

Indigenous stewardship and co-management in action: a case study on blue carbon from a mangrove ecosystem on the Great Barrier Reef

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ABSTRACT

Blue carbon ecosystems play a vital role in climate change mitigation and adaptation through their capacity to sequester and store organic carbon. Queensland, Australia, contains over 500,000 ha of mangroves, much of it under the stewardship of Traditional Custodians. The mangrove forests of the Bidakarra (Barron River) estuary provide a unique opportunity to demonstrate how Indigenous leadership, scientific research, and local industry partnerships can advance both ecological and cultural outcomes. We present a co-designed case study from Kukujuum (Ellie Point), an area co-managed by Cairns Airport, Yirrganydji Gurabana Aboriginal Corporation, and the Yirrganydji Land and Sea Ranger Program through Dawul Wuru Aboriginal Corporation. The project combined collaborative planning, field-based carbon assessments, and community engagement to exchange Traditional Knowledge and scientific expertise. Results showed *Ceriops tagal* as the dominant species, with tree densities from 1000 to 4400 ha⁻¹. The forest stores ~120,000 tonnes of organic carbon to 1 m depth, with 69 % in sediments (accumulating at 1.84 ± 0.11 tonnes C ha⁻¹ yr⁻¹) and 31 % in biomass. By embedding Indigenous stewardship into blue carbon assessment, this work highlights governance models that align climate and biodiversity goals with cultural priorities. The findings provide actionable insights for policy frameworks seeking to integrate nature-based solutions, equitable benefit-sharing, and community-led coastal management, offering a replicable approach for other regions balancing ecological sustainability with Indigenous rights.

1. Introduction

Blue carbon ecosystems (e.g., mangrove forests, saltmarshes, and seagrass meadows) are highly efficient at sequestering and storing organic carbon, making them valuable nature-based solutions for climate change mitigation and adaptation (Macreadie et al., 2021). Among these, mangroves are distributed across 14.7 million hectares along the world's coastlines (Bunting et al., 2022) and are recognised as one of the most effective carbon sinks (Duarte et al., 2013; Macreadie

et al., 2021; Mcleod et al., 2011). On average, a single hectare of mangrove soil can store approximately 386 tonnes of carbon (IPCC, 2014), while sequestering around 1.74 tonnes of carbon per hectare annually (Alongi, 2014). However, the capacity of mangroves to sequester and store carbon varies significantly due to local environmental factors such as geomorphology, tidal regimes, and vegetation types (Alongi, 2020). Beyond their role in carbon cycling, mangroves offer a range of essential ecosystem services to coastal communities, including biodiversity support, nursery habitat for fisheries, nutrient

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cycling, and protection from coastal flooding and erosion (Barbier et al., 2011; Friess et al., 2020; Himes-Cornell et al., 2018). As such, mangrove conservation and restoration are increasingly recognised as key natural climate solutions, offering cost-effective strategies to avoid carbon emissions and enhance carbon sequestration (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 stands out as a key region, containing around 42 % of the nation's blue carbon stored within tidal marshes and mangroves and 58 % within seagrass meadows (Duarte de Paula Costa et al., 2023). These ecosystems collectively store an estimated 569 Tg of carbon (Duarte de Paula Costa et al., 2023), representing 4–53 % of Australia's total blue carbon (Serrano et al., 2019) and 2–7 % of global stocks (Macreadie et al., 2021). However, coastal wetlands have been extensively modified for agricultural, urban, and industrial development in the past (Waltham and Sheaves, 2015). Despite that, recent estimates provided some

positive signs in the disturbance rates of these ecosystems (<0.1 % net loss during 2005–2013; Adame et al., 2019), with terrestrial protected areas, marine parks, and areas of matters of State environmental significance playing an important role to protect mangroves in Queensland (Duarte de Paula Costa et al., 2023). Additionally, Indigenous co-governance and management play a vital role in the ongoing conservation and restoration of these coastal ecosystems in the region (Cvitanovic et al., 2021).

The responsibilities and cultural obligations of Traditional Custodians to managing land and water is based on the core principle that “Country is held by Indigenous People and that if you look after Country, Country will look after you” (i.e., ‘Caring for Country’; (Woodward and Marrfurra McTaggart, 2019). In the past few years, there has been growing opportunities to shift towards Indigenous co-governance and management in Australia (Goolmeier et al., 2022). For example, these opportunities led to the creation of Aboriginal Corporations and Ranger programs that have a key role in managing land and water on Country

Box 1

Yirrganydji Peoples' perceptions on the value of research and mangroves from Kukujum (Ellie Point)

For thousands of years, the land, sea and waters around the Lower Barron River had been under the custodianship and stewardship of our People. This custodianship is passed down from generation to generation from our ancestors to us today. It is our cultural responsibility and obligation to continue that tradition of custodianship and to pass it onto the next generation. The role of custodianship is about the care of land, sea and waters. Our cultural activities and customary practices are all part of custodianship. We want to continue exercising and/or re-introducing our Indigenous led-cultural management 'custodianship' into the landscape.

Gaining a wholistic understanding of an ecosystem involves input from Elders, young People, male and female representatives, and individuals from different family groups. The co-design of a project from the beginning is important. This includes early meetings, consultation on locations and dates for fieldwork, knowledge exchange, genuine collaboration, and recognition through co-authorship of project reports and publications.

We acknowledge our partners (Cairns Airport, Blue Carbon Lab and RMIT University), through this project for allowing us to continue our cultural responsibilities for Kukujum, Bidakarra and surrounding area.

Gavin Singleton, Yirrganydji.

The Yirrganydji People 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 this blue carbon project was conducted is identified by my 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 team's visit to Cairns, they were first expected to learn and understand us, as the Yirrganydji People, which they did. Whilst working alongside them, 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 Custodians 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 Research team saw that as well. The whole Yirrganydji team appreciated the respect given from the research team and condone their efforts in the work they did and the work they continue to do.

Ashlyn Skeene, Yirrganydji.

We live in a different world now and our People are still here. This modern environment comes with new challenges that were not part of our story, but these challenges need to become part of our story. Problems caused by carbon in the air were never a concern for us. It's the last thing we would have worried about. Our old People didn't sit down and tell us stories about climate change. This is a new story that we have to understand and start teaching our young People.

Mangroves are important to Yirrganydji People. It's a place that we can go to hunt and gather food. We know that it's a very important nursery for our fish and crab stocks and it's a habitat that manages itself. Mangroves don't need farmers, but they need support from Traditional Custodians and the community. This gives them a voice. It's the whole community that needs to be part of a solution and co-management is possible through genuine partnerships.

This project was really important to me as a Yirrganydji person. It showed us that mangroves are important to help us deal with modern challenges.

Brian Singleton, Yirrganydji.

and effectively contributing to the conservation and restoration of ecosystems. In Queensland, more specifically in the region between Cairns and Port Douglas, Yirrganydji People have undertaken a range of projects and initiatives in environmental conservation, social and community development through Yirrganydji Gurabana Aboriginal Corporation (e.g., Yirrganydji Rangers, Cultural Heritage Management, Native Title, Welcome to Country & Cultural Performances, Reef Conservation, Indigenous Art & Design, Elders Group Program) and Dawul Wuru Aboriginal Corporation (e.g., Yirrganydji Land and Sea Ranger Program, Junior & Cadet Ranger Program, Estuarine Crocodile Monitoring Program, On-Country Maintenance Program). As part of the ongoing connection Yirrganydji People have to Sea Country, including the mangroves in the region, there was a growing interest to understand the concept of 'blue carbon' and the methodologies used to collect and analyse the samples. In this case, a partnership to promote knowledge sharing between Yirrganydji People and blue carbon scientists was identified as the main step to fulfill this capacity gap (Box 1).

Here, we present a case study from Kukujum (Ellie Point), which is located within the Bidakarra (Barron River) estuary, where Cairns Airport has supported an 8+ years of partnership with the Yirrganydji Land and Sea Ranger Program (supported through Dawul Wuru Aboriginal Corporation) as well as with Yirrganydji Elders and community through Yirrganydji Gurabana Aboriginal Corporation to manage and restore the area, including 15 species of mangroves. With

the increasing interest of coastal stakeholders in blue carbon around Australia, this study aimed to evaluate and quantify the potential contribution of mangroves within Bidakarra, by: 1) developing an initial spatial assessment of mangroves in the region, including an analysis of temporal change using the multi-decadal mangrove distribution in Australia (Lyburner et al., 2020); and 2) estimating sediment, below- and aboveground carbon stocks in mangroves in the area. We describe the co-design process for the project to ensure the exchange of scientific and cultural knowledge throughout the study.

2. Materials and methods

2.1. Study area

Cairns is the largest city in northern Queensland, situated within the Wet Tropics Natural Resource Management Region (NRM). The region stretches from Townsville in the south to Cooktown in the north (Fig. 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). 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 seagrasses

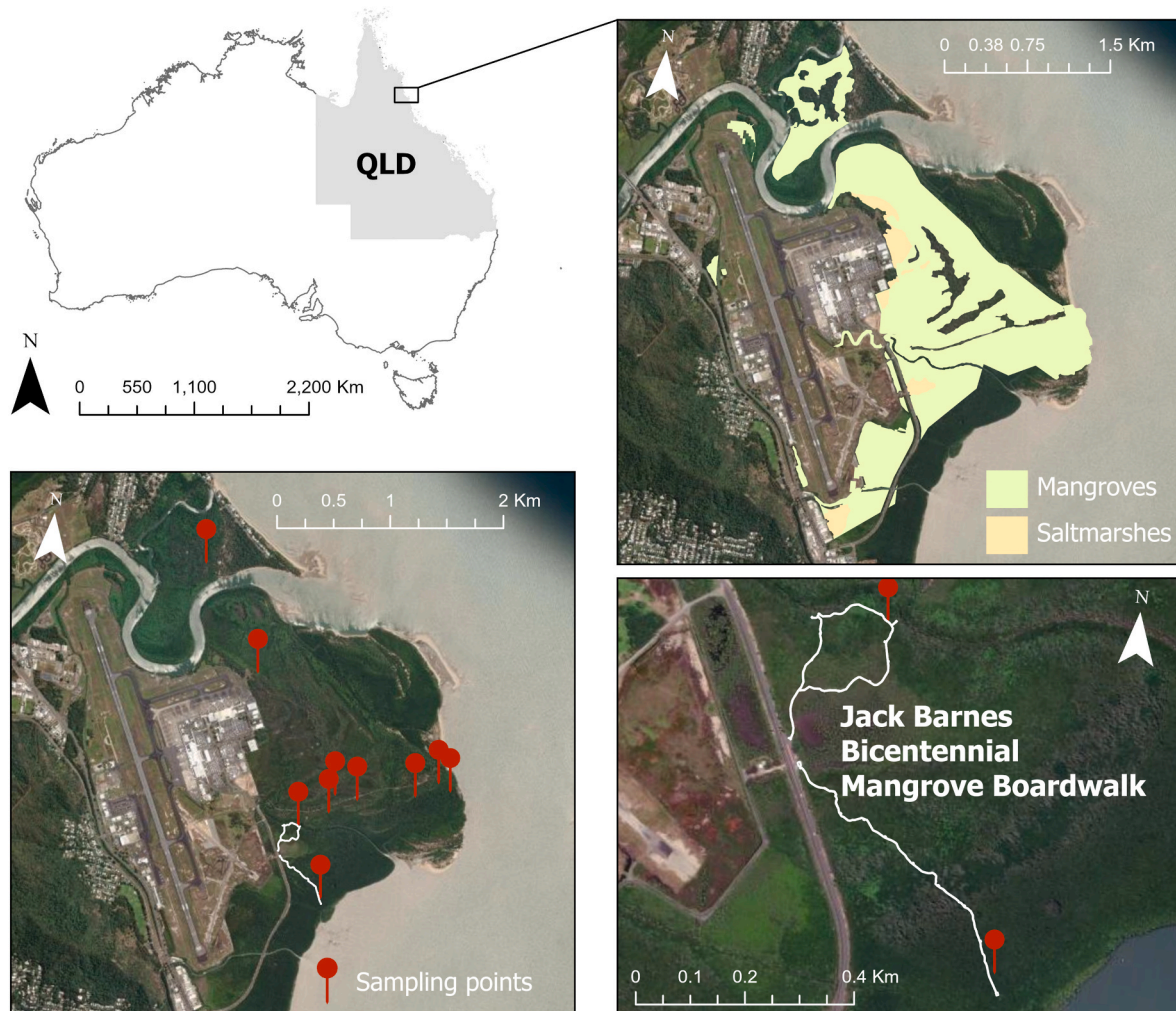


Fig. 1. Mapped distribution of mangroves and saltmarshes along the Bidakarra (Barron River) estuary (Department of Environment and Science Queensland, 2019a). Detailed maps show the sampling locations for the sediment core samples from mangroves taken during the fieldwork campaign conducted in this study, and the location of the Jack Barnes Bicentennial Mangrove Boardwalk.

that provide critical habitat for numerous species of birds, fish, insects and other flora and fauna including threatened species. The mangrove forests within the Cairns region, including Bidakarra (Barron River), are distributed across approximately 4440 ha (Department of Environment Science and Innovation Queensland, 2025) and are highly diverse, providing a variety of ecosystem services to coastal communities.

2.2. Knowledge sharing

2.2.1. Project co-design

Initial discussions about developing the study started in February 2021, which led to several video meetings where the team members discussed the project design. The team meetings were informally structured to allow enough time for the members to develop relationships, share knowledge of Country, and personal experiences. It is important to note that the co-design period was also affected by the COVID pandemic, which limited the in-person interactions between the teams.

Based on the knowledge shared in these meetings, an initial sampling plan was co-designed with the first draft mainly based on the Jack Barnes Bicentennial Mangrove Boardwalk (Fig. 1) for safety reasons. Then, the plan was improved in the coming months based on the suggestions and interests from the members of the Yirrganydji Land and Sea Ranger Program until May 2022 (Table S1), when the fieldwork was conducted. While the scientific team had access to vegetation maps showing the distribution of mangroves in the regions (Department of Environment and Science Queensland, 2019b), the spatial data lacked information at species level. Therefore, the sampling design drawn on the Traditional Knowledge of Country to ensure that we had a good representation of different species in our study.

The fieldwork occurred between 15 and May 20, 2022. The schedule for fieldwork campaign included an in-person meeting ('Meet and Cultural Induction') with the entire team to be working in the field sampling. After this initial meeting, the team conducted a first visit to Ellie Point, where the Yirrganydji Land and Sea Rangers welcomed the scientific team to their Traditional Land and guidance to conduct an initial site assessment. Then, in the following days, the team worked together to sample mangrove blue carbon data, while also having the opportunity to exchange knowledge in history, biodiversity, culture, and language.

2.2.2. Community day

The fieldwork campaign was marked with a 'community day' where we received 20+ People from the community and relevant stakeholders from the region to demonstrate the work we conducted during the week. The activity was realized around the Jack Barnes Bicentennial Mangrove Boardwalk (Fig. 1). The participants included Yirrganydji People, airport staff, and representatives from Natural Resource Management (Terrain NRM) and Landcare (Wet Tropics Waterways) groups. The day was informally structured, where the scientific team explained and demonstrated sampling techniques to collect sediment samples and how to register mangrove vegetation data. Then, the participants had the opportunity to contribute to the sub-sampling of sediment samples (further details available in section 2.3).

2.3. Mangrove field campaign

2.3.1. Mangrove forest characteristics

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 1) 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).

2.3.2. Sediment sampling

We estimated soil organic carbon (SOC) content (%) from mangrove sediments at ten sampling sites (Fig. 1, Table S1). 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. The core was manually sunk into the sediment 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 sediment compaction, we measured the distance from the edge of the corer to the sediment surface in and out, and 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.

In addition, we collected one sediment core from six different sites using a PVC pipe (5 cm internal diameter, 155 cm length) to determine sediment accumulation rates (Fig. 1). To compensate for the compaction, 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 the lab at Deakin University (Melbourne, Australia).

2.3.3. Sediment processing

All sediment samples were processed for bulk density and SOC stocks. The syringe core samples collected from the top, middle and bottom sections of the cores were dried at 60 °C for 48–72 h, until they reached a constant weight, and recorded their weights. After correcting the sample volumes by using the compaction factor, we calculated the sediment bulk density (g cm^{-3}). Bulk density (g cm^{-3}) was determined by dividing the mass (g) of the dry sediment sample by the volume (cm^3) of the sample. We pulverized and homogenised all samples using a Retsch RM200 mortar grinder 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 inorganic carbon fraction (Howard et al., 2014).

We measured the organic carbon content of samples using an Euro-Vector 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 1021 °C to determine the percentage of organic C and N in samples. The sediment carbon stock for each depth strata was calculated using the C percentage and sediment bulk density of the layer (Howard et al., 2014; Kauffman and Donato, 2012). Then, for each sediment 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 sediment depth to keep it consistent with the IPCC guidelines (IPCC, 2014); however, since the sediment depth is known to be deeper than 15 m in some areas (Friend pers. comm. 2022), we also calculated sediment carbon stocks up to 3 m (i.e., conservative estimate) and up to 15 m. Therefore, it is important to highlight that future studies are needed to understand the carbon content at deeper layers of the sediment to improve our estimates.

The total carbon pool for each sampling site was estimated by

Table 1

Species-specific allometric equations and parameters used to estimate aboveground mangrove biomass (Kg DW ha⁻¹). We used a general equation to estimate the belowground biomass (Kg DW ha⁻¹; [Komiya et al., 2008](#)). 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
<i>Rhizophora</i> spp. (red mangrove)	0.1579*DBH ^{2.593}	0.199*WD ^{0.899*}	0.84	(Analuddin et al., 2020 ; Chave et al., 2009)
<i>Bruguiera</i> spp. (orange mangrove)	0.186*DBH ^{2.31}	DBH ^{2.22}	0.741	(Clough and Scott, 1989 ; Kauffman and Donato, 2012)
<i>Xylocarpus mekongensis</i> (cedar mangrove)	0.1832*DBH ^{2.21}		0.7	Kauffman and Donato (2012)
<i>Ceriops tagal</i> (yellow mangrove)	0.189*DBH ^{2.34}		0.88	(Chave et al., 2009 ; Clough and Scott, 1989)
<i>Avicennia marina</i> (grey mangrove)	0.308*DBH ^{2.11}		0.65	(Chave et al., 2009 ; Comley and McGuinness, 2005)
<i>Aegialitis annulata</i> (club mangrove)	0.251*WD*DBH ^{2.46}		0.64	(Balun, 2011 ; Komiya et al., 2008)

summing all the carbon pools: aboveground, belowground and sediment. For that, each of the carbon pools was averaged across all samples and in each site.

2.3.4. Soil carbon accumulation rates

Sediment cores for age dating were extruded and sectioned in the laboratory. We followed a high-resolution subsampling strategy, which included: 1) the upper 20 cm was sliced at 1 cm-thick resolution, 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; [Gulliver et al., 2020](#)).

The analysis of ²¹⁰Pb 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). The concentrations of ²¹⁰Pb were determined via the measurement of its decay product ²¹⁰Po by alpha spectrometry after acid digestion of the samples in the presence of a known amount of ²⁰⁹Po as a yield tracer and plating onto silver disks ([Sanchez-Cabeza et al., 1998](#)). The concentrations of supported ²¹⁰Pb were estimated by determining ²²⁶Ra by gamma spectrometry in selected samples along each core. The excess ²¹⁰Pb-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](#)); following [Arias-Ortiz et al. \(2018\)](#)). 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 yr⁻¹).

2.4. Spatial assessment

In this study, 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 study region. For 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. All the spatial layers were projected to the same coordinate system, and all spatial analyses were conducted in ArcGIS 10 ([Esri, 2011](#)). Finally, the total carbon stock for the study area was estimated by multiplying the average carbon pool (estimated in this study) by the total mangrove cover. The mangrove area was calculated from the best available mangrove distribution maps for Queensland ([Department of Environment and Science Queensland, 2019b](#)).

3. Results

3.1. Knowledge sharing

The project co-design, mangrove sampling campaign and community day offered a valuable opportunity to share knowledge on the site, local species, and sampling techniques, thus promoting mutual learning and enhancing future management efforts in the study region. During the first day of the field campaign, the team from the Yirrganydji Land and Sea Ranger Program introduced Yirrganydji Country through their virtual reality videos. Relationships matter; therefore, researchers and Traditional Custodians importantly took the time to get to know one another before getting on Country and working together. In addition, during the field campaign, informal discussions amongst the team members led to the exchange of knowledge on sediment sampling techniques, plant identification, and the ecological roles of different mangrove species. This dialogue strengthens partnerships, builds capacity within Indigenous communities, and ensures that conservation strategies are culturally appropriate, respectful, and effective in the long term. Such collaboration empowers Indigenous Peoples as stewards of their Sea Country and reinforces the importance of integrating Traditional Knowledge into modern management practices.

3.2. Mangrove blue carbon

3.2.1. Forest characteristics

In this study, we assessed for the first time the characteristics of the mangrove forest within the study region. Overall, 4 species and 2 genera were sampled during the survey campaign ([Table 2](#)). The mangrove species *Ceriops tagal* was the most abundant species in the study area, while *Aegialitis annulata* was the least abundant species ([Table 2](#)). 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 m, with *Xylocarpus mekongensis* having the highest average tree height ([Table 2](#)). Despite that, the tallest sampled tree was a *Rhizophora* spp. tree. Overall, mangrove tree density varied from 1000 to 4400 trees ha⁻¹, with an average value of 2263 trees ha⁻¹ ([Table 2](#)). Considering the different species, *C. tagal* had the highest tree density.

3.2.2. Mangrove biomass and carbon stocks

Mangrove biomass and carbon stocks varied substantially among species and sampling sites ([Fig. 2](#) and [Table S2](#)). Overall, *Rhizophora* spp. showed the highest average value for aboveground carbon biomass among different species ([Table S2](#)), ranging from 6.5 ± 2.2 to 141.7 ± 14 kg DW tree⁻¹ ([Table 2](#)). In contrast, average plant biomass was lower in *A. annulata* ([Table S2](#)). 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 3](#) and [Fig. 3](#)).

On average, the biomass of the mangrove forest in the region holds 98.3 ± 6.5 tonnes ha⁻¹ in aboveground carbon stocks and 29.4 ± 1.7

Table 2

Detailed summary of the main forest characteristics for each species sampled in the Barron River estuary. *Indicates species that occurred on only one sampling point. Values were rounded to the nearest integer.

Forest Parameter	<i>Rhizophora</i> spp.	<i>Bruguiera</i> spp.	<i>Xylocarpus mekongensis</i>	<i>Ceriops tagal</i>	<i>Avicennia marina</i>	<i>Aegialitis annulata</i>
Number of trees measured	58	64	14	148	19	10
Average trunk height (m)	6	6	7	4	4	1
Average diameter at breast height (cm; min – max values)	17 (4.8–29.6)	11 (1.6–35.3)	12 (3.5–17.5)	7 (2.5–22.6)	8 (3.2–16.6)	5 (3.2–8.9)
Tree density (trees ha ⁻¹ , ±SE)	1160 (±531)	1280 (±661)	1400*	4416 (±163)	1900*	1000*



Fig. 2. Knowledge sharing during different stages of the mangrove blue carbon fieldwork campaign conducted in May 2022 on Yirrganydji Country. Top left: Brian Singleton at Northern Boardwalk, Top right: Matthew Skeene, Bottom Left: Matthew Skeene & Gavin Singleton, Bottom Right: Yirrganydji team (Matthew Skeene, Ashlyn Skeene, Gavin Singleton, Brian Singleton, Tarquin Singleton) and Noyan Yilmaz. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3

Estimated changes in the mangrove distribution within the study region across different time periods.

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

tonnes ha⁻¹ in belowground carbon stocks, not including soil carbon stock. As expected, our results also show that *Rhizophora* spp. holds the highest plant carbon stocks (Fig. 3). Based on the allometric equations

used in this study (Table 1), all six mangrove species included hold most of their carbon stocks within their aboveground stems, branches and leaves (Fig. 3). Furthermore, across sampling sites, #3, which was dominated by *Rhizophora* spp. (Table S3), showed the highest plant carbon. 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 to 29.6 cm (Table 2).

3.2.3. Soil properties, carbon stocks and accumulation rates

In the region, the soil properties varied substantially across depth intervals considering all sampling sites (Fig. 4). 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 sediments in the study region have an average 4.72 % (0.19 %–20.1 %) carbon content, 0.69 g cm⁻³ (0.23–1.86 g cm⁻³) bulk density and 2.8 g C cm⁻³ (0.20–10 g C cm⁻³) carbon density.

The soil organic carbon (SOC) stocks and sequestration rates varied substantially across sampling sites. For SOC stocks, we estimated the average SOC stocks at 280 ± 13 tonnes C ha⁻¹ (down to 1 m soil depth). Overall, we found that among sampling sites, sites 3 and 4 showed the highest average SOC stocks (378 ± 67 tonnes ha⁻¹ and from 363 ± 24 tonnes ha⁻¹, respectively) (Fig. 5). In this case, both sampling sites were dominated by different species, where site 3 was dominated by individuals of *Rhizophora* spp., while *C. tagal* was the only species occurring on site 4 (Table S2). In this case, the SOC stocks could be 839 ± 40 tonnes ha⁻¹ (down to 3 m soil depth) and 4194 ± 593 tonnes ha⁻¹ (down to 15 m soil depth). Overall, mangrove soils account for approximately 69 % of the carbon stored in the mangroves in the area, with the remaining 31 % stored as plant biomass. Finally, we estimated that mangroves within the region sequester in average 1.84 ± 0.11 tonnes C ha⁻¹ yr⁻¹ based on the accumulation rates calculated from the ²¹⁰Pb models (Fig. 5).

The general decreasing trend in excess ²¹⁰Pb with depth (22 cm–50 cm of the sediment core) allowed to estimate an average sedimentation rate using the CF:CS model varying from 0.15 ± 0.03 g cm⁻² yr⁻¹ to 0.60 ± 0.05 g cm⁻² yr⁻¹ (or 2.2 ± 0.4 mm yr⁻¹ to 12.5 ± 1 mm yr⁻¹; Fig. 5). These results were representative of different time scales, with one core being representative for the last few decades, two cores representative for the last century, with the remaining three cores being representative for the last ca. 60, 70 and 80 years. Tables S4–S9 show the ²¹⁰Pb profiles for the different cores.

3.3. Long-term changes in mangrove extent

The current area of mangrove forest at Kukujuum is approximately 302 ha. The change analysis in mangrove distribution shows that the changes represent a small percentage change of the total mangrove distribution. The initial net loss was estimated at approximately 4.5 ha occurring between 1987 and 1990 (Table 3, Fig. 6). This was followed by a period of recovery and mangrove expansion within the region 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 (Table 3, Fig. 6).

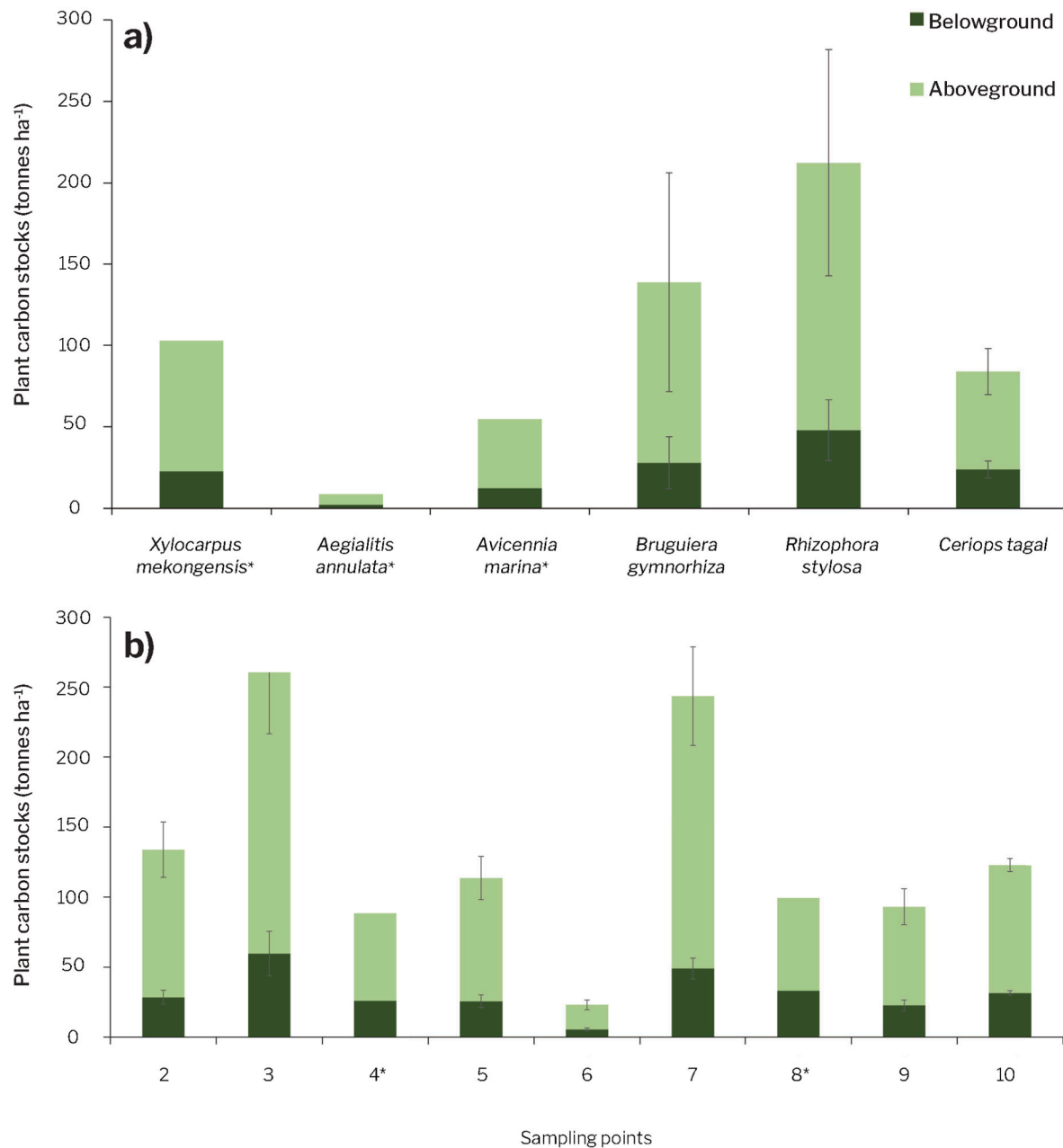


Fig. 3. Mangrove biomass carbon stocks (average $\pm$ SE; above- (AGC) and belowground (BGC) carbon stocks) within the study region across (a) different species and (b) sampling points (except for site 1, in which the vegetation survey was not conducted). *Indicates species that occurred on only one sampling point.

4. Discussion

The partnership developed for this study showed that such initiatives can lead to valuable actions contributing to mangrove management. Through our study, we confirmed that conservation is playing a key role in maintaining the health of the mangrove forest within Bidakarra (Barron River estuary) and their associated ecosystem services. More specifically, we showed that mangroves are playing an important role in sequestering and storing carbon in their plants and soils. We showed that the study area is home of 302 ha of mangroves, and that these mangroves stock in average 280 ± 13 tonnes C ha⁻¹ in the top meter of the sediment. This result also agrees with previous studies conducted in Queensland (313 Mg C ha^{-1} , Duarte de Paula Costa et al., 2023; 242 Mg C ha^{-1} , Hayes et al., 2017). In contrast to soil carbon stocks, the mangrove average soil carbon accumulation rate found for the region (i. e., 1.84 ± 0.11 tonnes C ha⁻¹ yr⁻¹) is relatively smaller than recent

global reviews ($2.3 \text{ tonnes C ha}^{-1} \text{ yr}^{-1}$, Jennerjahn, 2020; $2.4 \text{ tonnes C ha}^{-1} \text{ yr}^{-1}$, MacKenzie et al., 2021; $2.03 \text{ tonnes C ha}^{-1} \text{ yr}^{-1}$, Yan et al., 2025). We found that, despite some changes in mangrove extent since 1990, the mangrove forests along the Barron River remain relatively well-conserved and in good condition. This suggests that the long-term management of mangroves, led by the Yirrganydji People and their ancestors before them, plays a crucial role in sustaining this ecosystem and preserving its blue carbon assets. Ensuring effective conservation and management plans is essential for maintaining these favourable conditions into the future. In this context, integrating the knowledge from the Yirrganydji People is critical for long-term success, as it aligns management goals with culturally significant practices. By embedding these practices into conservation strategies, management plans can support both ecological resilience and cultural sustainability, creating a more holistic approach to mangrove stewardship.

Through this partnership, we showed that the blue carbon assets (i.

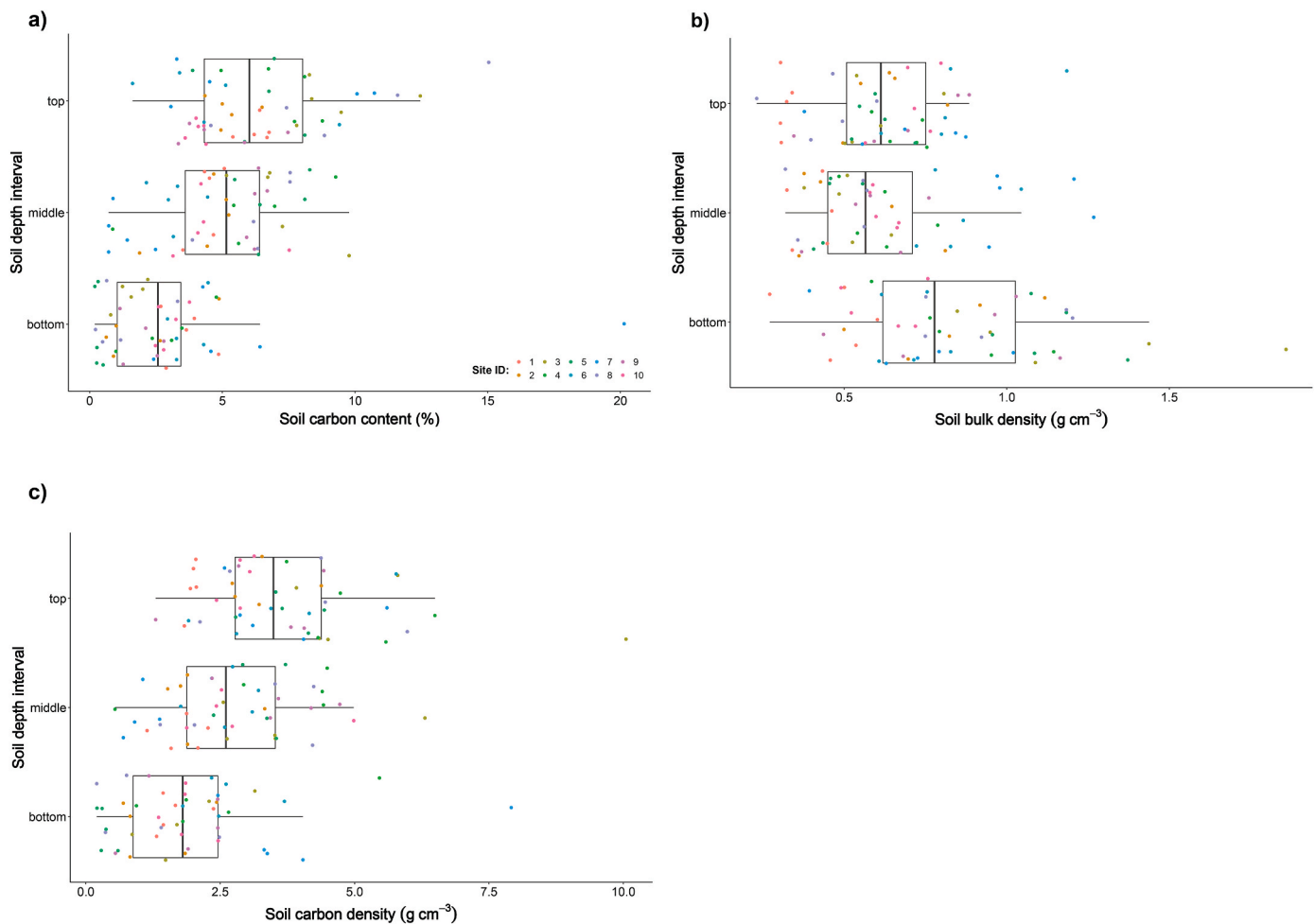


Fig. 4. Variation of soil properties across three depth intervals for soil samples collected in mangroves within the study region: a) soil carbon content (%), b) soil bulk density (g cm⁻³), and c) soil carbon content (g cm⁻³).

e., stocks, sequestration rates) vary substantially within the study region. 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). This leads to variability in their structure at different scales, which in turn can result in changes in the ecosystem services they provide to coastal communities (Owers et al., 2022). We also demonstrated that plant diversity might play a role in the variability of blue carbon stocks and sequestration rates. It is well established in the literature that carbon stocks can also be 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). Furthermore, 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). While our study provides an indication of the main species present in the study area, a detailed mangrove vegetation survey would be necessary to better investigate the contribution of different species to blue carbon stocks and sequestration rates.

Understanding the blue carbon potential of mangroves offers a significant opportunity to promote Indigenous-led land management to conserve mangrove ecosystems and maintain or increase the rate of blue carbon sequestration. By aligning blue carbon projects with Indigenous land and sea management practices, Australia can support Indigenous communities in several ways. For example, by integrating Indigenous

perspectives into blue carbon studies can also promote cultural preservation, ensuring that land management strategies respect cultural values and heritage (Brondízio et al., 2021). Additionally, mangroves are situated at the intersection of land and sea country, where Traditional Custodians have protected these environments for tens of thousands of years. Their deep ecological knowledge and cultural connection to these areas provide invaluable insights for sustainable management and conservation (Moore et al., 2022). Integrating Indigenous knowledge with scientific blue carbon studies, through partnerships like the one conducted for this study, can enhance ecosystem management, improving both carbon sequestration outcomes and the health of biodiversity (Brondízio et al., 2021; Moore et al., 2022). Furthermore, these studies can strengthen Indigenous stewardship and governance over land and sea resources by recognizing Indigenous-led conservation practices. While this study led to a partnership between scientists and the Yirrganydji People to understand the blue carbon potential in the study region, this was supported by the current partnership between the Yirrganydji People and Cairns Airport. In this case, the airport was the first in Australia to have a sustainability loan that accounts to both biodiversity and natural capital KPIs.

Conservation and restoration projects have the potential to provide economic benefits through carbon markets (Vanderklift et al., 2019). A significant risk for Traditional Custodians in coastal regions of Australia, like the Yirrganydji People, is the potential exclusion from carbon market opportunities due to their longstanding stewardship of Sea Country. In this context, additionality requirements for blue carbon projects tend to favour private landholders who have historically

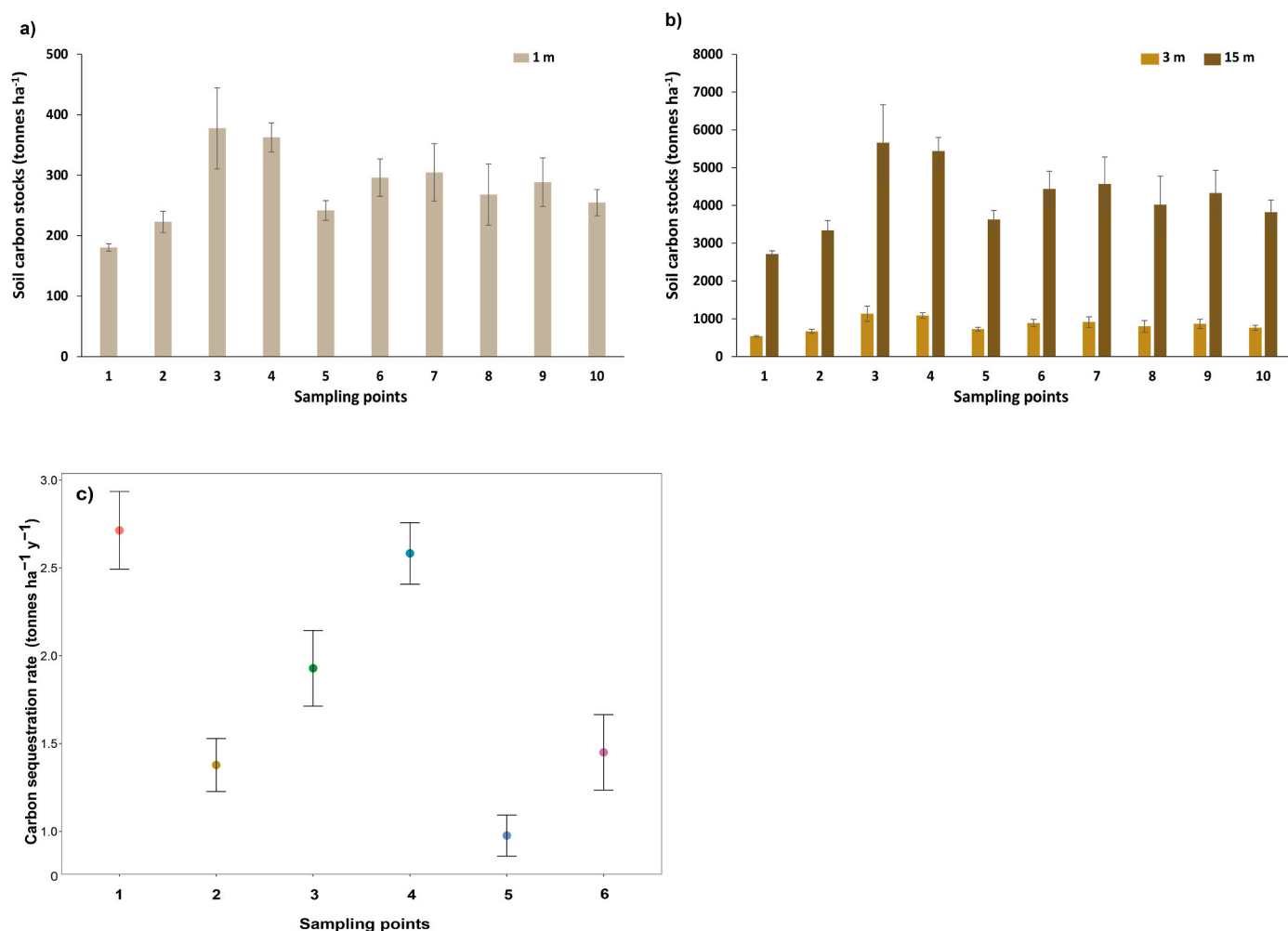


Fig. 5. Soil organic carbon stocks for three different soil depths included in the study: a) 1 m soil depth, b) extrapolation at 3 m and 15 m, and c) accumulation rates across different sampling sites in the Bidakarra (Barron River estuary) region.

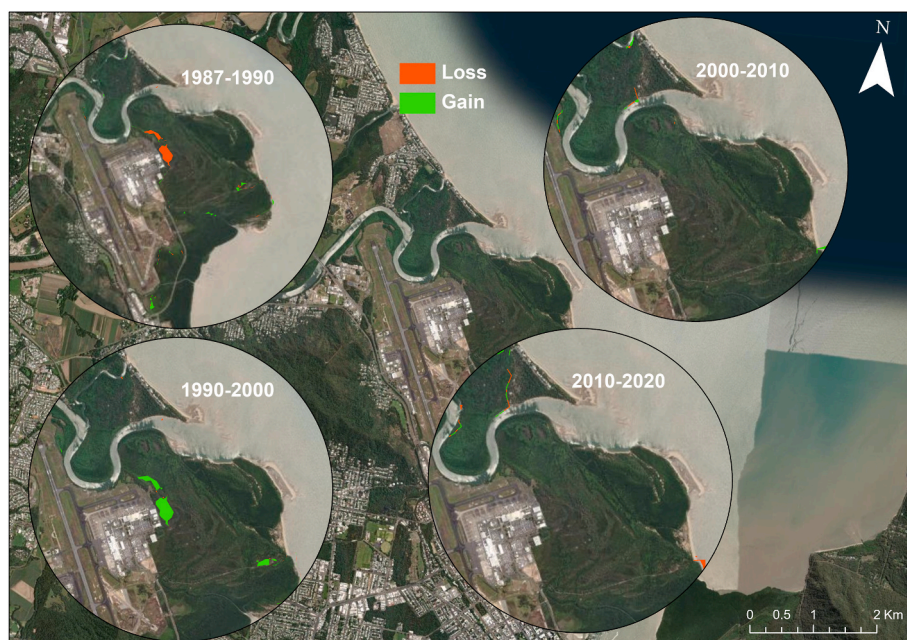


Fig. 6. Change analysis of mangrove distribution between four different time periods: 1987–1990, 1990–2000, 2000–2010, and 2010–2020. This analysis was conducted based on the mapped multi-decadal mangrove distribution at national level (1987–2020 from the DEA Mangrove Canopy Cover 2.0.2; [Lymburner et al., 2020](#)).

impacted coastal wetlands on their properties, potentially sidelining Traditional Custodians groups who have preserved these ecosystems (Bell-James and Lovelock, 2019). Similarly, in the study region, opportunities for blue carbon additionality are limited for the Yirrganydji People due to their long-standing role in maintaining the mangroves within their Country. We recommend investigating potential inequities in Indigenous access to blue carbon restoration projects, including consideration of stewardship payments, to ensure fair participation and benefit sharing in environmental markets (Sangha et al., 2024).

Overall, active engagement and knowledge sharing with coastal communities are essential for reconnecting People with nature and building awareness of coastal wetlands, along with the ecosystems and services they provide. Additionally, ongoing conservation actions and monitoring efforts are critical for sustaining healthy mangroves. This study demonstrated that by combining the scientific knowledge on blue carbon with long-term co-management of land, project co-design and community engagement on Country fosters a powerful and efficient partnership. Such collaborations not only strengthen ecological outcomes but also enhance cultural continuity and support locally driven conservation. Continued investment in these partnerships will be vital for adaptive, resilient coastal wetland management into the future. Traditional Custodians, such as Yirrganydji, have always taken care of their Sea Country, and cooperating effectively with researchers, local businesses and landholders, ensures that this will continue into the future. In addition, knowledge shared by Traditional Custodians about Country that they know so well is invaluable to tailoring management and research outcomes to specific sites such as Bidakarra.

CRediT authorship contribution statement

Micheli D.P. Costa: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **I. Noyan Yilmaz:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis. **Pawel Waryszak:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Rory Crofts:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Melissa Wartman:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Pere Masqué:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Brian Singleton:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Gavin Singleton:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Ashlyn Skeene:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Lucy Friend:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Peter I. Macreadie:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ocecoaman.2025.107971>.

Data availability

The mangrove distribution data used in this study is openly available at the cited sources. All other data is available in the publication and Supplementary Information.

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