angle to the treetop and the horizontal distance to the trunk and the angle and distance to the treetop. When compared these have been found to produce significantly different results between them (Réjou-Méchain et al, 2019). In a study by Larjavaara and Muller-Landou (2013) the sine method was found to underestimate tree height by 20%. Measuring the height of mangrove forests can be particularly difficult to do with equipment such as LiDAR as well as on-the-ground techniques due to many having dense, closed canopies (Yuen et al, 2016; Réjou-Méchain et al, 2019). The relationship between height and dbh can also change from a local scale to a regional one which can also cause overestimation (Kearsley et al, 2013; Réjou-Méchain et al, 2019).

Wood density has also been found to vary on a regional scale as it is impacted by many ecological factors such as soil fertility, humidity, light availability and climate zone (Yuen et al, 2016). The wood density of trees can vary not just between areas and species, but also between individuals of a species and the different biomass compartments e.g., branches, trunk (Henry et al, 2010). This variation, however, often goes undocumented in studies, as this factor is rarely measured from individual trees in a plot, or even from current field data, as many estimates of wood density are from online databases (Réjou-Méchain et al, 2019). Between these 3 key measurements there are numerous ways that bias, or error can enter AGB datasets and the forest and carbon inventories they are used for.

As it currently stands allometric equations are considered to be a basic method of estimating forest biomass, with guidelines from the IPCC ranking their use as a tier 1 level of data collection due to the use of default data as well as the lack of country-specific data for many sites (IPCC, 2000). But more concerning is that under the definition of good practice used by the IPCC, even current research into mangrove AGB may not match the expected standard, or even other types of forest as well (Timothy et al, 2016; Xing et al, 2019). Since 2000, good practice has been defined as “a set of procedures intended to ensure that greenhouse gas inventories are accurate, avoiding both systematic over- and underestimation and reducing uncertainties as far as is practicable” (IPCC, 2000). But with the use of the common allometric equations, the difference in estimates from site and species-specific values on a systemic level AGB in mangroves is in dire need of more study. This must be done in as many places as possible to sample the different environmental ranges of mangroves, and with both data and equations based on the local scale before any new attempts at creating common allometric equations for the world’s mangrove forests can be made.

## Conclusions

Given the importance of carbon storage in the world’s forests and potential for reductions due to land use and climate change, it is clear that current common allometric equations for mangroves are not fit for purpose and require and much larger volume of data covering the wide range of locations mangroves are found in, as well as the variation between and within tree species found in these ecosystems. But this will require standardisation of a common methodology for measuring forest plots, large amounts of physical resources and time, and due to the proven inaccuracy of height measurement methods such as the use of clinometers, the potentially necessary use of destructive sampling. Whilst destructive sampling is not an ideal option for research often aimed at protecting forest area, it unfortunately is necessary to test the validity of many common equations and regression models based on small sample numbers in a low number of countries and regions. Overall, this study establishes the need for more studies measuring biomass directly from the local level and the further testing of how mangrove biomass may vary from predicted patterns from common equations in areas lacking previous study.

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## The variation in Florida mangrove AGBC estimates with the use of generalised carbon content values

### Abstract

In Florida, mangroves contribute greatly to the tourism industry and to reducing storm damage, but carbon markets have not been considered for additional income despite state efforts to increase money earned from the environment. For accurate emissions data, fieldwork must be undertaken but due to its difficulties many mangrove researchers used generic allometric equations or carbon values as allowed in the current IPCC methodology. This research investigates whether the use of generic carbon values produces significantly different aboveground biomass carbon estimates (AGBC) than estimates made using site-specific data. AGBC was estimated through measurement of plots and sampling of plant biomass in Bonita Springs, FL and it was found that most general carbon values collected from the literature produced significantly different AGBC estimates than the site-specific data. The species and site-specific carbon value was estimated at 48.96%, with the plot AGBC ranging between 1.784tCha and 23.065tCha. The total AGBC of the sites were 101.283tCha for 2019 and 82.775tCha for 2022 but the use of general estimates was found to result in underestimation of up to 20.55% for AGBC. Therefore, site-specific carbon values should be used for mangrove AGBC to prevent errors in the estimation of potential stored carbon and their economic value for future carbon credit projects or estimates of financial worth.

### Introduction

In 2020 at the COP16 summit for the United Nations Framework Convention on Climate Change (UNFCCC) in Cancun, the Call to Action Protecting Mangroves for Climate Change Mitigation and Adaption was raised by wetland scientists to build a framework for creating economic incentive and support for protecting and re-establishing mangroves along tropical coastlines (Zwick and Hett, 2020). Whilst mangroves could be included in a country's estimate of carbon stock and sequestration potential under the current framework for activities under Reducing Emissions from Deforestation and Forest Degradation (REDD+), mangroves had to be in that country's definition of a forest, and this has previously led to the exclusion of mangroves from these estimates (Landis, accessed 2023). Even after a joint trial project between Mangroves for the future and the Norwegian Agency for Development Coordination (Norad) looking into more consistent measurement of mangrove carbon under REDD+ starting in 2017, it took until the 3<sup>rd</sup> Mekong Mangrove Forum in 2020 to announce large-scale projects run by the UN-REDD programme itself (Norad, 2016; FAO, 2020). These included projects such as the "Integrating mangroves into REDD+ Implementation in Myanmar" initiative, evaluating net greenhouse gas emission reduction through use of mangroves (FAO, 2020; IUCN, 2022).

REDD+ was set up in 2008 by the UN as a tool to encourage countries to reduce their rates of deforestation, whilst also supporting economic growth through the protection of forests using carbon finance markets (Blue Carbon Project, 2019; UNREDD, accessed 2023). Through the initiation of results-based payment schemes and support for assessing eligibility, e.g. ART-TREES, countries are better equipped to gain entry to different carbon markets and as a result of the work of the 65 partner countries it is estimated that over 700 million tCO<sub>2</sub> of forest emissions have been reduced through forest conservation and restoration (ART, 2022; UNREDD, accessed 2023). These calculations of reduced emissions and the value of tropical forests protected are calculated using a number of factors such as annual emissions, deforestation rate and activity data and scope (ART, 2021). All of which require accurate data collected over long periods of time to be eligible for inclusion. Activity data and emissions require more ground-truthing in many cases despite improvements in remote sensing technology (Pham et al, 2019; ART, 2021; Brede et al, 2022). But evaluating the accuracy of this data is much more difficult, with fieldwork requiring large amounts of time, resources and often funding, where it may seem unnecessary, especially as default values such as allometric equations and generalised carbon conversion factors are considered allowable for emissions estimation under Tier 1 level of IPCC methodology (Komiya et al, 2008; Kauffman and Donato 2012; Hiraishi et al, 2013). This is particularly true for mangrove forests.

Mangroves have been proven important to many economies in the tropics through the resources they provide and environmental protection as well. One example is that mangrove ecosystems are important nurseries for many economically important species of fish, crustaceans and shellfish and therefore contribute to tropical fisheries around the world (Heald and Odum, 1970). It is estimated that per hectare, mangroves contribute an average of between US\$17,090.10 and US\$23,613 each year directly to fisheries, producing an average of 539kgha<sup>-1</sup>yr<sup>-1</sup> of fish, shellfish and molluscs, with an additional 146kgha<sup>-1</sup> of shrimp produced annually, whilst indirect benefits to fisheries from potentially reach US\$37500ha<sup>-1</sup> (Salem and Mercer, 2012; Mukherjee et al, 2014; Jakovac et al, 2020).

In many countries mangroves are also a source of income from eco-tourism or as home to many activities such as fishing, paddleboarding or wildlife watching (Spalding and Parrett, 2019). In a study by Spalding and Parrett (2019), a total of 3945 attractions related to mangroves were found between 93 countries including visitor centres, viewing towers, boating and hiking. The highest number of attractions was found in the USA with 783. In other locations such as the Galapagos where 47% of tourism sites include mangroves, it was estimated that the ecotourism from mangroves brought in up to \$16,958 per hectare annually (Tanner et al, 2019). Worldwide, it is

estimated that tourism brings in on average \$37,297 per year for every hectare of mangroves (Salem and Mercer, 2012).

Mangroves are also considered an important barrier between storms and cyclone events and coastal settlements, with several studies proposing that these forests act as barriers to large storm surges and high winds, reducing storm surge wave energy by up to 66% and retaining sediment that reduces erosion and contributes to soil stabilization (Thampanya et al, 2006; Mclvor et al, 2012a; Mclvor et al, 2012b; Mclvor et al, 2016). This results in reduced damage to properties built behind mangrove forests. But mangroves around the globe are threatened with degradation and deforestation for many reasons including oil spills, changes in sediment and nutrient loads in waterways, and removal for land development, or creation of salt pans or shrimp farms (Salem and Mercer, 2012; Radabaugh et al, 2017).

The state of Florida in the USA contains roughly 231,380ha of mangroves made up of 3 true mangrove species, *Avicennia germinans*, *Rhizophora mangle* and *Laguncularia racemosa*, as well as several species of mangrove associate including *Conocarpus erectus* (FDEP, 2022; Radabaugh et al, 2017). The mangroves of Florida are important to the state economically for many reasons including tourism and for flood protection. The Everglades National Park sees roughly 1 million tourists visiting each year, making the mangroves there particularly important to the local economy and job market (Spalding and Parrett, 2019). In Florida it is also estimated that the mangroves prevent property damage costs of up to \$11.31 Billion to coastal homes and developments each year against storms and hurricanes (Menéndez et al, 2020). But the mangrove forests are threatened in Florida by habitat loss, changes in hydrology and sea level rise, as well as illegal trimming of mangroves in residential areas (Radabaugh et al, 2017). Previously in 2016, the Florida Senate passed a revised bill allowing state parks to be used for purposes other than conservation such as hunting, cattle grazing and includes the need for economic valuation of these lands (House Bill 1075, 2016). Carbon finance could provide an additional source of income to the state through the protection of the mangroves in these areas if estimates of the aboveground biomass carbon (AGBC) or soil carbon are made within the conservation areas and carbon credits can be generated for emissions reduced through conservation of the mangroves.

Due to the difficulties of field research in mangrove forests many scientists use allometric equations to estimate the aboveground biomass (AGB), then a generalised carbon content factor to estimate the carbon stored in that biomass (Komiya et al, 2008; Kauffman and Donato, 2012). These carbon conversion factors assume that the proportion of biomass that is carbon is uniform among all mangrove species and in all the countries mangrove are in, however this does not align

Table 1: The range of generalised carbon content values found from the literature. 13 different values from a range of tissue types and species were found in 17 sources that were cited in the literature, ranging from 40-50%, with some values having several sources.

Generalised carbon content value (C%)	Source of the generalised C% value
40	Schlesinger (1997)
41.5	Bouillon et al (2008)
42.6	Rodrigues et al (2014)
44	Ewe et al (2006)/Bouillon et al (2008)
44.1	Rodrigues et al (2014)
45	Kauffman and Donato (2012)/ Houghton et al (1983)/ Howard et al (2014)/ Lasco et al (2001)
45.1	Hiraishi et al (2013)
46	Kauffman and Donato (2012)
46.4	Kauffman et al (2011)
47	IPCC (2006)/ Kauffman and Donato (2012)/ Abino et al (2014)
48	Kauffman and Donato (2012)
49	Kauffman and Donato (2012)
50	IPCC (1996)/ Komiyama et al (2008)/ Golley et al (1962)/ Gifford (2000)/ Birdsey (1992)/ Brown (1997)/ Kauffman and Donato (2012)

with the results of several studies that have taken place over the last decade (Thomas and Martin, 2012; Rodrigues et al, 2014; Bulmer et al, 2016). Currently, there are no recent estimates of the carbon stored in the aboveground biomass (AGBC) for Florida found in the literature from the last 10 years. For 2 of the previous papers the carbon content estimate used for Florida, the value used came from unpublished sources and other carbon content estimates found throughout the literature range from between 40-50% (Table 1) (Schlesinger, 1997; Kauffman and Donato, 2012). Therefore, the hypothesis of this research is that there will be a significant difference between estimates of AGBC in Florida produced using site-specific data and the different generalised carbon content conversion factors found in the literature.

## Methods

The study sites chosen were based in the mangroves growing close to the FGCU Vester research station in Bonita Springs, Florida (See chapter 3 for map). The sampling period were in April 2019, and March and April 2022. Research plots set up by researchers at FGCU measured 10x10m<sup>2</sup> were used to collect data on species, using a DBH tape for diameter at breast height (dbh=1.3m) and a telescopic pole for tree height. Trees with a DBH of less than 3cm were excluded from the data pool. These measurements were put into the species-specific allometric equations from Smith and Whelan (2006) to produce an estimate for each individual tree, the study plots, and the total tonnes of biomass per hectare.

From a subset of trees, biomass samples were taken of leaves, branches, propagules, and trunk samples. Most were collected by hand apart from the trunk samples taken using an incremental borer. These plant biomass samples were then dried for up to 3 days at 80°C. The samples were transported back to Bangor University and dried again for 48 hours at 80°C. The biomass leaf and branch samples were then ground finely by machine (Retsch MM 400 mixer mill) and run through both total C% (TC%) using a CHN analyser (Leco Instruments Truspec CN Analyser) and total organic C% (TOC%) and total nitrogen (TN) using a TOC analyser. The trunk and propagule samples were only run on the TOC analyser (Analytik Jena Multi 2100S TOC TN Analyser). The average TC% values of mangrove tissues were used for each species to produce species-specific C% values before an average was taken of all the species and tissue types tested as has been done previously in the literature to produce carbon content estimates for mangrove AGBC. Generalised carbon content values were collected from the literature and AGBC was calculated using the averaged TC% value collected at the site or the generalised values, and the AGB estimates of the plots and site totals. For TOC analysis an extraction was done using a 1:5 ratio with the plant biomass samples and 0.5 M K<sub>2</sub>SO<sub>4</sub>. The solution was shaken for 30 minutes at 200rpm before being centrifuged for 5 minutes at 4000rpm (or 2057rcf). The K<sub>2</sub>SO<sub>4</sub> was diluted using ultrapure water in a 1:5 ratio to prevent corrosion of the TOC analyser catalyst.

The data was tested using a Kolmogorov-Smirnov test for normal distribution and Levene tests for equality of variances to check if the assumptions for parametric tests could be met. Due to the results of these tests both ANOVAs and Kruskal-Wallis tests were used to test for differences between the species and biomass types. For differences between the individual species and biomass types, the homogeneity of the data was tested with Mann-Whitney U tests, apart from the total leaf carbon which was parametric and required an independent t-test was used to compare the data. The data for TOC was not parametric so instead a Kruskal-Wallis was chosen for testing the

differences between the 3 species and the biomass types, with Mann-Whitney U tests used for testing if there were significant differences between each species and biomass type.

## Results

The total AGB of the study sites measured 168.37tha in the plots. The sites had a high number of *R.mangle* with 98 individuals, compared to only 19 *A.germinans*, 9 *L.racemosa* and 3 trees of unknown species. The total range of dbh was between 3.6-63.6cm and the heights of the trees ranged from 0.8-12.6m (Figure 1).

The site-specific C% of the mangrove biomass at the Vester field station averaged to 48.96% for the total biomass. The leaves C% averaged to 47.15% with a range of 44.1-51.7% and the branches averaged to 50.77% with a range of 41-68.5%. There was found to be a significant difference in C% of the biomass of *L.racemosa* and *R.mangle*, and *A.germinans* and *R.mangle* ( $p=0.00$ ), but not for *L.racemosa* and *A.germinans*. These produced average biomass carbon contents of 51.05% for *R.mangle*, 48.1% for *A.germinans* and 47.72% for *L.racemosa*. The biomass of the mangroves was also tested for TOC% which found that plant biomass had an average of 27.97% for TOC.

TOC was highest in the propagule biomass with an average percentage of 56% compared to 38.05% for leaf biomass, 18.35% for branches biomass and 17.45% for trunk biomass.

Average TN for each species ranged between 52.33mg/L for *R. mangle*, 586.48mg/L for *A.germinans* and 39.97mg/L for *L.racemosa*. In the different biomass compartments it averaged to 404.2mg/L in leaves, 142.66mg/L in the branch samples, 12.12mg/L in the trunk samples and 174.98mg/L for the propagules. When using the site-specific C%, the average for the AGBC of the study site was found to be 82.775tCha. AGBC was found to range from 10.433tCha to 23.065tCha between the study plots, with the highest AGBC found in plot A6 and the lowest in A8. The AGBC also varied greatly between species found with the highest proportion of AGBC coming from the

Table 2: The AGB of the plots and the AGBC calculated using the species-specific values and the averaged site-specific value.

	AGB of plots (tha)	AGBC using Spp-specific C values (tCha)	AGBC using average site C% values (tCha)
A6	47.270	23.065	23.143
A7	30.110	14.855	14.742
A8	21.310	10.597	10.433
A9	31.490	15.525	15.418
A10	38.190	18.736	18.698
Atotal	168.370	82.775	82.434



Table 3: Table showing the data for each species studied of the species-specific C% value from the TC% analysis, the AGB estimate for each species using the specific equations from Smith and Whelan (2006), the AGB estimates produced using the species-specific C% values and the averaged value. Average TOC% and TN of each species was also included.

Species	Species C% value	AGB (tha)	Spp-specific AGBC	Average site AGBC	TOC%	TN (mg/L)
A.germinans	0.481	135.661	66.414	65.972	36.180	586.483
L.racemosa	0.477	38.141	18.672	18.548	27.841	39.973
R.mangle	0.511	90.070	44.095	43.801	15.355	52.327
Unknown	Mixed	5.356	2.622	2.605		

*A.germinans* trees with 66.414tCha, followed by *R.mangle* with 44.131tCha and *L.racemosa* with 18.672tCha. The unidentified trees contributed 2.622tCha. Whilst there was no significant difference ( $p=0.733$ ) between the AGBC of *Avicennia germinans* and *Laguncularia racemosa*, there was between each of those species and *Rhizophora mangle* ( $p<0.05$ ).

Differences between plots related most to the species composition with the highest AGBC values coming from plots containing large *A.germinans* individuals or larger numbers of either *A.germinans* or *L.racemosa* stems. It was found that using most of the generic C% factors produced a significant

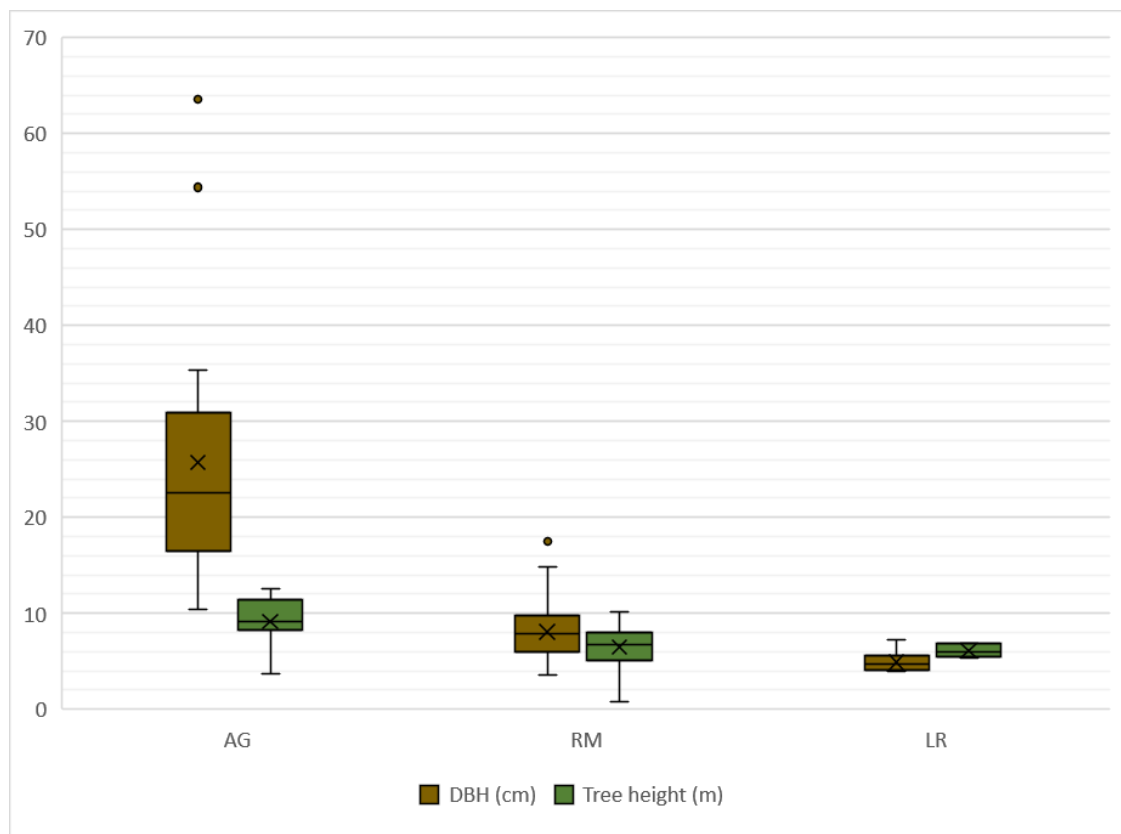


Figure 1: Diameter at breast height (DBH) values and tree heights between the 3 species present at the Vester field site; *Avicennia germinans* (AG), *Rhizophora mangle* (RM) and *Laguncularia racemosa* (LR). The X represents the means, and the whiskers show the data ranges with the dots representing outlier datapoints.

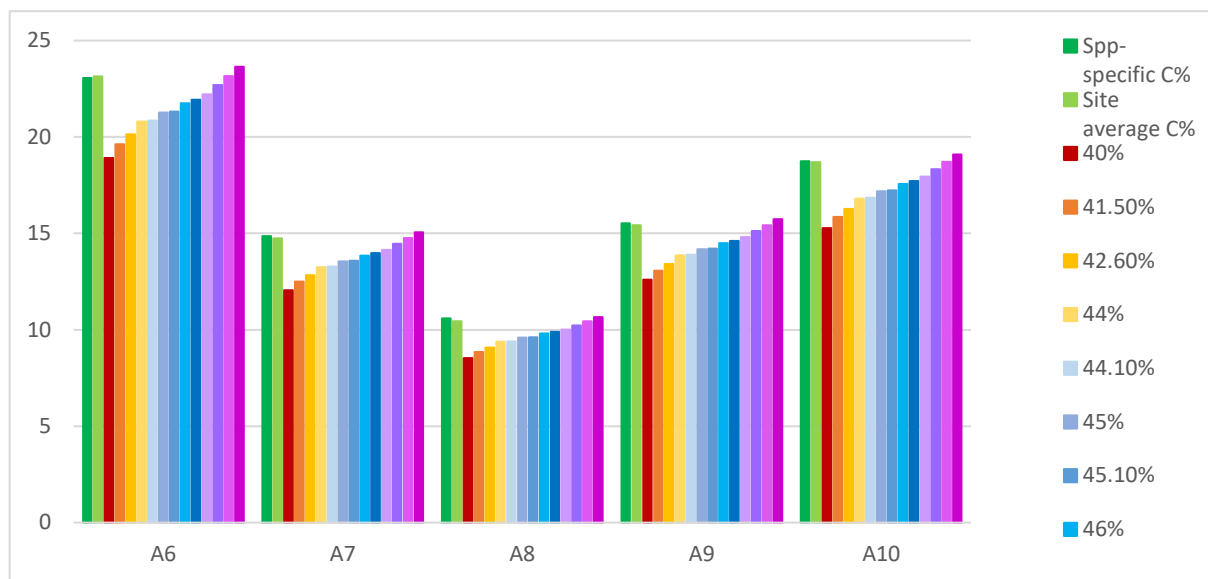


Figure 2: Variation in estimates of AGBC of plots produced for each plot (A6-A10) using species-specific C%, average site C% values, and the 13 generalised carbon conversion factors. All the estimates of AGBC produced using the generalised values were significantly different from the site-specific and species-specific values ( $p < 0.05$ ).

difference in estimates of AGBC ( $p < 0.05$ ), apart from where the species-specific estimates were compared to the site-specific value ( $p = 0.658$ ) or the generalised value of 49% ( $p = 0.601$ ) (Figure 2 and Tables 4.1 and 4.2). This generalised value was the closest factor tested to the carbon data collected from the site. The use of the generalised C% factors created a range of AGBC from 67.348-84.185tCha in the 2022 estimate. The use of the generalised C% factors resulted in underestimation of up to 22.4% for the AGBC estimate of the mangroves at the Vester site.

## Discussion

The AGB of the mangroves at the Vester site was found to be higher than several other sites measured in Florida by other researchers. The closest estimates found were from Castañeda-Moya et al (2013) at Shark River with  $162.2 \text{ tha}^{-1}$  and Lugo and Snedaker (1974) at Ten Thousand Islands with up to  $135.5 \text{ tha}^{-1}$ . The lowest estimates came from sites that were predominantly or exclusively made up of *R. mangle* trees including Taylor Slough where the lowest AGB found was  $7.9 \text{ tha}^{-1}$  (Lugo and Snedaker, 1974; Coronado-Molina et al, 2004). Most of the sites previously estimated in the literature were on the East coast of Florida, with only 3 on the West coast including this study and a small number to the South in the Everglades (Lugo and Snedaker, 1974; Ross et al, 2001; Coronado-Molina et al, 2004; Castañeda-Moya et al, 2013; Radabaugh et al, 2018). The furthest North in the state explored was at Merritt Island where AGB was found to be  $114 \text{ tha}^{-1}$  (Doughty et al, 2016).

Whilst there are several estimates of AGB for Florida mangroves found in the literature, it is much more difficult to find data for AGBC. Simpson et al (2017) used the carbon content value 48% to estimate AGBC on the East coast of Florida between 61.2 and

93.2tCha<sup>-1</sup> for their mangrove plots made up of established “medium-sized” trees. Meanwhile in a study of Tampa Bay on the West Coast by Radabaugh et al (2018) found that AGBC averaged at 40.8tCha<sup>-1</sup> and ranged between 34.3 and 47.7tCha<sup>-1</sup>, using 44% as a generalised carbon content sourced from Ewe et al (2006) and Bouillon et al (2008). The study plots from this research had a much lower range of AGBC per plot between 1.78 and 23.07tCha<sup>-1</sup>, potentially due to the choices of allometric equation for the initial AGB estimate, with Radabaugh et al (2018) including crown height as a part of the equations used and Simpson et al (2017) using different equations from Ross et al (2001) for measuring the dwarf *R.mangle* mangroves as well as the Smith and Whelan (2006) equations for the other mangroves present in their study area. The variation in the AGBC values of the plots may also be due to factors such as stand structure and age of the trees in the stands.

*R.mangle* is a shade tolerant, pioneer mangrove species which may explain its dominance in the plots where the canopy is already established and allows lower levels of light to the forest floor (Ross et al, 2006; Lopez-Hoffman et al, 2007; Rivera-Monroy et al, 2019). There were much fewer individuals of *L.racemosa* in the plots which suggests that the *L.racemosa* individuals were unable to establish before the canopy grew in as they are considered shade intolerant (Ross et al, 2006;

Lopez-Hoffman et al, 2007; Rivera-Monroy et al, 2019). The largest DBH values for the plots came from *A.germinans* trees. *A.germinans* does produce larger stems and this reduces the risk of wind damage that causes higher mortality for *R.mangle* and *L.racemosa* in high wind events (Doyle et al, 1995; Imbert, 2018). However, *A.germinans* does not appear to be as shade tolerant as only

Table 4: Underestimation and overestimation of AGBC produced by the use of generalised carbon content factors AGBC compared to species-specific and average site C% values. Underestimated values are shown as positive numbers and overestimation as negative numbers

Generalised C content value (%)	Percentage differences between AGBC estimates	
	Spp-specific	Average
40	23.08	22.4
41.5	18.63	17.98
42.6	15.56	14.93
44	11.89	11.27
44.1	11.63	11.02
45	9.4	8.8
45.1	9.16	8.56
46	7.02	6.43
46.4	6.1	5.52
47	4.75	4.17
48	2.56	2
49	0.47	-0.08
50	-1.54	-2.08

established trees were found in the study plots suggesting a lack of successful establishment of saplings after the canopy closed (Pickens et al, 2019).

The 2 papers from Florida providing AGBC estimates used 2 different carbon content values of 44% and 48%. The 44% comes from 2 sources, Bouillon et al (2008) and Ewe et al (2006), but both source papers came to this value from unpublished data or unpublished and uncited literature. This makes it difficult to analyse the validity of this value for use in situ. For this study for example, the use of 44% as the carbon content would have resulted in AGBC being underestimated by 11.27%. The other value used was 48% sourced from Kauffman and Donato (2012). This is a commonly cited source of carbon content values for mangrove forests, but the working paper states that mangrove carbon can be estimated using a value between 46-50% “if local or species-specific values are not available”. This highlights another problem with the current literature on mangrove carbon as content values for mangroves in Florida could not be found for any of the native species in that region. There is also no clear indication of why 48% was chosen out of the range of values given by Kauffman and Donato (2012) either. Use of 48% as the carbon content value for this study produced 2% underestimation in the AGBC estimates for the Vester site, which was still found to be significant ( $p < 0.05$ ).

The use of general carbon content values for calculating AGBC and the economic value of carbon in trees, including mangroves, has become a source of concern in the literature over the last decade. Rodrigues et al (2014) studied site-specific carbon in the mangrove forests of Brazil and found that using the IPCC’s 2006 recommended forest value of 50% for carbon resulted in a 13.6% deviation of the AGBC from the study’s AGBC estimate calculated using the species-specific values for the site. Bulmer et al (2016) in New Zealand found that using the recommended wetlands carbon content value of 45.1% from the Hiraishi et al (2013) overestimated biomass carbon by 9.4%, equal to roughly 21000tC every year being overestimated as the mangrove area increases (Bulmer et al, 2015). Even for other types of trees in tropical regions, generalised carbon conversion factors can result in overestimation of 5.3% (Martin and Thomas, 2011). Mangrove carbon varies by species and site around the world and the use of generalised values without prior measurements at the site is a large source of error when assessing AGBC. For this study, using the Bouillon et al (2008) value of 44% created estimates that underestimated AGBC by over 10%, but for the study by Rodrigues et al (2014), this was the closest generalised value to the carbon measurements for the site and resulted in non-significant differences.

This underestimation of the AGBC of the mangroves in Florida has implications for any future inclusion of blue carbon in carbon credits projects. If the mangroves at the Vester site were measured for potential emissions released if the area was lost, the carbon stocks of the AGBC can be

converted to a CO<sub>2</sub>e volume using a conversion factor of 3.67 which would produce an estimate of 303.78mtCO<sub>2</sub> per hectare for the plots at the Vester site (Kauffman et al, 2014; Zeng et al, 2021; Rovai et al, 2022). At the current value of carbon taken using the current price of \$31tCO<sub>2</sub>e from the California Cap and Trade program from the Carbon Pricing Dashboard (April 2023), the mangroves at Vester could be worth up to \$9417.18 per hectare in terms of mitigated carbon loss. But with the level of underestimation seen in this study, the price could be underestimated by as much as \$1935.23 if the generalised mangrove carbon content value of 40% (Schlesinger, 1997) was used to estimate AGBC instead of site-specific data. Thus, it is vital that current use of generalised carbon content values is halted until true carbon content in mangroves can be tested for further analysis and use in financial programs.

## Conclusions

As the state of Florida investigates options for additional funding for the state parks, the potential addition of a cap-and-trade system designed for Florida businesses to offset their emissions whilst providing funding for park maintenance and mangrove conservation could be an interesting concept for lawmakers and action groups to explore. But the current trend in the literature of using the generalised carbon content values rather than local species and site-specific estimates cannot continue to prioritise ease over accuracy when these underpinning measurements are so influential in decisions regarding blue carbon legislature. The generalised values only allow for tier 1 level analysis of carbon stocks where higher tiers are considered ideal by the IPCC, and this will likely be further encouraged by the increased prevalence of carbon trading projects and the inclusion of mangroves into REDD+. Old mangrove AGBC estimates also need to be investigated to test if the AGBC has improved or declined in areas where research has moved on from the base measurements that further analysis such as total carbon sequestration or total productivity relies on.

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## **Discussion chapter**

### **Aims of the thesis**

The aims of this thesis were to review the current literature on mangrove carbon research for potential sources of error or bias that would reduce the accuracy of estimates of aboveground biomass carbon (AGBC). This project consisted of sections, with the first 2 chapters of which focused on evaluating the current literature for geographical bias in the countries and species studied and the potential error of using generalised carbon values in previous AGBC estimates from the literature. The specific research questions in this section of the thesis were:

1. Is the distribution of mangrove carbon studies reflective of geographical and species distributions of mangroves?
2. Is the current literature on mangrove carbon research reflective of authors from low- and high-income countries?
3. Does the use of generalised carbon values result in significant overestimation or underestimation when compared to site-specific values found in the literature?

The second section (2 chapters) was based on fieldwork undertaken in South Florida and studied the direct effects of the use of generalised biomass equations on estimates of aboveground biomass (AGB) and generalised carbon values on AGBC estimates when compared to site- and species-specific data. For these chapters the research questions were the following:

1. Does the use of generalised aboveground biomass equations result in significantly different estimates of AGB than those produced by species-specific equations?
2. Does the use of generalised carbon values produce significantly different AGBC estimates to site-specific carbon data?

### **Summary and Synthesis**

The systematic evidence map (SEM) of chapter 1 found that only 64 of the 124 countries (51.6%) that contain mangroves were recorded within the literature compiled from the databases. The most underrepresented regions were the continent of Africa with a total of 77 study locations and 19 out of 34 countries with mangrove forests represented, and 32 island nations missing from the literature between the Pacific and the Caribbean with 43 only study locations. This shows that geographical bias is a factor that needs to be considered when common equations of generalised carbon values

are developed as this underrepresentation of certain regions may skew the underpinning data used and increase the probability that these tools for AGBC measurements are incorrect and will not give accurate estimates. Other papers have had similar patterns of locations excluded from the literature, including statistical modelling of factors influencing study location choice in Reboredo Segovia et al (2020), which also lacked records for many island nations. However, there was no evidence to suggest that there was any previous concern about the geographical distribution of mangrove research in general, with much of the focus of previous large-scale reviews being on the ecosystem services that mangroves provide, land-use changes and more recently on the use of remote sensing (Faunce and Serafy, 2006; Giri et al, 2016; Cardenas et al, 2017; Wang et al, 2019; Sasmito et al, 2019). This underrepresentation of many mangrove ecosystems will have impacts for not just the calculation of AGBC but also for potential work on restoration of the mangroves in these countries as there will be a lack of base data to about previous carbon stock volumes in the underrepresented areas. This lack of global data may also be reflected in other areas of environmental science including soil carbon and disturbance events which would result in projects being underinformed on key ecological factors that will impact the outcome of restoration efforts.

The most studied region according to the results of the SEM was Asia. Mangroves in Asia are particularly threatened by expansion of agriculture and aquaculture, specifically expanding rice cultivation and shrimp farming (Ahmed et al, 2018). Shrimp farming also introduces pollutants into healthy mangrove forests surrounding the ponds which degrades them before the ponds are abandoned and new shrimp farms are set up without work to restore the original site (Anh et al, 2010; Ahmed et al, 2018). Some of these pollutants include heavy metals such as mercury, lead and tin (Sandilyan and Kathiresan, 2014). But on the African continent mangroves face different challenges. In countries such as Mozambique the pollution that degrades mangrove forests is most often due to oil spillages which are both toxic to mangroves and can smother the roots and seedlings when coated (Kadafa, 2012). Deforestation of mangroves in African countries is cited in several papers as partially due to the demand for wood products, from timber for housing, fuelwood and for charcoal, as well as other non-timber products from the forests such as plants for medicinal purposes (Yessoufou and Stoffberg, 2016; Teka et al, 2019). On the other hand, island nations are considered to be the most at-risk countries for rising sea levels. Combined with increasing population size this puts more pressure on the resources the mangroves provide (Donato et al, 2012; Courchamp et al, 2014). As a result, each region would need region-specific restoration plans based on data taken from the specific area being targeted to improve the success rate of the work and make sure that the threats to the ecosystem are targeted by the plan. At present, the lack of studies of African mangroves or island forests results in less region-specific information available to assist in

conservation decisions which may lead to restoration projects doomed to fail before they are even started.

When the literature search for the SEM was started helicopter research was a concern due to broader reading of the issues in the fields of forestry and environmental science as well as in projects replanting and restoring mangrove forests around the world (Adame, 2021; Hsu et al, 2021). Helicopter research (also known as parachute research) describes a situation where researchers from higher-income countries travel to lower-income countries for projects where they use local knowledge, resources, and samples before returning to their home institutions to analyse and publish the data, often without properly crediting the local people they worked with or sometimes obtaining the correct permissions for their sampling (Minasny and Fiantis, 2018; Nordling, 2018; Minasny et al, 2020). But 73% of the studies had first authors based at an institution in the country that the study was located in. This suggests that in the field of mangrove carbon research there is reason to be less concerned about the potential of helicopter research. There is a caveat to this statement though as there were areas where there were noticeably fewer authors from institutions in the countries being studied. One of these was Africa with only 35 studies with a first author from an African research institution, with these papers coming from 10 countries: Egypt (7), Tanzania (6), South Africa (5), Nigeria (5), Kenya (4), Madagascar (3), Mozambique (2), Senegal (1), Gabon (1) and Sudan (1). This means that for 9 of the African countries in the dataset there were no papers with first authors based in the studied country. A similar trend was found in the data for North and Central America as there were 15 countries present in the dataset, but first author papers were only found for 4 of them with the USA and Mexico producing the most papers (131 and 17 respectively), with Panama and Costa Rica each contributing 1 paper to the dataset. Whilst most papers in the dataset were authored by researchers from the country that they studied, this hides the lack of studies in many countries and the pockets where helicopter research is potentially prevalent. Many of the 9 countries on the West coast of Africa lacking published papers from local institutions were only included in the dataset once as part of a large-scale study conducted by researchers from the USA (Tang et al, 2016). Of the remaining papers from this region others were authored by researchers from Nigeria, Italy and Belgium as well as other Americans. In total, European countries such as the UK and France appeared as first authors on mangrove carbon papers 141 papers out of the 857 total studies (16.5%).

Whilst only population size produced a significant correlation when number of study locations was tested there are potential theories for why some locations were more studied. The first is that researchers in different countries and regions may simply have different research priorities. For example, much of the search results for 'pacific island mangroves' is about the response of species

to climate change, sea-level rise and anthropogenic disturbance (Krauss et al, 2010; Duffy, 2011; Godoy et al, 2015; Gilman et al, 2016). For 'West Africa mangroves' the search results turned up more papers on current mapping of the mangroves and assessing both the degradation of the habitat and the ecosystem services from these forests (Bodin et al, 2013; Carney et al, 2014; Feka, 2015; Gnansounou et al, 2021). It may be that with different research priorities this reduces the output of carbon studies from certain regions due to a lack of interest and therefore funding towards these projects. It was suggested in (Reboredo Segovia et al, 2020) that where governmental funding is focused on other areas of science international grants could be used to encourage research into fields such as mangrove carbon research, but where funding is made open to international researchers it may still only encourage helicopter research with little benefit locally, as reported by Minasny et al (2020).

The SEM found that the pattern of distribution in mangrove carbon research showed geographical bias in the current literature that would result in several regions where mangroves exist needing to use non-specific data for the region to estimate AGBC. This extends to the common mangrove allometric equations for calculating AGB and the generalised carbon values for AGBC which are often based on literature reviews and regional biomass research. In the literature search for chapter 2 only 6 papers out of 175 were found to include primary data on AGB as well as carbon content of mangroves at the site of the study (Mitra et al, 2011; Ray et al, 2011; Kathiresan et al, 2013; Bulmer et al, 2016; Owers et al, 2018; Rozainah et al, 2018). But with all the redone AGBC estimates produced using generalised carbon values proving significantly different from the original estimates calculated with site-specific and often species-specific data, the reliance of the remaining collated papers on generalised values presents a potentially significant error in the current literature. Furthermore, out of the 6 papers providing both AGB and carbon data, 3 were from India with the remaining 3 coming from Australia, Malaysia and New Zealand. The small number of studies and the concentration in the Indo-West Pacific is not reflective of the diversity of mangrove species or the differences in the environmental conditions between the regions where mangroves are present (Cameron et al, 2021). In Rodrigues et al (2014), studying mangroves in Brazil, the use of generalised carbon content values such as those in the IPCC guides were found to lead to significant deviations in AGBC estimates. Since this study was published, at least 3 papers have cited the site and species-specific carbon content values produced by Rodrigues et al (2014) for use in their own studies in Brazil, which may still result in deviation from the true carbon content of the study sites as there was little exploration of the potential regional variations in factors such as hydrology, precipitation, or vegetation structure (Santos et al, 2017; Ferreira et al, 2019; Virgulino-Júnior et al, 2020).

In chapter 3 it was shown that the use of the common equations for calculating AGB of mangroves resulted in significantly different estimates than when species-specific equations were used. The range of AGB values for the plots at the Vester field station were between 168.36tha and 410.29tha, with the species-specific equation giving the lowest estimate and the common equations giving estimates of 171.97tha for the correct Chave et al (2005) equation, 285.61tha for the incorrect version and Komiyama et al (2005) producing the largest estimate at 410.29tha. The significant variations could be caused by multiple factors. The researchers who develop these equations also often rely on small sample sizes that may not be representative of the ecosystem (Muukkonen, 2007; Xing et al, 2019). Before measurements are even taken, mangrove trees with structures such as knots or hollow areas may be excluded from the study, reducing the accuracy of the equations when applied to less cosmopolitan forests (Henry et al, 2010). Taking field measurements for AGB or carbon stock measurements are incredibly labour, cost, and time intensive due to issues traversing mangroves and setting up equipment so many equations rely on 3 factors: DBH, height and wood density. It is only in the last 25 years that DBH has become more standardized with measurements taken from either 1.3m or 1.4m (Réjou-Méchain et al, 2019). This study used the more common measurement of 1.3m. As a result of low sample sizes many equations are based on data with low ranges of DBH, with the combined range for the equations used in this study between 0.5cm-42cm. The other most common factor in designing the mangrove biomass equations is wood density. The wood density of a mangrove has been found to vary due to environmental factors such as soil fertility, humidity and light availability, and can vary between individuals of the same species (Yuen et al, 2016; Réjou-Méchain et al, 2019). This variation within a species is often overlooked in favour of using a mean value often recorded in databases or taken from previous literature.

The last variable used for some AGB equations is height. The taking of height measurements has its own problems due to the significant difference in heights taken using clinometers and the height pole in the fieldwork for AGB in this thesis. Whilst a measuring pole was found to produce measurements much closer to the total height of the trees in the plots, it was physically taxing to use and carry into and out of the field. But the use of the clinometer was found to be significantly different and clearly inaccurate once the accompanying calculations were done. One tree in plot A6 was measured as 12.1m tall using the height pole, but only 4.2m using the clinometer. The clinometer needs measurements of angle to the top of the tree from DBH as well as distance from the tree that this angle is taken, so if there is little canopy foliage as was found after the site was hit by Hurricane Ian the top of the tree is more visible and less distance is needed to observe the treetops. Whilst generalised equations for calculating AGB have been a feature of the literature for several decades now, very few papers have shown examples using field data of how those equations



may result in different estimates of biomass. Many areas of forestry have deemed them a source of error for different forest habitats, and it is clear from the results of this chapter that the accuracy of mangrove AGB estimates are also impacted by their use.

Whilst the direction of AGB measurements in mangrove forests turns towards use of remote sensing and LiDAR it is important to consider the reference data that is used to calibrate the models used (Olagoke et al, 2016). Particularly in forests with a high density of trees it is difficult to retrieve the ground data needed for calibration and to identify individuals where the remote sensing algorithm is based on crown delineation due to the overlap often found in mangroves (Yin and Wang, 2019). It is important for improvements in remote sensing accuracy for mangrove forests to improve estimates of AGB on the ground to assist in creating more algorithms for specific regions that will provide estimates that can be used for schemes such as emission reduction projects.

The final factor that can introduce error discussed in this thesis was the use of generalised carbon content values. The carbon content of the mangroves averaged 48.96%. When compared to estimates for the Vester site using the site and species-specific carbon content values this was not significantly different, but it was high compared to many of the generalised carbon values found in the literature and compared to the specific estimates of carbon calculated (40-50%). Only 1 generalised carbon value was found to not result in a significant difference in the AGBC estimate from the site-specific average as it was only 0.04% higher at 49% than the site value. Of 3 previous carbon values used for Florida, the carbon content at Vester was most similar to the results of Simpson et al (2017) who found carbon on the East coast measured at 48%, but results of AGBC using the 44% suggested by the unpublished literature reviews and datasets of Ewe et al (2006) and Bouillon et al (2008) of 44% produced greater underestimation of the AGBC of the site. Both overestimation and underestimation were found in chapter 2 when site-specific carbon content was tested against the generalised carbon values as well, showing a consistent pattern of error where generalised carbon content values were used without testing against the site and species present. This has been shown in papers from countries such as Brazil, Australia, and New Zealand, but has previously not been shown in studies from the USA (Rodrigues et al, 2014; Bulmers et al, 2016; Owers et al, 2018). The data collected in chapter 2 also shows that even on a regional scale carbon can vary within a country as the range of site-specific carbon values from India ranged over the 4 studies included from 42% to 45.2%, demonstrating further proof that even within one country generalised values could create significant error in AGBC estimates (Ray et al, 2011; Mitra et al, 2011; Mitra et al, 2012; Kathiresan et al, 2013). In conclusion, there are multiple sources of error introduced to mangrove AGBC calculations through the use of common AGB equations and generalised carbon content values that are not representative of global mangrove forests,

compounded by a further lack of research into whole species and regions of mangrove forests. For improvements to current and future estimates there must be a focus on collecting site and species-specific data from currently understudied countries, as well as more data transparency on the sources of generalised values.

### Limitations of the studies

Whilst the SEM initially returned a large amount of data, there were limits to the study selection that could impact the overall scope of the research. The first is that only 2 databases were interrogated. Whilst Proquest and Web of Science provided many papers there will be others on different databases or exclusively in journals which will have been missed. Proquest also would not allow more than 10000 papers to be exported from a search therefore several languages and types of grey literature were excluded from the search. The languages excluded were French, German, Chinese, Polish, Russian, Indonesian, Turkish and Czech. The 2 most likely to have caused exclusion of studies from the current literature in the dataset would be Chinese and Indonesian, however the lack of understanding of these languages would have required use of google translate which may not have yielded accurate translations of the research. Some of the literature excluded also included data reports and pre-prints which also may have resulted in missed studies but very few studies were removed from the original pool when the literature type filter was included.

Chapter 2 on the other hand had the issue of much more limited data than that of chapter 1. Despite going through 175 papers there were only 10 with primary data on both AGB and carbon content of the mangroves at the study site. These 10 studies had a total of 141 AGB estimates but the number in each study ranged between 2 and 48, resulting in a small sample size for the comparison of carbon content values. The studies were also all located in the Indo-West Pacific region of the world with 4 Asian countries as well as Australia and New Zealand. This limits the application of the results to other regions of the world as many of the generalised carbon values do not state where they were developed or from what biomass data. To make global comparisons it would be important to collect larger volumes of data particularly from the continents of Africa and North and South America which were completely absent from the analysis in this chapter due to lack of data.

The fieldwork done for chapters 3 and 4 was done over an area of 500m<sup>2</sup> in Southwest Florida. Whilst many mangrove systems around the world follow zonation patterns, the researchers from Florida Gulf Coast University who work in this area have previously stated in personal communications that the mangroves at this site do not fit within the current models of zonation,

potentially due to the effects of disturbance at the site, which may make the results of the study difficult to compare to other systems (Lugo and Snedaker, 1974, Conrad, 2022). The mangroves of Florida also grow in different stand heights and species densities, with forests in the North of the state being primarily made up of *Avicennia germinans* due to their frost tolerance. For further investigation of the accuracy of the common equations and generalised carbon content values there would need to be studies done at different latitudes and the East coast of Florida. Whilst the sample size for the AGB and AGBC calculations was large compared to the samples of trees used to produce the equations, the sample was only 129 trees of which the majority were *Rhizophora mangle*. If the common equations were designed using species characterised by lower wood densities, the high numbers of *R.mangle* with a wood density could explain why there is such variation between the estimates created with common equations and the species-specific equations.

In order to compare 2 common methodologies for the measurement of tree height clinometer height data in April 2023, at the same time of year and on the same trees as those measured in 2022. But there may have been some growth or loss of top biomass, particularly after the hurricane hit and it may be that some of the trees may have lost biomass at the top of trees which could have made the clinometer measurements more accurate for the current height of the trees. However, on inspection of the plots there was little evidence of branch damage which could impact the heights of the trees and many of the clinometer height measurements were different to the heights taken using the telescopic pole by several meters, making this an unlikely issue.

The element of the equations that is most likely to create issues with accuracy is DBH. The DBH is the most commonly used tree measurement used in biomass equations along with wood density, however many equations are developed with small sample sizes and low ranges of DBH. The Chave et al (2005) common equation was developed from 2 studies with 84 trees total and 4 species, the Komiyama et al (2005) common equation sampled 104 trees comprising of 10 species of mangrove and the Smith and Whelan (2006) species-specific equations were created using a total of 32 trees (8 *A.germinans*, 14 *R.mangle* and 10 *L.racemosa*). The study by Komiyama et al (2005) had the largest variations in DBH in their sample with a range from 5.1-48.9cm. The DBH measurement ranges recorded in the studies used for the Chave et al (2005) equation were 1.3-40.7cm and 6.6-42cm (Imbert and Rollett, 1989; Fromard et al, 1998). But the species-specific equations designed by Smith and Whelan (2006) were only created with trees with a DBH range of 0.5-21.5cm between the 3 species. This is a limited range of DBH, especially as 13 of the 19 *A.germinans* trees included in this study had DBH measurements over 22cm and combined with the small sample size, this does introduce doubt over the accuracy of estimates created with this equation. It may prove interesting comparison in the future to compare other species-specific estimates to these equations. However,

to create a measurement to compare them to there would likely need to be destructive sampling which goes against many researchers' goals of conservation of the mangroves themselves and the carbon they store.

The other limit of the study is the C% collected for the Vester field site itself. The data for the site-specific carbon data was collected in Spring 2019. The original intention was to collect the data for AGB and AGBC in the Spring of 2020 and at least one other fieldwork season but then the COVID pandemic shut down travel for over a year. Whilst the site and species sampled for carbon were the same as in 2019, there could have been changes in AGBC missed due to the use of the previous carbon values gathered for the site.

In the October of 2022, hurricane Ian hit Bonita Springs directly and the area of mangroves studied during this research did take damage. Reports from the researchers at Florida Gulf Coast University included that the storm surge that hit the area was 10ft and a large volume of sediment was deposited over the site, as well as large pieces of debris such as a canoe. Other items found in the branches of nearby mangroves included cars and boats. Out of 126 live trees measured for AGB and AGBC in the thesis, only 20 were alive when we returned in April 2023 for additional height and DBH data for comparisons, with most trees in the mid to late stages of dying or already dead. As a result, further testing of the results of this study would not be possible at the original site and would need to include research from other sites not hit by Hurricane Ian. On the other hand, the study conducted in this thesis gives a good framework to potentially measure the changes of AGB and AGBC as a result of hurricane damage and record regeneration of the mangroves at the Vester site. Further testing could be done on the dying trees to study if carbon content of the biomass changes as the tree dies and whether there is variation between the 3 species present. Seedling plots could be studied for species composition could be used to estimate the number of seedlings that manage to establish with the removal of the canopy and if there is a shift in species composition between shade tolerant *R.mangle* and the shade intolerant *L.racemosa* and *A.germinans* seedlings and how this may impact the future AGBC of the site due to differences in wood density and environmental factors altered by the hurricane such as hydrology and salinity.

#### Contribution to research and future applications

As countries work to reduce carbon emissions and reduce the impacts of climate change, particularly along the world's coasts, understanding the carbon potential in the AGB will be important for countries interested in carbon payment schemes such as REDD+ which have recently begun to

include mangrove forests where emissions estimates meet the required quality of data. The SEM produced in chapter 1 shows a comprehensive view of current mangrove research and the places that are currently understudied. This map will help to demonstrate the lack of research particularly in islands and the African continent, even though 24 of the countries in the SEM dataset currently work on REDD+ projects (Forest Carbon Partnership Facility, 2023). Introducing mangrove assessment could increase the area of forest protected for the future whilst providing an outside source of income that could support local populations whilst finding sustainable ways to continue traditional practices and industries (Ajonina et al, 2014; Aziz et al, 2015; Ahmed and Glaser, 2016; Aziz et al, 2016). REDD+ may also become an option for many island nations to expand on with the inclusion of mangroves with the funding and support to produce accurate measurements of AGB and carbon.

The SEM provides a basis as well to study other potential biases or influencing factors on mangrove research topics. Potentially there may be patterns in the gender split of research if there is a dominance of one gender for topics such as soil carbon or research in particular regions that could be further explored, or there could be a lack of inclusion in certain regions or topics. Other potential expansions of the research could be to open it to other languages or to investigate sources of external funding that may show patterns in distribution of international grants and funding compared to money coming from local organizations or governments. Metrics could also be designed to investigate if the journal published may also help to further investigate potential stumbling blocks for researchers from lower income countries that may prevent their work being viewed globally, such as publishing costs or rate of subscription by higher education institutions.

The analysis of the use of common equations for AGB and generalised carbon content for AGBC shows that error can easily be introduced through the use of non-specific values. Previously there has been no published studies from the USA about this topic despite producing 15.3% of the papers in the SEM dataset. As a result, this thesis becomes a part of a small but growing area of mangrove carbon research containing studies on this potential error, primarily from Oceania and South America, as well as studies on other tropical ecosystems (Rodrigues et al, 2014; Bulmer et al, 2016; Owers et al, 2018; Chave et al, 2019). As the number of studies on mangrove carbon increase as shown in chapter 1, it is important for more studies to be conducted in different countries with a range of environmental conditions to continue to test how the use of these generalised factors impact the accuracy of AGBC stock estimates.

Due to their importance in the expansion of remote sensing use, it is important that more funding is made available to take ground measurements to test for variations in factors such as wood density,

height, and DBH that AGB equations are based off, with as much standardization of the methodology as possible in a difficult environment like mangrove forests. As much as destructive sampling is against conservation goals and difficult to execute, where possible it may be beneficial to do more testing of AGB equations against sampled biomass, either where mangroves are dying or dead from storm damage, or through trees collected from areas that have been planted for research or silviculture. Those developing future species-specific equations should also take into account variation within species. Many trees in the genus *Rhizophora* can be multi-stemmed but there are few standardized ways of estimating AGB for these individuals or for how to include them in AGB equations being used. Many species also have wide geographical ranges and little research has been done to test potential variations in important factors such as wood density between these sites and if even the use of a species-specific equation may result in incorrect reporting of AGB. For example, if a researcher on the West coast of Africa wanted to measure AGB of *R. mangle* trees, would an equation designed using *R. mangle* in Florida be appropriate for use or would a new one specific to the country or region need to be designed?

Overall, the use of common equations for AGB and generalised carbon content values has introduced unknown levels of error into mangrove carbon data around the world. To increase the accuracy of future estimates of AGBC for projects on emissions reduction or carbon sequestration there needs to be a renewed focus in current research in ground-truthing these values and proving that they are fit for use. From this work, the use of generalised carbon content values needs to be investigated in more regions to test if these values cause more overestimation or underestimation in particular areas of the tropics. Testing at sites should be done to compare whether other countries see significant differences in AGBC when using site-specific values, especially where there is potential to set up carbon emission reduction schemes. This could even be done over several sites in the same country to test effects of different forms of degradation or pollution on AGBC stocks and how these may change with site restoration measures. In the future with further investigation of site or species-specific carbon values, more mapping of the literature and primary data could be used to illustrate variation in AGBC of mangroves between and within countries that could then be used as a resource for choosing an appropriate carbon content value from existing literature for the site where the data exists. Further mapping would also allow researchers to estimate the volume of carbon that may be released with further deforestation, either through burning of trees from human use or wildfire events, or from loss of carbon sequestration with removal of mangrove forests.

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