Blue Carbon in Cairns Airport

Blue Carbon Lab

DEAKIN UNIVERSITY

Disclaimer

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The project occurred on Yirrganydji land, and we would like to thank Yirrganydji People for welcoming us in their Country.

The whole team would like to thank Lucy Friend from Cairns Airport for establishing this project and bringing the Dawul Wuru and Blue Carbon Lab together. The field campaign had a great success thanks to Lucy's planning, and her dedication to this project.

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Acknowledgement of Country

Deakin University acknowledges Aboriginal and Torres Strait Islander peoples as Australia’s first peoples, and the Yirrganydji People as the Traditional Owners and custodians of the land and sea where this research focused.

We pay respect to all Aboriginal and Torres Strait Islander community Elders past and present, whose knowledge and relationships to Sea Country are fundamental to the health of the coastal environment and the success of any strategy to protect and rehabilitate blue carbon ecosystems.

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Executive Summary

Cairns Airport contains considerable areas of blue carbon ecosystems: saltmarsh, seagrass and particularly mangrove forests. These ecosystems are extremely effective at sequestering and storing organic carbon, therefore they are important nature-based solutions to climate change mitigation. This report aims to quantify and verify the carbon storage and sequestration capabilities of the mangrove forests in the Barron River (Cairns Airport) in order to inform and provide opportunities for their management, protection and potential enhancement. As a result, this allows Cairns Airport to demonstrate its commitment to sustainability, climate change mitigation and environmental conservation.

To quantify blue carbon stocks in the region, an initial spatial assessment of blue carbon ecosystems in the area, including temporal changes in mangrove distribution, was conducted. This was followed by an estimation of above, belowground and soil carbon stocks. This data was collected through mangrove surveys following the international standards for blue carbon sampling and established allometric equations for above and belowground biomass. In addition, soil cores were collected across the site and later analysed for their carbon stock and carbon accumulation rate.

Cairns Airport is home to 302 ha of mangrove forest, which we estimate stores approximately 123,268 tonnes of organic carbon within its plants and soils (up to a depth of 1 m), equivalent to 452,394 tonnes CO_2e. Carbon sequestration rates were on average 1.84 ± 0.11 tonnes C $ha^{-1} yr^{1}$, which means that these mangrove forests can sequester a potential 2,042 tonnes of CO_2e per year, equivalent to 13% of Cairns Airport's operational emissions in 2019.

This project delivered the first carbon stock and sequestration data for this site, and several recommendations of actions to protect, manage and potentially enhance these blue carbon ecosystems. These priority actions should continue to engage and support the land management efforts of the Yirrganydji Indigenous Land and Sea Rangers from the Dawul Wuru Aboriginal Corporation. In Box 1 (page 25), Ashlyn Skeene, a Yirrganydji woman, describes the Yirrganydji Peoples' perceptions on the value of mangroves from Barron River.

Graphical summary of key findings

Mangroves' blue carbon in Kukujum

Mangroves from Kukujum
sequester approximately
2,042 tonnes CO_2e yr^{-1}

Mangroves

Area extent
302 ha

Above ground stocks
98 tonnes C ha^{-1}

Below ground stocks
29 tonnes C ha^{-1}

Soil carbon stocks
280 tonnes ha^{-1}

Saltmarshes

Area extent
18 ha

SOC stocks*
281 tonnes ha^{-1}

Seagrasses

Area extent
395 ha

SOC stocks*
84 tonnes ha^{-1}

*Data from Costa et al. 2023. Science in the Total Environment

Glossary and Acronyms

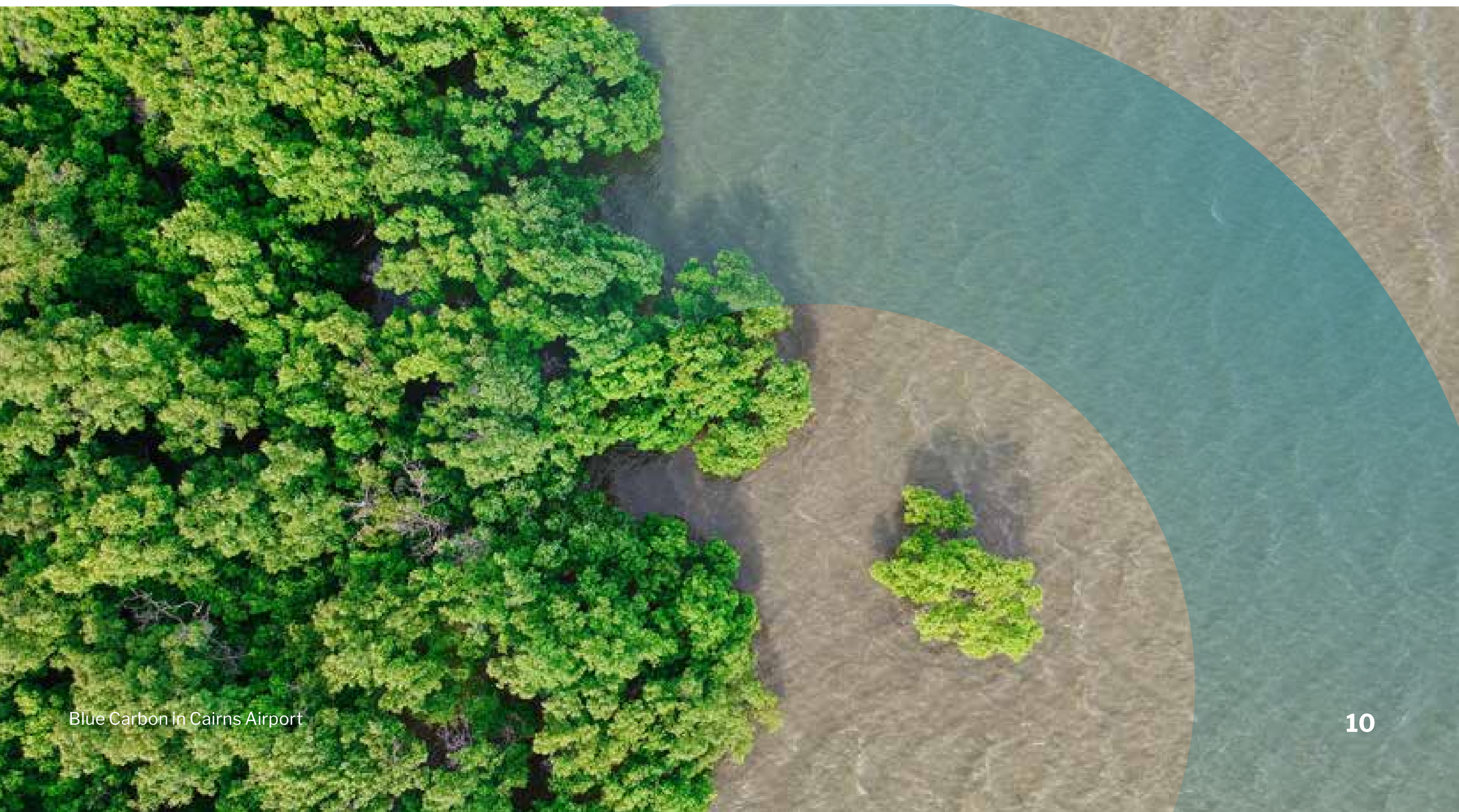
Term	Acronym	Definition
Aboveground biomass	AGB	Biomass contained within the plant's living leaves, branches, stems or aerial shoots. Values usually reported in ton DW ha^{-1} for mangroves and g DW m^2 for seagrasses.
Aboveground carbon	AGC	Organic carbon stored within the plant's AGB. Values reported in ton C ha^{-1}.
Allometric equations/ models	-	Models for mangrove species are usually based on tree height, diameter at breast height (DBH). Equations can be species- or site-specific.
Belowground biomass	BGB	Biomass contained within the plant's living roots and rhizomes. May include necromass (litter or any detrital materials). Values usually reported in ton DW ha^{-1} for mangroves and g DW m^2 for seagrasses.
Belowground carbon	BGC	Organic carbon stored within plant's BGB. Values reported in ton C ha^{-1}.
Blue Carbon	-	Carbon captured and stored by marine and coastal ecosystems.
Carbon dioxide equivalent	CO_2e	Unit of measurement used to standardise the climate effects of various greenhouse gases. The conversion factor 3.67 is used for organic carbon, which represents the molecular weight ratio between CO_2 and C.
Carbon:Nitrogen elemental analyser	CN analyser	A lab instrument used to measure carbon and nitrogen elemental concentrations in a given sample (such as soil)
Diameter at breast height	DBH	Forestry measure in which the diameter of the tree trunk is recorded at 137 cm from the ground. Values reported in cm and often used in allometric equations.
Greenhouse gases	GHG	Gases that absorb and emit radiant energy within the thermal infrared range, which can cause the greenhouse effect [e.g., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)]
Nationally Determined Contribution	NDCs	Emission reductions commitments that countries need to submit to the United Nations Framework Convention on Climate Change (UNFCCC) under the Paris Agreement.
Soil organic carbon	SOC	Organic carbon stored within the soil/sediment. Values reported in ton C ha^{-1}. SOC is usually reported down to a specific depth (e.g., 100 cm depth).
Soil organic matter	SOM	Organic matter is any living or dead animal and plant material.
Standard error	SE	Standard deviation of its sampling distribution or an estimate of that standard deviation.

Introduction

Blue carbon ecosystems (e.g., mangrove forests, saltmarshes, and seagrass meadows) are highly efficient at sequestering and storing organic carbon, which make them important nature-based solutions to climate change mitigation and adaptation. From these ecosystems, mangroves are recognised as one of the most effective carbon sinks, with a single hectare storing on average 386 tonnes of carbon (IPCC, 2014) and potentially sequestering 1.74 tonnes of carbon per hectare per year (Alongi, 2014). Overall, mangroves capture and store carbon 30-50 times faster than terrestrial ecosystems, locking away carbon in their soils for millennial timescales (Duarte et al., 2013; Macreadie et al., 2021; Mcleod et al., 2011).

In addition to acting as an efficient carbon sink, mangroves also provide other key ecosystem services to coastal communities, such as biodiversity support, fisheries enhancement through the provision of nursery habitats, nutrient uptake, and coastal protection against flooding and erosion (Barbier et al., 2011; Carnell et al., 2022; Friess et al., 2020; Himes-Cornell et al., 2018). These ecosystems occur in approximately 36 million hectares around the world's coastline (Macreadie et al., 2021), and have been recognised for their role in mitigating and adapting to climate change (Duarte et al., 2013; Macreadie et al., 2021). In this sense, mangroves have been identified as a key natural climate solution, with their conservation and restoration playing an important role as a cost-effective option to avoid carbon emissions and/or enhance carbon sequestration, respectively (Macreadie et al., 2021).

Australia is the world's largest contributor to blue carbon wealth (US$22.8 ± 3.8 bn yr^{-1}; Bertram et al., 2021), with 5%-11% of global blue carbon stocks (Serrano et al., 2019). Within Australia, Queensland



has the largest blue carbon area with 40% of tidal marshes and mangroves, 65% of the seagrass and almost half (48%) of all the blue carbon stocks in Australia (Serrano et al., 2019). However, coastal wetlands have been extensively modified for agricultural, urban and industrial development (Waltham and Sheaves, 2015). Recent estimates provided some positive signs in the disturbance rates of these ecosystems (<0.1% net loss during 2005-2013; Adame et al., 2019). Terrestrial protected areas, marine parks and areas of matters of State environmental significance play an important role to protect mangroves in Queensland (Costa et al., 2023). However, we can expect that future conditions in temperature, rainfall and sea level are likely to significantly alter their distribution and the carbon sequestered and stored in these ecosystems (Finlayson et al., 2013).

Recent blue carbon assessments in Queensland focused on large scale estimates of soil carbon stocks, showing that coastal wetlands in Queensland hold approximately 569 million tonnes of organic carbon (C; Costa et al., 2023), which is within the range previously estimated from 300 million tonnes of C (Young et al., 2021) and 766 million tonnes of C (Serrano et al., 2019). Mangroves alone represent 30% of this total, ranging from 95 to 1,555 tonnes C ha^{-1} (average = 313 tonnes C ha^{-1}). Furthermore, another study focusing only on the Great Barrier Reef catchments, which comprises 25% of Queensland's mainland area, estimated that 137 million tonnes C is stored only within blue carbon ecosystems in this region (Costa et al., 2021). Despite the importance of large-scale assessments, we still lack information for mangrove forests at local scale to help better understand the carbon storage variability at finer resolution, while also informing on-ground works for blue carbon protection or restoration.

Queensland's mangrove forests are comprised of > 40 species and cover approximately 510,333 ha

(Department of Environment and Science, 2019a) distributed throughout the coastline. In Queensland, the Cairns Airport region contains substantial quantities of blue carbon within its mangrove forests, which is playing an important role in carbon sequestration, but this has not been verified and quantified yet. These mangrove forests therefore have the potential to provide opportunities for Cairns Airport to demonstrate sustainability through their management, protection, and enhancement of blue carbon stocks within the airport. This is likely to occur through a combination of demonstrating how current management practices are keeping these carbon sinks protected (e.g., through engagement of Yirrganydji rangers) as well as new opportunities to improve blue carbon management. Therefore, this study aims to evaluate and quantify the potential contribution of mangroves within the limits of the Cairns Airport by 1) developing an initial spatial assessment of blue carbon ecosystems in the airport area, including an analysis of temporal change of mangrove distribution using existing multi-decadal change in their distribution in Queensland (Lymburner et al., 2020); and 2) estimating soil, below- and aboveground carbon stocks in mangroves in the airport area.


TOP
B

Methods

Study Area

Cairns is a city in northern Queensland situated within the Wet Tropics Natural Resource Management Region (NRM), which stretches from Townsville in the south to Cooktown in the north (**Figure 1**). The region is known for its high rainfall, up to 7000 mm per year in some locations (Nott, 2003), and characterised by a series of mountain ranges that run generally parallel to the coast and are largely covered by rainforest, while the Great Barrier Reef is situated along the coastline (Bohnet and Pert, 2010; Williams, 2006). This area possesses tremendous natural and cultural value and hosts the highest levels of biodiversity in Australia, with extensive coastal areas of mangroves, saltmarshes and seagrass that provide critical habitat for numerous species of birds, fish, insects and other flora and fauna. The mangrove forests within the Cairns region, including the Barron River and the Cairns Airport, are highly diverse (> 40 species) and provide a variety of ecosystem services to coastal communities.

Table 1: Detailed information for the mangrove survey campaign conducted in Cairns during May 2022, including GPS coordinates for each sampling location for aboveground biomass, soil stocks and age dating.

Sampling site	Aboveground biomass		Age dating		Soil carbon stocks		
	Lat	Long	Lat	Long	Core ID	Lat	Long
1			-16.88706	145.76482	1A	-16.88714	145.76484
					1B	-16.88712	145.76505
					1C	-16.88698	145.76487
					1D	-16.88702	145.76495
					1E	-16.88687	145.76486
2	-16.87760	145.77481	-16.87778	145.77489	2A	-16.87759	145.77465
					2B	-16.87761	145.77502
					2C	-16.87773	145.77496
					2D	-16.8777	145.77495
					2E	-16.87765	145.77487
3	-16.87826	145.77197	-16.8785	145.77196	3A	-16.87903	145.772
					3B	-16.87902	145.77197
					3C	-16.87902	145.77197
					3D	-16.87899	145.77199
					3E	-16.87906	145.77191
4	-16.87897	145.76722	-16.87906	145.76732	4A	-16.87903	145.76726
					4B	-16.87902	145.76736
					4C	-16.87902	145.76724
					4D	-16.87899	145.76744
					4E	-16.87906	145.76738

Table 1: Detailed information for the mangrove survey campaign conducted in Cairns during May 2022, including GPS coordinates for each sampling location for aboveground biomass, soil stocks and age dating.

Sampling site	Aboveground biomass		Age dating		Soil carbon stocks		
	Lat	Long	Lat	Long	Core ID	Lat	Long
5	-16.87703	145.77379	-16.87679	145.77373	5A	-16.87697	145.77367
					5B	-16.87682	145.77371
					5C	-16.87701	145.77378
					5D	-16.87688	145.77376
					5E	-16.87678	145.77375
6	-16.86959	145.75806	-16.86962	145.75815	6A	-16.86962	145.75807
					6B	-16.8696	145.75821
					6C	-16.86962	145.75817
					6D	-16.86965	145.75807
					6E	-16.86956	145.75824
7	-16.861275	145.75297			7A	-16.86108	145.75323
					7B	-16.8612	145.75328
					7C	-16.86115	145.75323
					7D	-16.86109	145.75314
					7E	-16.86112	145.75322
8	-16.87871	145.76536			8A	-16.87877	145.76537
					8B	-16.87872	145.76535
					8C	-16.87881	145.76537
					8D	-16.8789	145.76538
					8E	-16.87879	145.76538
9	-16.88016	145.76497			9A	-16.88021	145.76501
					9B	-16.88012	145.76486
					9C	-16.88026	145.76486
					9D	-16.88015	145.76517
					9E	-16.88036	145.76511
10	-16.88140	145.76257			10A	-16.88156	145.7627
					10B	-16.8814	145.76257
					10C	-16.8816	145.76259
					10D	-16.88144	145.76263
					10E	-16.88157	145.76268

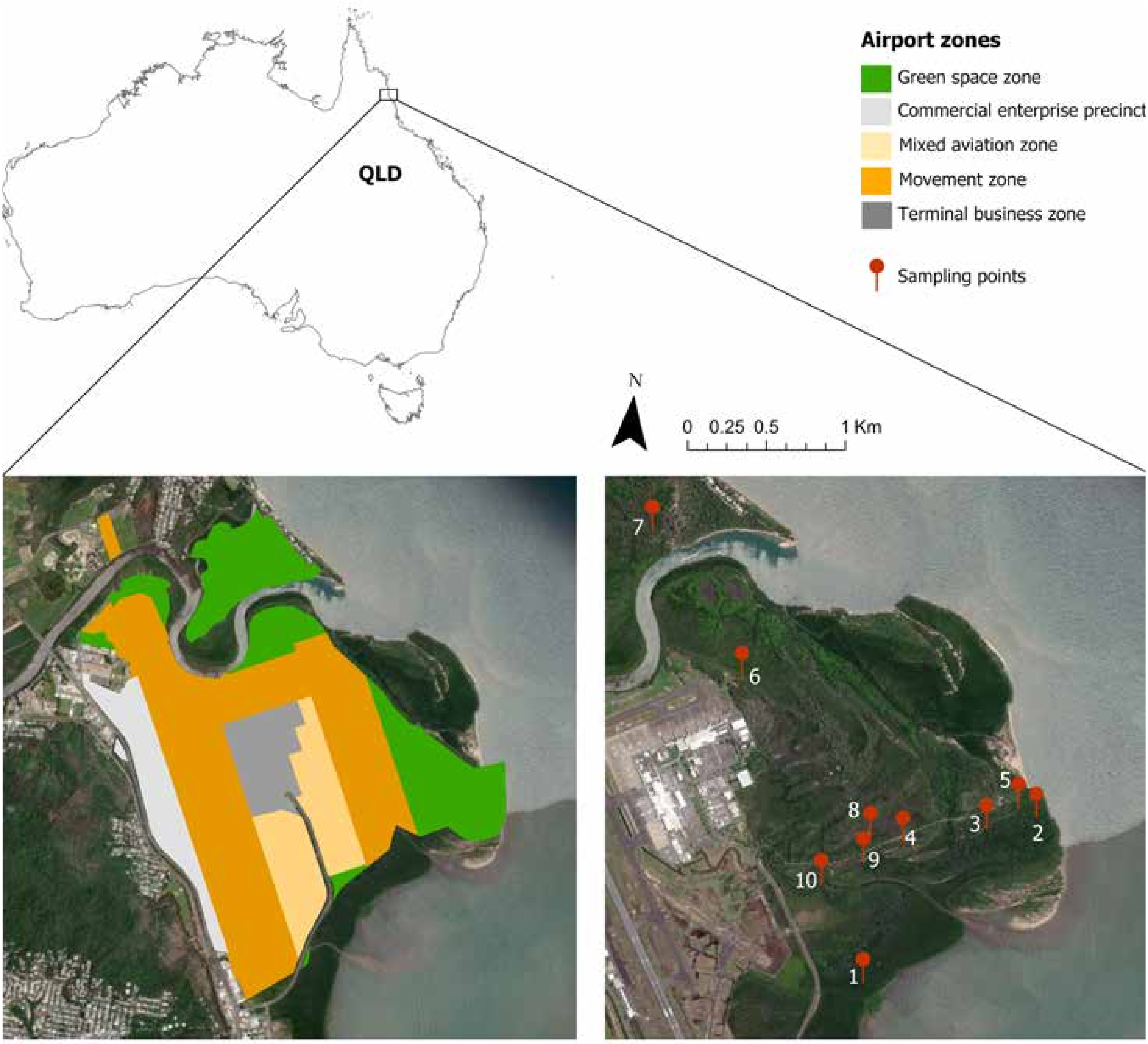


Figure 1: Detailed maps showing the location of Barron River and the Cairns Airport in Queensland, its different land use zones, and the location of the sampling points.

Mangrove survey

Following the international standards for blue carbon sampling (Howard et al., 2014; Kauffman and Donato, 2012), we sampled mangrove forest characteristics at each sediment sampling site with a 10 × 10 m vegetation survey plot. In each plot, all mangrove trees higher than 1.5 m height (smaller trees were considered “saplings”) were identified and a sub-sample of 10 trees were surveyed for tree height and diameter at breast height (DBH, cm).

Field measurements collected for mangrove trees (i.e., tree height, DBH) were then used within species-specific allometric equations collected from the literature (**Table 2** and **Figure 2**) to estimate the aboveground and belowground biomass (Kg DW ha^{-1}; DW = dry weight). At each sampling point, we estimated the mangrove tree biomass per area (tonnes DW ha^{-1}) by summing the values for all trees within the plot and then adjusting it by plot size. Then, values for above- and belowground biomass were transformed to carbon stocks (tonnes C ha^{-1}) using the conversion factors of 0.47 and 0.39, respectively (Kauffman and Donato 2012).

Table 2: Species-specific allometric equations and parameters used to estimate aboveground mangrove biomass (Kg DW ha^{-1}). We used the general equation proposed by Komiyama et al., (2008) to estimate the belowground biomass (Kg DW ha^{-1}). DBH= diameter at breast height; WD= wood density; H= tree height.

Species name (common name)	AGB allometric equation	BGB allometric equation	Wood density (g cm^{-3})	References
Rhizophora spp. (red mangrove)	$0.1579*DBH^{2.593}$	$0.199*WD^{0.899}*DBH^{2.22}$	0.84	Analuddin et al., 2020; Chave et al., 2009
Bruguiera spp. (orange mangrove)	$0.186*DBH^{2.31}$		0.741	Clough and Scott, 1989; Kauffman and Donato, 2012
Xylocarpus mekongensis (cedar mangrove)	$0.1832*DBH^{2.21}$		0.7	Kauffman and Donato, 2012
Ceriops tagal (yellow mangrove)	$0.189*DBH^{2.34}$		0.88	Chave et al., 2009; Clough and Scott, 1989
Avicennia marina (grey mangrove)	$0.308*DBH^{2.11}$		0.65	Chave et al., 2009; Comley and McGuinness, 2005
Aegialitis annulata (club mangrove)	$0.251*WD*DBH^{2.46}$		0.64	Balun, 2011; Komiyama et al., 2008

Figure 2: Measurement of mangrove tree biomass in Cairns' mangrove forest during May 2022.

Soil sampling

We estimated soil organic carbon (SOC) content (%) from mangrove sediments at ten sampling sites (**Figure 1**). At each sampling site, we collected five sediment cores (1 m deep or until bedrock was reached) using a PVC pipe (5 cm internal diameter, 150 cm length) to profile the SOC content and stock (**Figure 4**). The core was manually sunk into the soil with the help of a rubber mallet, which was used to hammer the top of the core until it reached the maximum depth possible. To account for soil compaction, we measured compaction in and out (**Figure 3**) and followed the steps:

C1 = total pipe length – compaction in

C2 = total pipe length – compaction out

Compaction Factor = C1/C2

Then, the compaction correction factor was applied to the bulk density value before estimating the soil carbon stock. Each of the sediment cores were immediately sub-sampled at the top, middle and bottom section with a 30 ml syringe through the pre-drilled holes (3 cm internal diameter, 10 cm between the hole centres). The wet sediments were weighed and stored at 4 °C until transportation to Deakin University (Melbourne, Australia) for processing.

Soil accretion rates

We collected one soil core from six different sites using a PVC pipe (5 cm internal diameter, 155 cm length) to determine soil accretion rates in Cairns' mangrove forests. To compensate for the compaction (**Figure 3**), we took 6 to 10 measurements of the difference between the "inside" core depth, and actual core depth for each core. Excess parts of the pipe were cut off and both ends were air sealed and kept upright during transportation to our lab at Deakin University (Melbourne, Australia).

Soil processing in the lab

All soil samples were processed at Blue Carbon Lab's facilities in Deakin University (Melbourne/ Australia) for bulk density and SOC stocks.

The syringe core samples collected from the top, middle and bottom sections of the cores sampled in Cairns' mangroves were dried at 60ºC for 48-72 h, until they reached a constant weight. Then, we recorded their weights to calculate the sediment bulk density (g cm^{-3}) using the following equation:

$$\text{Soil bulk density (g cm}^{-3}\text{) = Mass of dry soil (g)/ original soil volume sampled (cm}^{3}\text{)}$$

We pulverized and homogenised all samples using a Retsch RM200 mortar grinder (Baldock et al., 2013) and subjected them to an effervescence acid test to identify the presence of inorganic carbon (e.g., fragments of shells). The samples containing inorganic carbon were then acidified according to the wet acidification method to quantify the

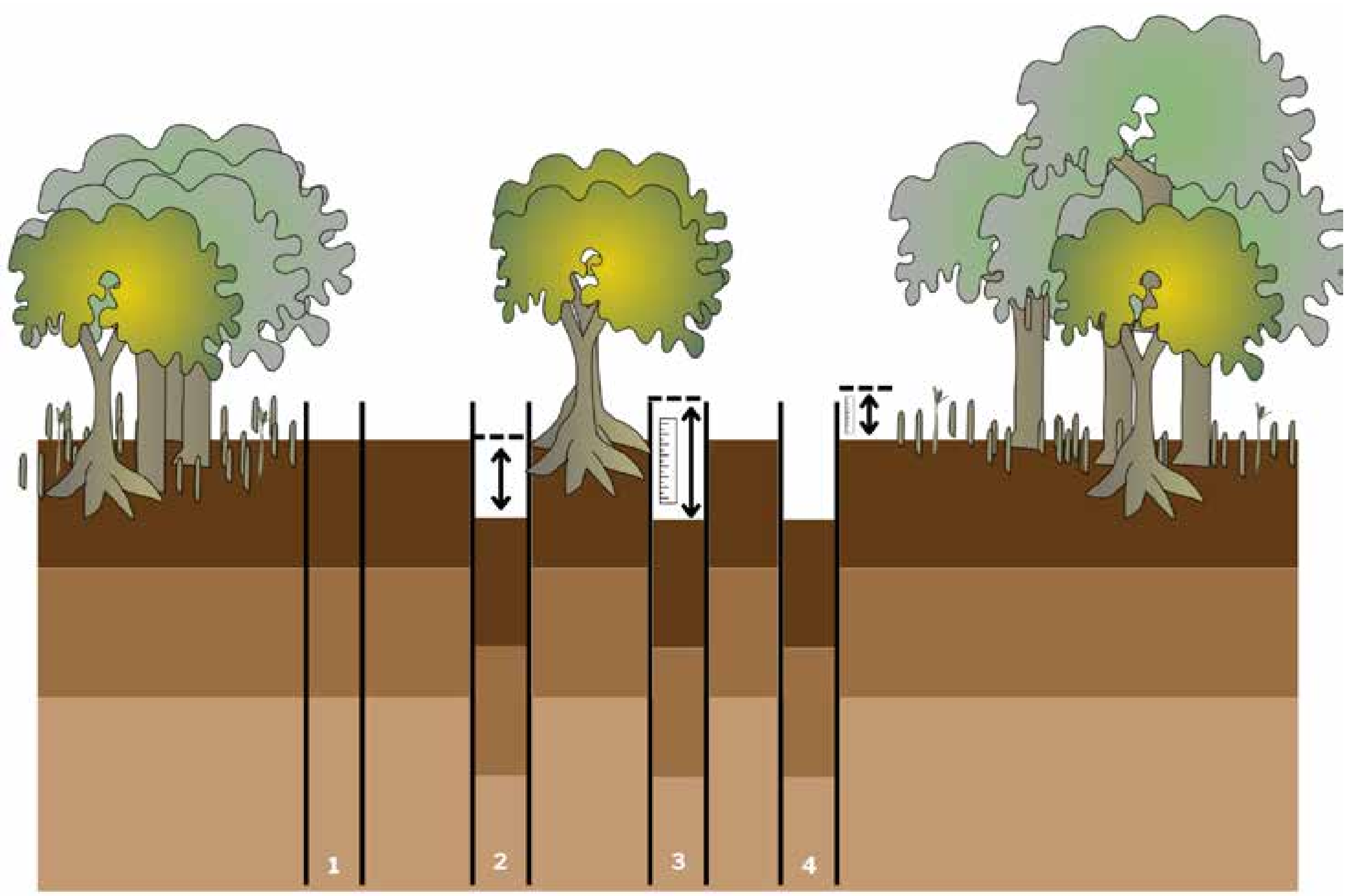


Figure 3: Schematic drawing showing how compaction was measured during the soil sampling: 1= non-compacted core, 2= compacted core, 3= measuring compaction in, and 4= measuring compaction out.

inorganic carbon fraction (Howard et al., 2014).

Soil carbon stocks

We measured the organic carbon content of samples using an EuroVector EuroEA3000 automated elemental carbon and nitrogen analyser. We used 0.5-1.2 mg Acetanilide standard (71.09% C) to calibrate the elemental analyser. Then, 5 – 10 mg of ground sediment was enclosed in tin capsules and combusted at 1,021 ^{0}C to calculate the percentage of C and N in samples. The soil carbon stock for each depth strata was calculated using the C percentage and sediment bulk density of the layer using the following formula (Howard et al., 2014; Kauffman and Donato, 2012).

$$\text{Soil C pool (tonnes ha}^{-1}\text{) of each depth section} = \text{bulk density (g cm}^{-3}\text{)} * \text{SOC\%}$$

Then, for each soil core, we determined the total soil carbon per core by summing the carbon stocks for all depth sections. In this study, we calculated carbon stocks up to 1 m soil depth to keep it consistent with the IPCC guidelines (IPCC, 2014); however, since the soil depth is known to be deeper than 15 m in some areas, we also calculated soil carbon stocks up to 3 m (i.e., conservative estimate) and up to 15 m.

Total carbon pool per sampling site

The total carbon pool for each sampling site was estimated by summing all the carbon pools: aboveground, belowground and soil. For that, each of the carbon pools was averaged across all samples and in each site. The averaged values were then summed together to obtain the total carbon pool.

$$\text{Total carbon pool per site (tonnes ha}^{-1}\text{)} = \text{average AGC pool (tonnes ha}^{-1}\text{)} + \text{average BGC pool (tonnes ha}^{-1}\text{)} + \text{average Soil C pool (tonnes ha}^{-1}\text{)}$$

Soil carbon accumulation rates

Age dating cores were extruded and sectioned in the laboratory. We followed a high-resolution subsampling strategy, which included: 1) the first 20 cm section of the core that is close to the surface was sliced at 1 cm-thick layers, 2) the 20-50 cm section was sliced at 2 cm-thick layers and, 3) the section below 50 cm of the core was sliced at 3 cm-thick layers. We dried all samples at 60°C for 48-72 h, until they reached a constant weight, which were recorded to calculate the dry bulk density. We subsampled a fraction of the dried mass to determine high-resolution soil carbon stocks as described above. We wet sieved the remaining part of the sediment through a 63-µm stainless steel mesh and dried both below and above fractions, recorded their dry weights and pulverized and homogenised the <63 µm fraction using a mortar grinder (Retsch RM200). See Gulliver et al. (2020) for a detailed protocol.

The analysis of ^{210}Pb was carried out on the fine fraction of the sediment samples (<63 µm), which were sent to the Environmental Radioactivity Laboratory (Edith Cowan University, Perth, Australia). This analysis provides an estimate of the age of the sediment at different depth by alpha spectrometry following Sanchez-Cabeza et al. (1998). ^{210}Pb-derived mass accumulation rates (g dry weight sediment cm^{-2} yr^{-1}) and sedimentation rates (mm yr^{-1}) were calculated based on the Constant Flux: Constant Sedimentation model (CF:CS; Krishnaswamy et al., 1971) and the Constant Rate of Supply (CRS; Appleby and Oldfield, 1978). The average carbon accumulation rate (CAR, tonnes C ha^{-1} yr^{-1}) was calculated by multiplying the weighted mean of soil organic carbon content (%) in each core by the mass accretion rate (MAR, g cm^{-2} year^{-1}) estimated for each dated sediment depth. The age-dating analysis was determined across the top 50 cm sediment sections from six sampling sites.

Spatial assessment

In this study, we used the Wetlands Mapping version 5.0 (Department of Environment and Science, 2019a) available for the state of Queensland to conduct a first-pass assessment of the distribution of mangroves and tidal marshes within the Cairns Airport area. Then, we used the mapped multi-decadal mangrove distribution at national level (1987-2020 from the DEA Mangrove Canopy Cover 2.0.2; Lymburner et al., 2020) to estimate changes in mangrove extent (ha) through time within the limits of the Cairns Airport. For the purpose of this study, the change analysis was conducted between the following time periods: 1987 to 1990, 1990 to 2000, 2000 to 2010, and 2010 to 2020. This analysis was limited to mangroves due to the lack of long-term change information for other blue carbon ecosystems. Furthermore, for seagrasses, we used the combination of the nation-wide Seamap Australia [version 1] (Lucieer et al., 2019) and mapped seagrass from 1984 to 2014 for the Great Barrier Reef World Heritage Area (Carter et al., 2016). All the spatial layers were projected to the same coordinate system, and all spatial analyses were conducted in ArcGIS 10 (ESRI, 2011).

Total Blue Carbon stocks

The total carbon stock for the mangroves sampled within the limits of Cairns Airport was estimated by multiplying the average carbon pool (this study)* by the total mangrove cover of the region. The mangrove area was calculated from the best available mangrove distribution maps for Queensland (Department of Environment and Science, 2019a).

$$\text{Total carbon pool (tonnes)} = \text{average carbon pool (tonnes ha}^{-1}\text{)} * \text{mangrove area (ha)}$$

Then, we used existing data on average SOC stocks for Queensland to estimate the potential carbon stocks in tidal marshes and seagrasses within the Cairns Airport: 281 tonnes ha^{-1} and 84 tonnes ha^{-1}, respectively (Costa et al., 2023).

** Due to the lack of high-resolution maps showing the distribution of each mangrove species, average carbon stocks had to be used to estimate potential total carbon stocks across the entire mangrove distribution in the Cairns Airport region. This approach is expected to produce conservative estimates, which can be updated once these maps are available.*

Figure 4: Collection of soil cores in Cairns' mangrove forests with pre-drilled PVC pipes. The sediment sub-samples were collected with use of 30 ml syringe from top, middle and bottom sections of the pre-drilled PVC pipe.

Results & Discussion

Mangrove forests within far North Queensland are highly diverse, with more than 40 species occurring within region (Duke, 2006). This ecosystem plays an important role in helping coastal communities to mitigate and adapt to climate change, with mangrove conservation particularly important to the maintenance of biodiversity and cultural values in the Barron River estuary (Cairns Airport). This project has delivered the first field campaign to estimate blue carbon stocks (e.g., soil and plant) and sequestration rates within the mangrove forest in the estuary. The Blue Carbon Lab team worked closely with the Yirrganydji Indigenous Land and Sea Rangers from the Dawul Wuru Aboriginal Corporation. This collaboration provided the rangers step-by-step guidance on the standards, methods and equipment needed to obtain high-quality mangrove plant and soil carbon data. This capacity building is key for Cairns Airport and the Yirrganydji Peoples to continue monitoring blue carbon within their land (**Box 1**).

Forest characteristics

Mangrove forests vary in their structure at different scales, and therefore, resulting in changes in the ecosystem services they provide to coastal communities (Owers et al., 2018). In this study, we assessed for the first time the forest characteristics of the mangrove forest within the Barron River estuary. Overall, we found 4 species and 2 genera were sampled during the survey campaign within the limits of the Cairns Airport (**Table 3** and **Figure 5)**. The mangrove species *Ceriops tagal* was the most abundant species in the study area, while *Aegialitis annulata* was the least abundant species (**Table 3**). Furthermore, *Xylocarpus mekongensis*, *Aegialitis annulata* and *Avicennia marina* were limited to only one sampling point, while *Bruguiera* spp., *Rhizophora* spp., and *Ceriops tagal* occurred in 5+ sampling points.

Average mangrove height varied between approximately 1 to 7 meters, with *Xylocarpus mekongensis* having the highest average tree height (**Table 3**). Despite that, the tallest sampled tree was a *Rhizophora* spp. tree.

Overall, mangrove tree density varied from 1,000 to 4,416 trees ha^{-1}, with an average value of 2,263 trees ha^{-1} (**Table 3**). Considering the different species, *C. tagal* had the highest tree density. Overall, intertidal environments are highly complex, with site-specific conditions, such as the duration and intensity of flooding, porewater salinity, and microbiome, playing an important role in determining species abundance and forest structure (Hill et al., 2021; Hurtado-McCormick et al., 2022; Knight et al., 2008; Krauss et al., 2006).

Box 1: Yirrganydji Peoples' perceptions on the value of mangroves from Kukujum

The Yirrganydji people are the Traditional Owners/Custodians of the coastal lands and waters between Cairns to Port Douglas in North Queensland, Australia. We are both coastal and rainforest bama (people), meaning we have a strong connection to both ecosystems. Our land is within the Wet Tropics Rainforest and the Great Barrier Reef areas, giving us the best of both worlds and allowing us to see the benefits and impact on each place. The area in which the blue carbon project was conducted is identified by my people (Yirrganydji people) as Kukujum (Ellie Point). This area has been occupied by our people for many years both prior to and post colonisation time. To this day, Yirrganydji people maintain connection to this area and manage it in partnership with the Cairns Airport. This is done through ongoing beach clean ups, maintenance of the tracks, cultural surveys, biodiversity surveys, compliance and biosecurity activities, and frequent visits that contribute to keeping our connection to the area as strong as it was in the past. As a Yirrganydji person, it is not seen as a job but as a sense of responsibility to keep Kukujum as clean and healthy as possible. Therefore, when the idea of the Blue Carbon Project came up, it was only right for us to first know and understand the project better, before allowing people onto our land to conduct work. Prior to the Deakin University

Blue Carbon Lab team's visit to Cairns, they were first expected to learn and understand us, as the Yirrganydji people, in which they did. Whilst working alongside Pete and his team at Deakin, the exchange of knowledge and stories from both parties made the days go faster and the work easier, even though we were in the mud and mangroves for majority of the time, it was rewarding. We gained scientific knowledge from the team and learnt a lot more about blue carbon. The team not only showed us how to take the samples and collect the data but also explained why it was done that way. The scientific knowledge mixed with our cultural knowledge just made sense, the importance of the balance of both sides increases the work being done and gives everyone a sense of pride whilst doing so. My grandfather George Singleton took part in the project, and he said that, *"It is important for us Traditional Owners to be included in this sort of stuff."* He also stated that, *"Understanding and managing our own resources is good, as the responsibility gets put back into our hands."* It was a blessing to have my grandfather there as an elder, it really helps put things into perspective and I think the Deakin team saw that as well. The whole Yirrganydji team appreciated the respect given from the Deakin University Blue Carbon Lab Team and condone their efforts in the work they did and the work they continue to do.

Ashlyn Skeene
Yirrganydji

Table 3: Detailed summary of the main forest characteristics for each species sampled in the Cairns Airport region. *Indicates species that occurred on only one sampling point.

Forest parameter	***Rhizophora* spp.**	***Bruguiera* spp.**	***Xylocarpus mekongensis* ***	***Ceriops tagal***	***Avicennia marina****	***Aegialitis annulata****
Number of trees measured	58	64	14	148	19	10
Average trunk height (m)	6.2	6.3	6.6	4	4.5	1.3
Average diameter at breast height (cm; min – max values)	17.1 (4.8 - 29.6)	11 (1.6 – 35.3)	11.8 (3.5 – 17.5)	7.4 (2.5 – 22.6)	7.8 (3.2 – 16.6)	5 (3.2 – 8.9)
Tree density (trees ha^{-1}, ± SE)	1,160 (± 531)	1,280 (± 661.4)	1,400	4,416 (± 163.3)	1,900	1,000

Figure 5: Mangrove species identified in the Cairns Airport region. All photos taken during the field campaign in May 2022.

Xylocarpus mekongensis

Aegialitis annulata

Figure 5 (cont): Mangrove species identified in the Cairns Airport region. All photos taken during the field campaign in May 2022.

Avicennia marina

Bruguiera spp.

Figure 5 (cont): Mangrove species identified in the Cairns Airport region. All photos taken during the field campaign in May 2022.

Table 4: Average aboveground and belowground biomass (kg WD tree^{-1}) per species in the Cairns Airport region (average ± SE).

Carbon biomass (kg WD tree^{-1})	*Rhizophora* spp.	*Bruguiera* spp.	*Xylocarpus mekongensis*	*Ceriops tagal*	*Avicennia marina*	*Aegialitis annulata*
Aboveground carbon biomass	141.7 (±14)	86.8 (±20.7)	57.46 (±11.5)	21 (±2.8)	22.4 (±6.6)	6.5 (±2.2)
Belowground carbon biomass	105.9 (±9.1)	55.6 (±11.6)	41.3 (±7.5)	20.4 (±2.2)	16.7 (±4.2)	5.8 (±1.7)

Aboveground biomass

Mangrove forests are highly efficient in sequestering and storing carbon, with their aboveground biomass storing more carbon than saltmarshes or seagrasses (Alongi, 2020; Fourqurean et al., 2012; Mcleod et al., 2011). Furthermore, above- and belowground biomass is influenced by specific characteristics of the mangrove forest in combination with site-specific conditions (Owers et al., 2018). In Cairns Airport, mangrove biomass and carbon stocks varied substantially among species and sampling sites (**Table 4** and **Figure 6**). Overall, Rhizophora spp. showed the highest average value for aboveground carbon biomass among different species (**Table 4**), ranging from 6.5 ± 2.2 to 141.7 ± 14 kg DW tree^{-1} (**Table 4**). In contrast, average plant biomass was lower in *A. annulata* (**Table 4**). A similar pattern was found for belowground biomass with *Rhizophora* spp. showing the highest values across species; which varied from 5.8 ± 1.7 kg DW tree^{-1} to 105.9 ± 9.1 kg DW tree^{-1} (**Table 4** and **Figure 6**).

On average, the mangrove forest within the Cairns Airport region holds 98.3 ± 6.5 tonnes ha^{-1} in aboveground carbon stocks and 29.4 ± 1.7 tonnes ha^{-1} in belowground carbon stocks. As expected, our results also show that *Rhizophora* spp. holds the highest plant carbon stocks (**Figure 6**). Based on the allometric equations used in this study (**Table 2**), all six mangrove species included hold most of their carbon stocks within their aboveground stems, branches and leaves, **Figure 6**). Furthermore, across sampling sites, #3, which was dominated by *Rhizophora* spp. (**Table 5**), showed the highest plant carbon (**Figure 5**). In this case, the higher value of carbon biomass and stocks found for *Rhizophora* spp. might be a combination of the allometric equation used in this study, site-specific conditions, and the diameter at breast height found for this species, which varied from 4.8 – 29.6 cm (**Table 3**; Clough and Scott, 1989; Hill et al., 2021). However, future studies are still needed to understand the main drivers of local variability in above- and belowground ground biomass and forest structure within the study region.

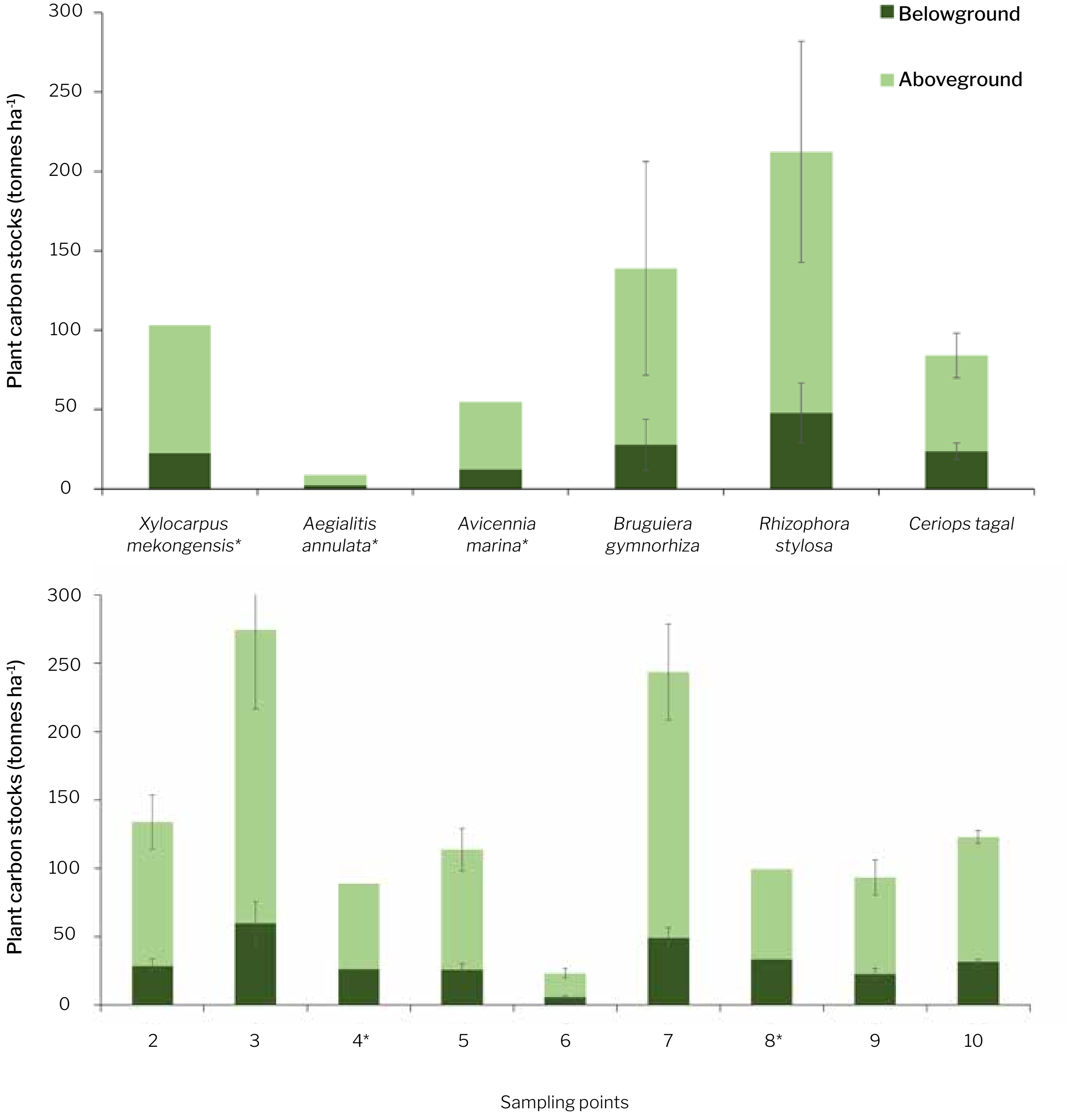


Figure 6: Mangrove plant carbon stocks (average ± SE; above- (AGC) and belowground (BGC) carbon stocks) within Cairns Airport across (a) different species and (b) sampling points (except for site 1, in which the vegetation survey was not conducted). Values for above- and belowground biomass (tonnes DW ha^{-1}) were transformed to carbon (tonnes C ha^{-1}) using the conversion factors of 0.47 and 0.39, for aboveground and belowground, respectively. *Indicates species that occurred on only one sampling point.

Table 5: List of species identified during the fieldwork campaign, showing the dominant species (*) in each plot. Here, dominant species were identified as those with > 60% of the trees registered within each plot. When the number of trees of each species was ≤ 60%, we used 'Mixed forests' (#) to classify the plot.

Plot ID	Species	Dominant species (%)
2	*Bruguiera* spp.	90.5*
	Rhizophora spp.	9.5
3	*Bruguiera* spp.	32
	Rhizophora spp.	68*
4	*Ceriops tagal var. australis*	100
5 (#)	*Xylocarpus mekongensis*	46.7
	Bruguiera spp.	13.5
	Rhizophora spp.	40
	Aegialitis annulata	25.6
6 (#)	*Avicennia marina*	48.7
	Ceriops tagal var. australis	25.6
7	*Bruguiera* spp.	39.4
	Ceriops tagal var. australis	60.6*
8	*Ceriops tagal var. australis*	100*
9 (#)	*Bruguiera* spp.	3.6
	Rhizophora spp.	39.3
	Ceriops tagal var. australis	57.1
10	*Rhizophora* spp.	35
	Ceriops tagal var. australis	65*

Soil properties

Overall, soil properties such as carbon density, soil bulk density and carbon content, are important factors driving the variability in soil carbon stocks (Sasmito et al., 2020). In Cairns Airport, these properties varied substantially across depth intervals considering all sampling sites within the Cairns Airport region (**Figure 7**). For example, the shallower depth interval showed higher values of carbon density and content, while the bulk density was higher in the bottom layers of the core. Overall, we found that mangrove soils in the Cairns Airport have an average 4.72% carbon content, 0.69 g cm^{-3} bulk density and 2.8 g cm^{-3} carbon density. While our sampling design accounted only for the top meter layer of the sediment, there is evidence that the mangrove forest in the area has a sediment layer deeper than 15 m. In this case, there is an opportunity to improve the precision of our estimates for soil properties and carbon stocks, by understanding the carbon variability in deeper layers of the soil (Sasmito et al., 2020).

Soil carbon stocks

Cairns Airport is home of 302 ha of mangroves (**Box 2**), with soil carbon usually varying substantially across landscapes (Ewers Lewis et al., 2020; Serrano et al., 2019). A recent study showed that mangroves in Queensland store on average approximately 313 tonnes ha^{-1} in the top meter of the sediment (Costa et al., 2023). We found that soil organic carbon (SOC) stocks varied substantially across sampling sites, with average SOC stocks estimated at 279.63 ± 13.32 tonnes ha^{-1} (down to 1 m soil depth); which is in agreement with previous studies in the state (Adame et al., 2020; Costa et al., 2023; Hayes et al., 2017). Overall, we found that among sampling sites, #3 and #4 showed the highest average SOC stocks varying from 377.52 ± 67 tonnes ha^{-1} and from 362.52 ± 24 tonnes ha^{-1}, respectively (**Figure 8**). In this case, both sampling sites were dominated by different species, where #3 was dominated by individuals of *Rhizophora* spp., while *C. tagal* was the only species occurring on #4 (**Table 5**). Variability in carbon stocks is also driven by species composition and abundance, with mixed mangrove stands expected to have higher SOC stocks per unit area (Atwood et al., 2017; Kauffman and Donato, 2012). Our study provides a first indication of the main species present in the study area, however, a detailed mangrove vegetation survey would be necessary to better investigate the contribution of different species to blue carbon SOC stocks.

Here, we focused on estimating SOC stocks within the top meter of the sediment, which aligns with the international standards to estimate carbon stocks (IPCC, 2014; Kauffman and Donato, 2012). However, since there is evidence that the mangrove forest in the area has a sediment layer deeper than 15 m, we also provide a broad estimate of the average SOC stocks at deeper layers. In this case, we suggest that

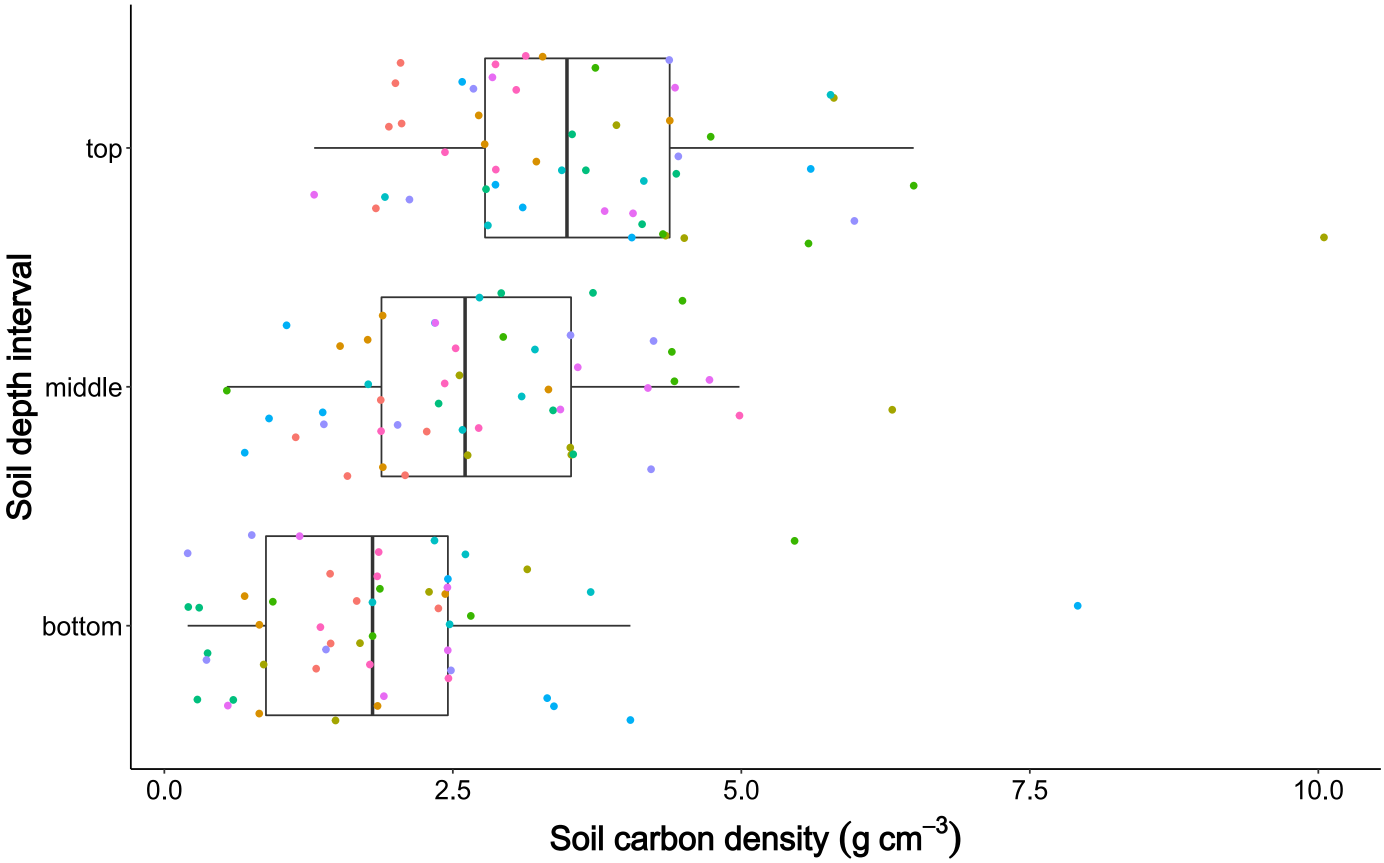
SOC stocks could vary from approximately 839 ± 39.96 tonnes ha^{-1} (down to 3 m soil depth) to 4,194 ± 593 tonnes ha^{-1} (down to 15 m soil depth). However, it is important to highlight that future studies are needed to understand the carbon content at deeper layers of the soil.

Soil sequestration rates

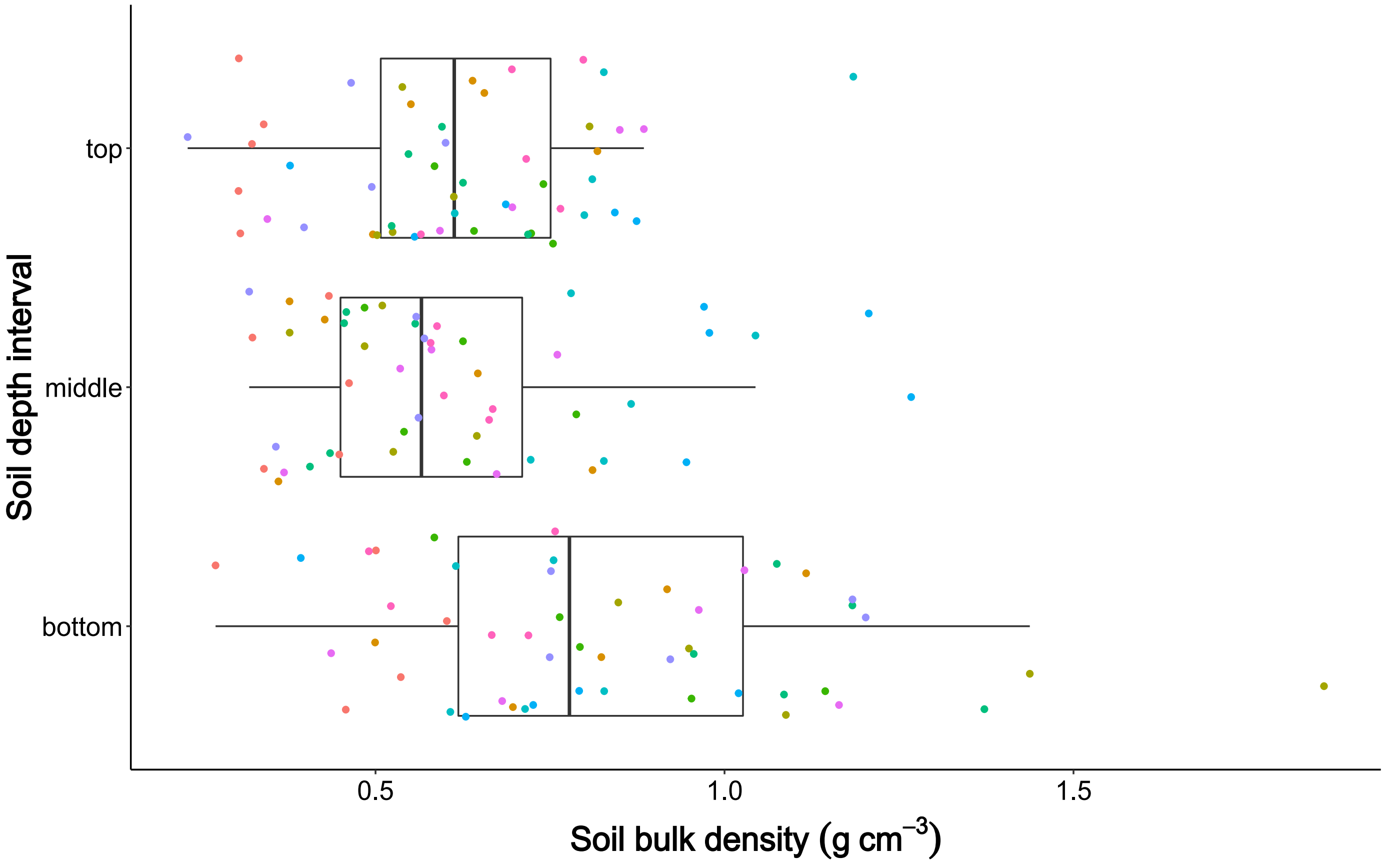
There is growing interest in mangroves' ability to sequester large amounts of atmospheric carbon and store it within the living plant (e.g., branches, leaves) and soil, and their role as nature climate solutions (Friess et al., 2020; Macreadie et al., 2021). Blue carbon ecosystems, such as mangroves, can accumulate high levels of carbon in their soils as they accrete sediment over time, with anaerobic conditions of the soils limiting carbon decomposition and securing their long-term permanence (Duarte et al., 2013; Lovelock et al., 2014; Mcleod et al., 2011).

In Cairns, we found that sequestration rates changed substantially depending on where in the mangrove forest the sample was taken (Figure 10). Following a similar pattern as for soil properties and carbon stocks in living plants and soil, this variation on soil sequestration within different sites can be explained by site-specific conditions and species composition (Lovelock et al., 2014). Furthermore, according to the ^{210}Pb age-dating analysis, we found that mangroves within the Cairns Airport region sequester in average 1.84 ± 0.11 tonnes C ha^{-1} yr^{-1}, which is within the global mangrove sequestration rate average of 1.74 tonnes C ha^{-1} yr^{-1} (Alongi, 2014). In this case, we estimated that the mangrove forest within the Cairns Airport region could potentially sequester 2,042 tonnes CO$_2$e per year, which is equivalent to 13% of Cairns Airport's 2019 operational emissions.

a)


Soil depth interval
top
middle
bottom
0.0
2.5
5.0
7.5
10.0
Soil carbon density (g cm^{-3})

b)


Soil depth interval
top
middle
bottom
0.5
1.0
1.5
Soil bulk density (g cm^{-3})

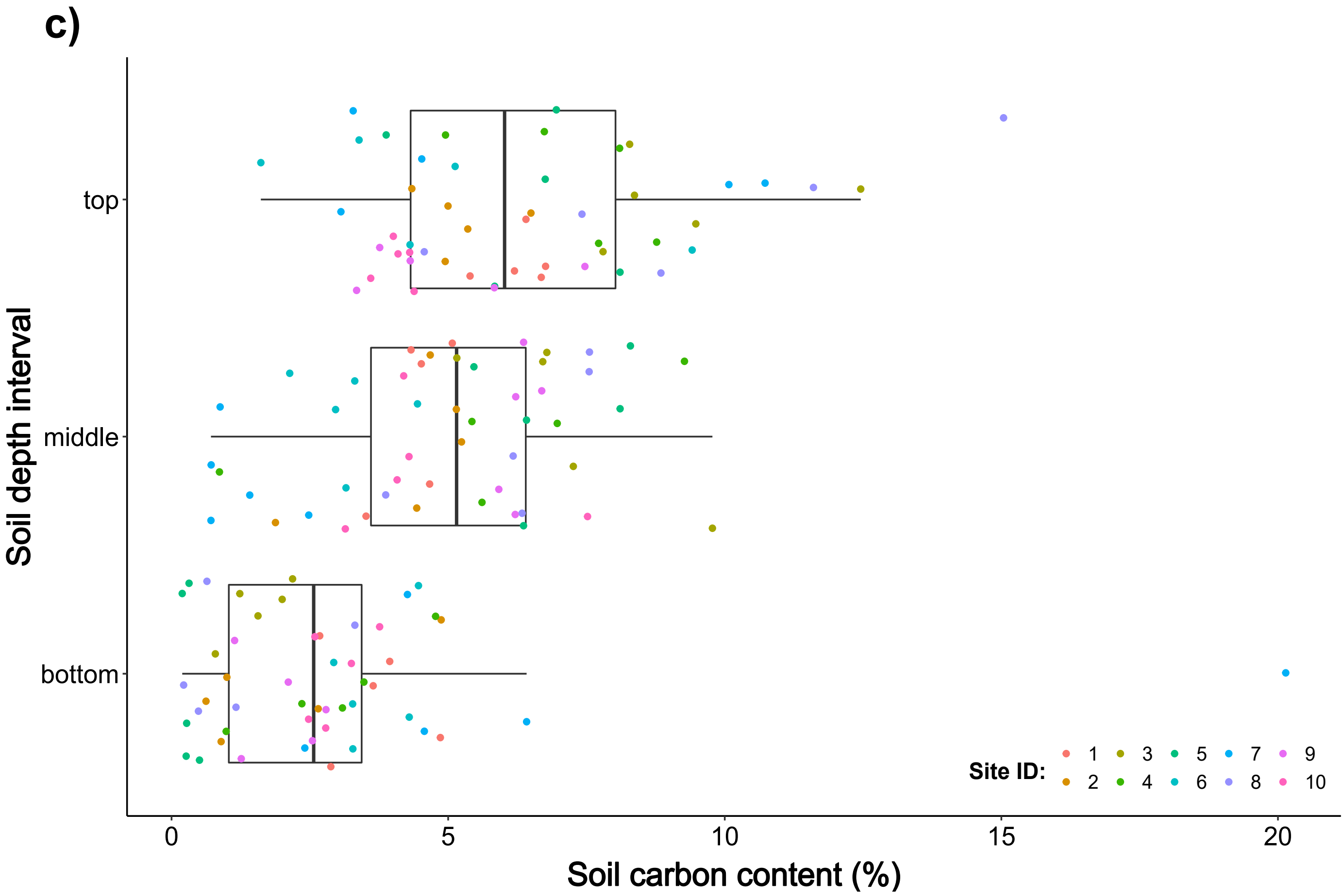


Figure 7: Variation of soil properties toward soil depth intervals for soil samples collected in mangroves within the Cairns Airport region: a) soil carbon density (g cm^{-3}), b) soil bulk density (g cm^{-3}), and c) soil carbon content (%).

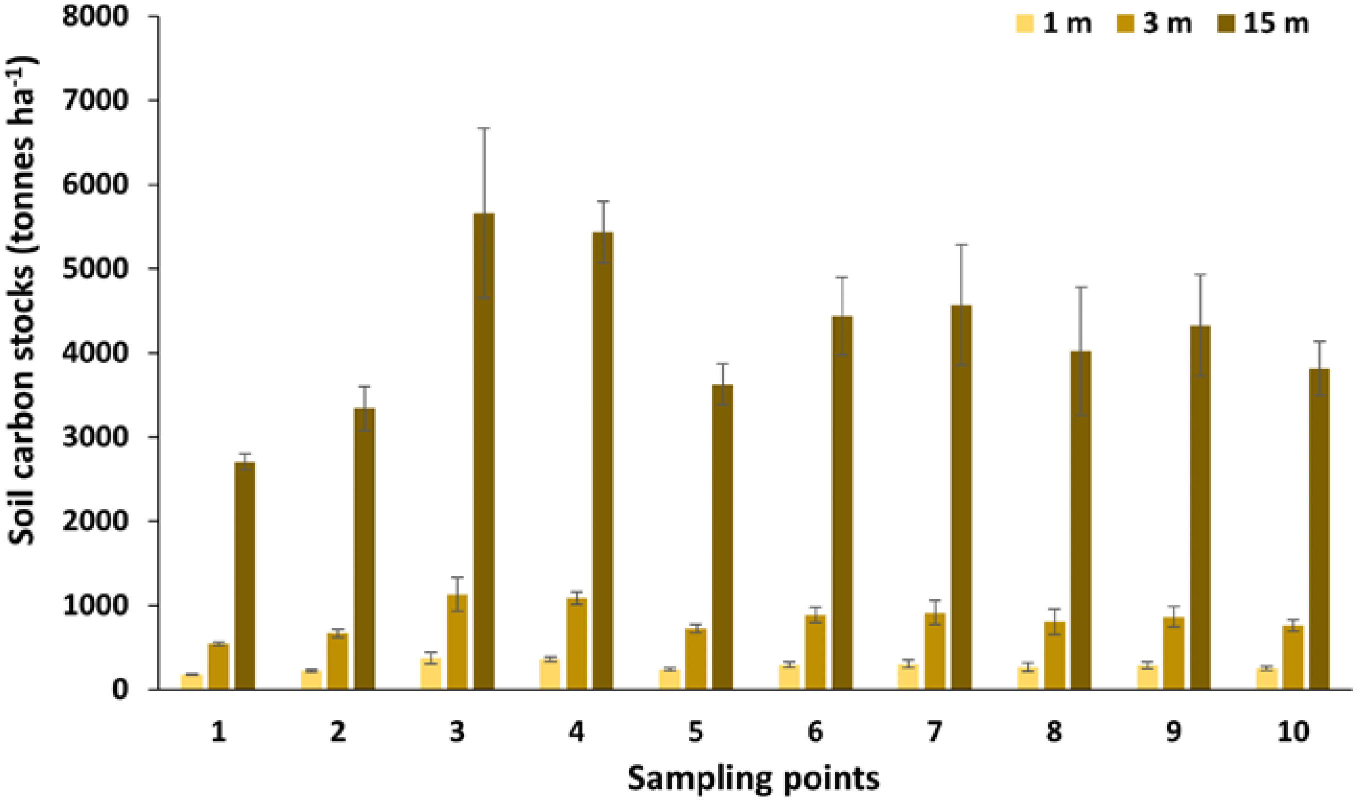


Figure 8: Mangrove soil carbon stocks (average ± SE) for three different soil depths included in this study (1 m, 3 m, and 15 m) across different sampling points (#) within the Cairns Airport region.

Figure 9: Mapped distribution of coastal wetlands (mangroves, seagrasses, and saltmarshes) within the Cairns Airport region. Sources of habitat distribution: mangroves (Department of Environment and Science, 2019), seagrass meadows (Carter et al., 2016; Lucieer et al., 2019), and saltmarshes (Department of Environment and Science, 2019).

Box 2: Saltmarshes and seagrasses within the Airport region

Saltmarshes and seagrasses are also key ecosystems in sequestering and storing carbon within their soils for long periods of time. We used existing data on the distribution of these ecosystems (Carter et al., 2016; Department of Environment and Science, 2019b; Lucieer et al., 2019) to broadly estimate their extent within the Airport region (**Figure 9**). Then, we combined this information with the average SOC stocks found for Queensland (Costa et al., 2023). In this case, we estimated that saltmarshes occur in 18.47 ha while seagrasses inhabit approximately 395.62 ha in the coastline adjacent to the airport limits. Based on this data, we estimate that these ecosystems are currently storing 38,422 tonnes of carbon within their soils in the Airport region, with seagrasses storing 33,232 tonnes while saltmarshes store approximately 5,190 tonnes. These results provide a first-pass assessment of the presence of saltmarshes and seagrasses within the area, and their potential for carbon storage. However, these estimates could be improved with future field assessments and the development of high-resolution blue carbon mapping.

Blue carbon potential at local scale

Conservation is playing a key role in maintaining the health of this mangroves in Cairns Airport and their associated ecosystem services (**Box 3**). Overall, we estimate that the mangroves within the Airport limits **stores approximately 123,268 tonnes of organic carbon within their plants and soils** (up to 1 m depth)**, which is equivalent to 452,394 tonnes CO_2e**. In this case, mangrove soils account for approximately 68.7% of the carbon stored in the mangroves within the Cairns Airport region, with the remaining 31.3% stored within the plant biomass.

These results are based on the mangrove extent calculated from the State-wide wetland mapping (Department of Environment and Science, 2019a), and can be updated once improved and high-resolution distribution maps are developed for the study region. For example, the best available data on the mapped distribution of mangroves and saltmarshes for the study region was developed by the Queensland Government through the wetland monitoring program (Department of Environment and Science, 2019a). The baseline map was released in 2006, and since then, eight other versions have been released to update the distribution extent of wetlands in the state. The most recent map was released in 2021 and included in the online platform WetlandInfo. More recently, it has been released the Australia-wide long-term mangrove mapping collection developed by Geoscience Australia (1987-2020 from the DEA Mangrove Canopy Cover 2.0.2; Lymburner et al., 2020). Both datasets were developed aiming to map these ecosystems at large-scale, which can limit their usage to site-specific assessments and smaller spatial scales. To fulfil this gap and solve potential uncertainties, we recommend the development of high-resolution maps (for example, via drones, high-resolution satellite imagery, or LiDAR) of blue carbon ecosystems within Cairns Airport which would also allow for improvements in the blue carbon assessment.

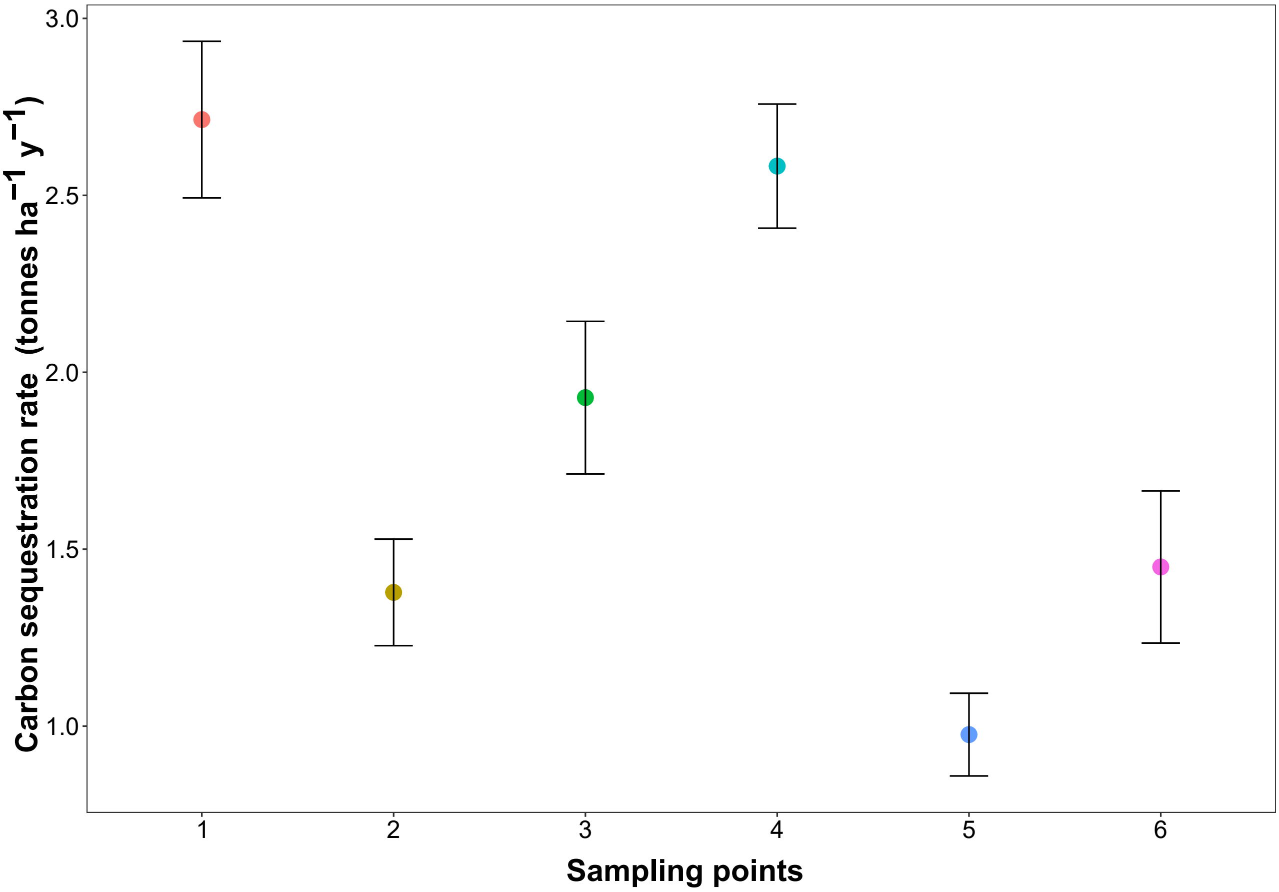


Figure 10: Mangrove soil carbon sequestration rates across different sampling points within the Cairns Airport region.

Box 3: Long-term changes in mangrove distribution within Cairns Airport

The long-term management of mangroves by the Airport within their boundaries in collaboration with the Yirrganydji Indigenous Land and Sea Rangers from the Dawul Wuru Aboriginal Corporation is essential for the maintenance of this ecosystem and its blue carbon assets.

The change analysis in mangrove distribution within the study region shows an initial net loss of approximately 4.5 ha occurring between 1987 and 1990, within the areas that are currently classified as 'mixed aviation zone' and 'movement zone' in the Airport zonation. This result is likely aligned with construction and expansion activities derived from the airport activities during the decade of 1980. This was followed by a period of recovery and mangrove expansion within the airport limits between 1990 and 2000, with a net gain of 7.1 ha. In the following two decades, we only identified marginal changes in mangrove forests within the airport area, which likely represents the result of management measures in place to conserve mangroves in the Yirrganydji land (**Table 6** and **Figure 11**). These results are based on the Australia-wide mangrove mapping collection developed by Geoscience Australia (1987-2020 from the DEA Mangrove Canopy Cover 2.0.2; Lymburner et al., 2020), and therefore, might underestimate the mangrove area within the Airport limits.

Table 6: Estimated changes in the mangrove distribution within the Cairns Airport limits in different time periods: 1987-1990, 1990-2000, 2000-2010 and 2010-2020. This analysis was conducted based on the mapped multi-decadal mangrove distribution at national level (1987-2020 from the DEA Mangrove Canopy Cover 2.0.2; Lymburner et al., 2020).

Area (ha)	1987 - 1990	1990 - 2000	2000 - 2010	2010 - 2020
Gain	2.0	7.3	0.1	02.
Loss	6.5	0.2	0.5	0.5
Net change	**-4.5**	**7.1**	**-0.4**	**-0.3**

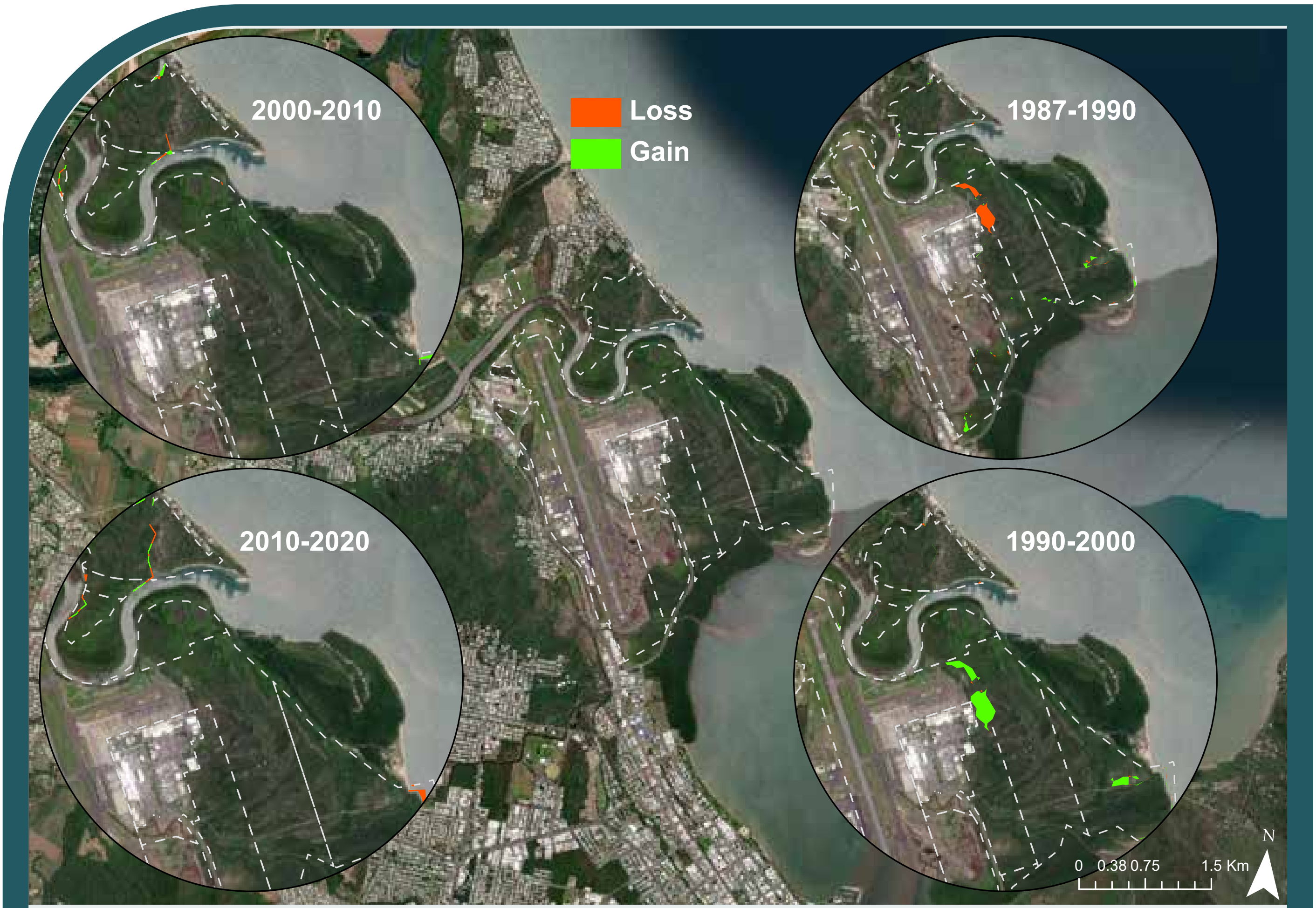


Figure 11: Change analysis of mangrove distribution between four different time periods: 1987-1990, 1990-2000, 2000-2010, and 2010-2020. This analysis was conducted based on the mapped multi-decadal mangrove distribution at national level (1987-2020 from the DEA Mangrove Canopy Cover 2.0.2; Lymburner et al., 2020).

While mangroves play a key role as natural climate solutions, if degraded, these ecosystems become sources of greenhouse gases, releasing stored carbon back into the atmosphere. Although mangroves in Cairns Airport have been maintained in healthy conditions for the past decades, it is important to secure management and conservation plans to ensure that such conditions prevail under future conditions. Under these conditions, the additionality opportunities for blue carbon projects is minimal within the study area (further details in the Recommendations section), with the only blue carbon method available in Australia accounting only for tidal reinstatement (Clean Energy Regulator, 2022). There might exist opportunities for other finance mechanisms, such as payment for ecosystem services or Traditional Owner steward payments, that may be applicable in the area (further details in the Recommendations section).

Recommendations

This project delivered the first site-specific data on both plant and soil organic carbon stocks and sequestration potential for mangrove ecosystems within Cairns Airport. To support the advancement of mangrove conservation and research in the area, we suggest four major priority actions, which should continue to engage with the Yirrganydji Indigenous Land and Sea Rangers from the Dawul Wuru Aboriginal Corporation.

1. Understand the natural capital values of coastal wetlands: evaluate and map ecosystem services:

In addition to carbon sequestration, mangroves also provide other ecosystem services to coastal communities such as enhancing coastal fisheries, protecting coastlines against flooding and extreme events, improving water quality, supporting biodiversity, and cultural services (such as recreational, tourism, and wellbeing). More importantly, coastal wetlands provide Indigenous cultural uses that should that should be recognised into natural capital accounting. In the study region, this is mainly important for the benefits associated with the importance of mangroves to Yirrganydji Peoples.

We recommend that quantification and mapping of ecosystem services that mangroves provide within the Airport area is essential for the continued conservation and management of the area, while also contributing to develop a market for the payment of co-benefits (Carnell et al., 2022, 2019; Costa et al., 2022). Natural capital accounting is increasingly being used to understand and valuate the services these ecosystems provide to people, and the potential impacts people may have on them.

2. How management actions (past, current, and future) can help maintain the natural value of the area:

Once the natural capital of the area is quantified and mapped, it is important to understand how management actions from the past and the business-as-usual compares to future management actions. This scenario analysis is key to inform decisions on the management of the area cost-effectively, including evaluating change of biodiversity and coastal wetlands over time.

3. Assessing stewardship payments for ecosystem services provided by coastal wetlands:

Opportunities for blue carbon additionality might be limited due to the Airport engagement with the Yirrganydji Indigenous Land and Sea Rangers from the Dawul Wuru Aboriginal Corporation and their key role in maintaining the mangroves within their country. Overall, additionality opportunities for blue carbon projects are likely to favour private landholders who historically impacted coastal wetlands within their lands. A major risk to Australia, and more specifically to coastal Aboriginal Corporations such as the Dawul Wuru Aboriginal Corporation, is that they may be excluded from carbon market opportunities since they have historically maintained the coastal ecosystems in good healthy.

In this case, we suggest the investigation of potential issues with the inequity access to Traditional Owners engagement in blue carbon restoration projects. More specifically, there might be an opportunity of blue carbon stewardship payments to Traditional Owners who are playing an important role in improving and maintaining coastal wetlands within their country. Considering the long-term collaboration of Cairns Airport with the Dawul Wuru Aboriginal Corporation, we suggest that the Airport could be at the forefront developing new opportunities to include Traditional Owners in blue carbon markets.

4. Citizen Science: connecting the community to coastal wetlands and blue carbon research:

Active engagement with coastal communities is important to reconnect people with nature, and therefore, build public awareness towards blue carbon ecosystems and ecosystem services they provide. In this case, in alignment with Cairns Airport's Environment & Sustainability Plan, we suggest the promotion of a blue carbon education and awareness program, including public and Airport staff, by connecting people to these ecosystems via immersive citizen science programs. These immersive experiences, including educational talks and engagement with scientific fieldwork, are expected to increase knowledge on coastal ecosystems, natural capital and climate change.

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