ZÜRICH UNIVERSITY OF APPLIED SCIENCES
SCHOOL OF LIFE SCIENCES AND FACILITY MANAGEMENT
INSTITUTE OF NATURAL RESOURCE SCIENCES

# Blue carbon, estimation of the mangrove carbon stock and restoration on the Brunswick River New South Wales

Bachelor Thesis

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Bachelor's degree Natural Resource Sciences

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## Abstract English

Mangroves, seagrasses, tidal- and saltmarshes are so called blue carbon ecosystems. These ecosystems can sequester carbon up to two to forty times faster than tropical forests, even though their area cover is two orders of magnitude smaller than terrestrial forests. Next to their carbon sequestration, blue carbon ecosystems provide numerous ecosystem services such as protection against floods, providing critical nursery grounds and improving water quality. Due to their proximity, the ecosystems are lost at an estimated global rate of 1-7% annually through anthropogenic and natural influences. When these ecosystems become degraded, the previously captured carbon is released, and ecosystem services are lost. On the Brunswick in River Northern New South Wales, degraded and unstable riverbanks and their ecosystems are being restored by both authorities and local organisations. Whilst the blue carbon ecosystems occur on the Brunswick River, their specific carbon stock is not well known. For the assessment of the mangrove carbon stock, a non-intrusive carbon stock methodology was developed for the species *Avicennia marina* and *Aegiceras corniculatum* and applied on a degraded riverbank area. Additionally, maps were developed to assist local organisations in finding potential restoration sites without major bureaucracy and including blue carbon potential. A total mangrove carbon stock of 50.84 ± 2.41 Mg $ha^{-1}$ was estimated for a degraded riverbank area. Approximately 96% of this carbon stock is stored in the species *Avicennia marina*, with 43.40 ± 2.00 Mg $ha^{-1}$ stored above ground and 5.68 ± 0.31 Mg $ha^{-1}$ belowground in the roots. The maps developed highlight where urgent restoration is necessary based on riverbank stability and show the blue carbon priority areas. Further studies and inputs from trained experts in the field of carbon stock measurements are recommended to fine tune and confirm the developed methodology.

# Abstract Deutsch

Mangroven, Seegräser, Gezeiten- und Salzwiesen sind sogenannte blaue Kohlenstoffökosysteme. Diese Ökosysteme können Kohlenstoff zwei- bis vierzigmal schneller binden als tropische Wälder, obwohl ihre Fläche um zwei Grössenordnungen kleiner ist als die von Landwäldern. Neben der Kohlenstoffspeicherung erbringen diese Ökosysteme zahlreiche Ökosystemleistungen wie Schutz vor Überschwemmungen, Raum für Laichgebiete und Verbesserung der Wasserqualität. Aufgrund ihrer räumlichen Nähe gehen diese Ökosysteme durch anthropogene und natürliche Einflüsse weltweit um schätzungsweise 1-7 % pro Jahr verloren. Wenn diese Ökosysteme geschädigt werden, wird der zuvor gebundene Kohlenstoff freigesetzt und die Ökosystemleistungen gehen verloren. Am Brunswick River im nördlichen Neusüdwales werden degradierte und instabile Flussufer und ihre Ökosysteme sowohl von den Behörden als auch von lokalen Organisationen wiederhergestellt. Zwar gibt es am Brunswick River blaue Kohlenstoffökosysteme, aber ihr spezifischer Kohlenstoffbestand ist nicht weit erforscht. Für die Bewertung des Mangroven Kohlenstoffbestands wurde eine nicht-invasive Kohlenstoffbestandsmethode für die Arten *Avicennia marina* und *Aegiceras corniculatum* entwickelt und auf ein degradiertes Flussufergebiet angewendet. Darüber hinaus wurden Karten entwickelt, die lokalen Organisationen dabei helfen sollen, ohne großen bürokratischen Aufwand potenzielle Wiederherstellungsstandorte zu finden, die auch blauen Kohlenstoffpotenzial enthalten. Für ein degradiertes Flussufergebiet wurde ein Gesamtkohlenstoffbestand der Mangroven von 50,84 ± 2,41 Mg $ha^{-1}$ geschätzt. Etwa 96 % dieses Kohlenstoffbestands ist in der Art *Avicennia marina* gespeichert, wobei 43,40 ± 2,00 Mg $ha^{-1}$ oberirdisch und 5,68 ± 0,31 Mg $ha^{-1}$ unterirdisch in den Wurzeln gespeichert sind. Die erstellten Karten zeigen, wo dringender Sanierungsbedarf aufgrund der Stabilität der Flussufer besteht und welche Gebiete für blauen Kohlenstoff vorrangig sind. Weitere Studien und Beiträge von geschulten Experten auf dem Gebiet der Messung des Kohlenstoffbestands werden zur Feinabstimmung und Bestätigung der entwickelten Methodik empfohlen.

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# Abbreviations

| | |
|---|---|
| BVL | Brunswick Valley Landcare |
| $C_{d\&dWood}$ | Dead and downed wood carbon pool |
| CI | confidence interval |
| $CO_2$ | Carbon dioxide |
| $CO_2e$ | Carbon dioxide equivalent |
| $C_{treeAG}$ | Above ground tree carbon pool |
| $C_{treeBG}$ | Below ground tree carbon pool |
| Dbh | Diameter at breast height (diameter measured at 1.37m above ground) |
| diam30 | Diameter measured at 30cm above ground |
| DPE | NSW Department of Planning and Environment |
| DPI | NSW Department of Primary Industries |
| EPIs | (NSW) Environmental planning instruments |
| FAO | Food and Agriculture Organisation of the UN |
| IOC | International Oceanographic Commission |
| IPCC | Intergovernmental Panel on Climate Change |
| LEP | Local Environment Plans (NSW) |
| Mg | Megagram = $10^6$g or tonne |
| NSW | New South Wales, Australia |
| PCFML | Positive Change for Marin Life |
| SEED | Central Resource for Sharing and Enabling Environmental Data in NSW |
| SEPPs | (NSW) State environmental planning policies |
| UNEP | United Nations Environment Programme |
| UNESCO | United Nations Educational, Scientific and Cultural Organisation |
| Zone C1 | Conservation zone 1 – National Parks and Nature Reserves |
| Zone C2 | Conservation zone 2 – Environmental Conservation |
| Zone C3 | Conservation zone 3 – Environmental Management |
| Zone C4 | Conservation zone 4 – Environment Living (NSW) |

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# 1 Introduction

With climate change, many new challenges arise, such as rising temperatures and an increase in severe floods. The need to address these challenges through adaptation and mitigation has become increasingly urgent. Restoration aids mitigation by enhancing the carbon sinks which accumulate greenhouse gases, such as carbon dioxide (IPCC, 2014). Furthermore, the restoration of degraded ecosystems supports adaptation by increasing their resilience and capacities to support a greater population of flora and fauna (Jamie Pittock, 2008; S. Crooks et al., 2011). Blue carbon is the atmospheric carbon captured and stored by marine and coastal ecosystems, mainly mangroves, seagrasses, tidal- and saltmarshes (Alongi, 2018; Lovelock & Duarte, 2019; Macreadie et al., 2019). The term blue carbon was coined in 2009 through a report by the UNEP, FAO and IOC/UNESCO, which completed the global carbon accounting assessment begun by the Intergovernmental Panel on Climate Change (IPCC) (Nellemann, 2009). Blue carbon ecosystems are capable of higher carbon sequestration per unit area than terrestrial forests, even though their global area cover is one to two order of magnitude smaller (Mcleod et al., 2011; Taillardat et al., 2018). Depending on the type and state of the ecosystems, their sequestration rates can be two to forty times higher than tropical forests, with carbon being stored for millennia instead of decades (Duarte et al., 2005; Murray et al., 2011; Nellemann, 2009; Taillardat et al., 2018). These ecosystems are therefore critical for climate change mitigation.

Besides their sequestration of carbon, blue carbon ecosystems provide numerous ecosystem services. These include, but are not limited to, coastal protection against floods and storms, providing habitats and nurseries for diverse species, supporting healthy fisheries, improving water quality, and providing tourism and recreational benefits (DPE, 2022a; Kelleway et al., 2017; Mapping Ocean Wealth, 2021; Nellemann, 2009). Despite these services and benefits, blue carbon ecosystems are some of the most threatened ecosystems on earth (Nellemann, 2009; Serrano et al., 2019). Globally, habitats are being lost at an estimated rate of 1–7% annually (Hopkinson et al., 2012). In Australia, approximately 52–78% of mangroves, 50% of saltmarshes and 20–26% of seagrass meadows have been lost since European settlement (DPE, 2022a). Between 1991 and 2015 an estimated 1148 ha of mangroves have been lost in South-Eastern Australia (Navarro et al., 2021). Due to their proximity, the ecosystems are subjected to anthropogenic influences such as land-use changes, clearing and degradation (Kelleway et al., 2017). When blue carbon ecosystems are degraded the ecosystem services are lost and previously captured carbon and other greenhouse gases, such as methane, are released (DPE, 2022a; Kelleway et al., 2017). Thus, there is a strong need to protect, strengthen and restore these ecosystems.

The Brunswick River, located in the Byron Shire in the Northern River Region of New South Wales (NSW) Australia, holds immense cultural and heritage value, whilst providing ecosystem services including habitat to all three blue carbon ecosystems, nursery grounds, recreational and commercial activities, and aquaculture (Marx & Goodsell, 2022). However, through anthropogenic and natural influence, the riverbanks have become degraded and unstable on numerous locations along the river. The biggest natural influences have been the flooding events which have occurred in 1974, 1976, 1978, 2005, 2017 and in early 2022 (Byron Shire Council, 2021). Through anthropogenic activities, such as logging and clearing of riparian areas, including mangroves, the riverbanks have lost their natural stability, with ground vegetation being cleared through grazing, and trampling by cattle and humans (ABS, 2010; Gale et al., 2004; Marx & Goodsell, 2022). In addition, parts of the river have been illegally stabilized with 'hard' measures, such as large rocks, restricting the natural river flow and regrowth of riparian vegetation such as mangroves and saltmarshes (Byron Shire Council, 2018). The NSW Department of Planning and Environment (DPE) (2019) graded the overall estuary health as poor in their water quality monitoring program. The most significant factor to seagrass habitat loss is degraded water quality, which has also been a main factor of decreased seagrass habitats on the Brunswick Rive. (Murray et al., 2011).

Whilst there is mapping of the blue carbon ecosystems in the Brunswick River Estuary, there is currently limited information of the specific carbon stock of these ecosystems, and if then only of intact habitats (DNR, 2006; MOW, 2022). Estimates for the mangrove and tidal marsh soil carbon stock on the Brunswick River range from 50 Mg $ha^{-1}$ to 300 Mg $ha^{-1}$ depending on the habitat location (MOW, 2022). For restoration projects, it is important to know the carbon stock and vegetation pre-restoration, as a measurement of success (or failure) of the completed restoration. Carbon stock measurements for seagrasses, tidal- and saltmarshes are scarce, difficult to measure due to the habitat location, requirement of expensive equipment and/or a laboratory, permission of the government and expert knowledge of the ecosystems (Fisheries Management Act 1994, 2022). The access to mangroves is geographically easier, allowing less cost intensive and safer measurements of the carbon stock. Even though many field methods for mangrove carbon stock measure have been developed, most require the harvesting and laboratory analysis of mangrove specimens within the study area to develop site specific allometric equations (Chave et al., 2005; Comley & McGuinness, 2005; Kauffman & Donato, 2012). Mangroves are protected in NSW under the Fisheries Management Act 1994 (2022), and thus any harvesting is prohibited without permission. However, allometric equations, formulas and accepted standards exist for a non-intrusive field estimate (Chave et al., 2005; Howard et al., 2019; Kauffman & Cole, 2010; Kauffman & Donato, 2012; Komiyama et al., 2005). Although these exist, they have not been collected and described for the non-intrusive field estimation of the mangrove carbon stock on the Brunswick River.

Restoration projects have been commenced by the Byron Shire Council and other authorities (Byron Shire Council, 2020). However, as large areas are affected by degradation and riverbank instability, local organisations such as Positive Change for Marine Life (PCFML) and Brunswick Valley Landcare (BVL) have started to restore smaller riverbank areas, which are not within state or council land (Marx & Goodsell, 2022; Ratcliffe, 2019). To date these areas have been chosen by surveying the river by boat or kayak, using local knowledge and researching if the potential areas are owned by council or state (Marx & Goodsell, 2022). Currently, no maps exist with the location of potential restoration sites based on degraded riverbanks, blue carbon potential and without major bureaucracy. Major bureaucracy is defined in this thesis as the application process through authorities for projects on council and governmental land, which can delay restoration projects up to years.

The aim of this thesis is to give an overview of the mangrove blue carbon ecosystem, provide information on the field methods for estimating the mangrove carbon stock and vegetation on a degraded riverbank on the Brunswick River, and show where on the Brunswick River potential restoration sites are, based on their feasibility to avoid major bureaucracy.

To specify the aim of the thesis, three research questions were developed:

- What is the methodology for non-intrusive field estimation of mangrove carbon stock, and what is the estimate for a degraded riverbank on the Brunswick River?
- Where on the Brunswick River are areas with degraded riverbanks, which can be restored without major bureaucracy, and which of these areas show blue carbon potential?
- Where do mangroves occur, how much carbon do they store and where?

Through literature research, the information on mangrove ecosystems will be gathered and presented. By planning and conducting a carbon stock and vegetation survey, the methodology will be developed, and the carbon stock per hectare for degraded riverbanks on the Brunswick River will be estimated and presented. In addition, the species diversity of the site will be calculated. Through data research, existing maps will be gathered, reviewed, and analysed to find future restoration sites which avoid major bureaucracy and show blue carbon potential. These will be presented as maps.

# 2 Literature and Data review

In the following sections literature of mangroves, with focus on NSW Australia, as well as data used for the search of potential restoration sites on the Brunswick River are reviewed.

## 2.1 Mangroves

Mangroves are salt-tolerant woody trees and shrubs that are adapted to intertidal areas within protected coastlines and estuaries (Alongi, 2018; Tran, 2014). They include around 70 true mangrove species of 40 genera in 25 families, and also a loosely defined group of mangrove associates (Alongi, 2018). In NSW, at least six different species are found, with the most common being the Grey mangrove (*Avicennia marina*) and the River mangrove (*Aegiceras corniculatum*) (PlantNET, 2022; Stewart & Fairfull, 2008). These are both the main mangroves found on the Brunswick River.

### 2.1.1 Location and habitat adaptations

Globally, mangroves are confined to tropical and subtropical coastal areas and grow above sea-mean (Alongi, 2018; Taillardat et al., 2018). They are generally restricted to the intertidal area of saline of brackish wetlands, which consist of anoxic saline sediments (Kauffman & Donato, 2012). Mangroves have adapted to this environment by developing specialised physiological, morphological and reproductive traits including salt-secretion pores, salty sap, wax coated leaves which limit saltwater penetration, low assimilation rates, nutrient-use efficiencies, viviparous embryos, and specialised root systems (Alongi, 2018; Stewart & Fairfull, 2008). Specialised root systems, such as pneumatophores, allow gaseous exchange for root tissues in the anoxic soils (see image 1) (Kauffman & Donato, 2012).

In NSW, mangroves are found all along the coast and are estimated to cover an area of 13'700 hectares (DPE, 2022a). *Avicennia marina* is found along the whole coast and *Aegiceras corniculatum* from Merimbula on the South Coast to the Tweed River on the North Coast (Stewart & Fairfull, 2008).

**Brunswick River**

The Brunswick River drains an area of 280 $km^2$ and flows 33.6 km from the headwaters in the Burringbar Ranges, through Main Arm and Mullumbimby to the ocean at Brunswick Heads where it forms a mature, open, wave-dominated estuary (*DPE*, 2018; Digital Atlas of Australia, 2022). The estuary covers 2.9 $km^2$, and includes 3 tributaries of the river: Marshalls Creek, Kings Creek, and Simpsons Creek (see image 2). (*DPE*, 2018). From Mullumbimby, the river is under the tidal influence of the estuary. It is in this tidal subjected area where blue carbon ecosystems including mangroves are located.

***Image 1**: Pneumatophores from Avicennia marina can be seen in the bottom half of the picture. The large tree trunk belongs to a Avicennia marina and the basitony growth-form behind to Aegiceras corniculatum.*

***Image 2:** Intact mangroves in Kings Creek, tributary of the Brunswick River.*

### 2.1.2 Mangrove carbon sequestration and storage

Biological carbon sequestration is the process of removal and storage of carbon dioxide from the atmosphere by photosynthesis (Nellemann, 2009). Three processes are involved in carbon sequestration and storage: The annual sequestration rate, the amount of carbon stored in above- and below ground carbon and the total carbon stock of an ecosystem (Alongi, 2018). The annual sequestration rate according to Alongi (2018) is defined as the annual flux of organic material in a mature ecosystem, transferred to anaerobic soils where no oxidation can take place and thus no $CO_2$ is released into the atmosphere.

**Above- and belowground carbon pools**

Mangroves store carbon both above- and belowground in their biomass and soils. The above- and belowground carbon can be separated into different component pools. The aboveground carbon pools are: trees (> 1.3 m height) both dead and alive, palms, shrub and dwarf mangrove, dead and downed wood and understory vegetation including seedlings, herbs, litter and pneumatophores (see figure 1) (Kauffman & Donato, 2012). The belowground carbon pool consist of roots and soil (Kauffman & Donato, 2012). Mangroves store more carbon below ground than aboveground, whereby more is stored in soils than roots (Alongi, 2012).

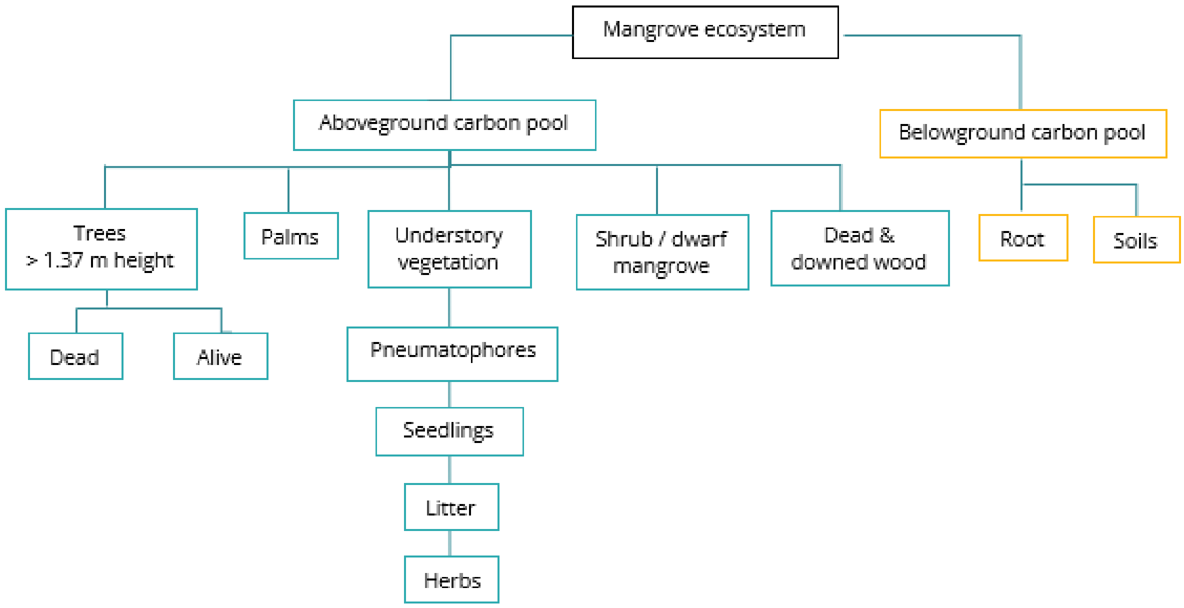


***Figure 1:*** *The mangrove ecosystem components for the qualification of biomass and ecosystem carbon stocks. Carbon is stored in each of the components within the biomass. Adjusted from Kauffman and Donato (2012)*

## Carbon sequestration and carbon stock

Carnell et al. (2019) estimated that on average, mangroves in Australia can sequester 4.8 Mg $ha^{-1}$ annually. However, mangrove carbon sequestration and carbon stocks vary both on local and regional spatial scales (Rovai et al., 2018; Sanderman et al., 2018; Simard et al., 2019). After a restoration project period of 25-40 years, the Richmond estuary sequestered 11.5 Mg $ha^{-1}$ annually (Carnell et al., 2019). This shows that successful restoration of mangroves can be an effective measure for climate change mitigation.

The carbon stock estimations vary for Australia. According to a review by Alongi (2018) the range of estimated carbon stocks lies between 662-2139 Mg $ha^{-1}$ for mangrove forests in Australia. In comparison, the aboveground carbon stock of mangroves average 125 ± 90 Mg $ha^{-1}$, and in soil carbon stock 251 ± 155 Mg $ha^{-1}$ according to Serrano et al. (2019). In NSW, the total mangrove carbon stock has been estimated to approximately 5 billion tonnes (DPE, 2022a).
Depending on how data was collected, and what allometric equations were used for the estimations, the biomass and therefore carbon stock predictions can yield large differences (Kauffman & Donato, 2012).

## 2.2 Data overview

In the following section the data used, it's origin and necessary background information for the search for potential restoration sites is described.

### 2.2.1 Riverbank stability maps

The riverbank stability layer was obtained from Positive Change for Marine Life (PCFML). In 2021 and 2022, pre- and post-flood, the riverbank stability was mapped by kayak-based surveys (Marx & Goodsell, 2022). Mapping was conducted from the beginning of Mullumbimby, where the river passes under the bridge at Coral Avenue, until the estuary mouth at Brunswick Heads.

The riverbank stability was recorded as a line feature class. Riverbanks were assigned the categories "stable", "unstable", "high risk", "artificial stabilisation" and "cleared vegetation" (Marx & Goodsell, 2022). The categories were defined by Marx and Goodsell (2022) as follows; "stable banks are well vegetated or stabilised with gentle slopes and intact banks, unstable banks show sings or erosion and lack of stability, and high-risk banks show clear signs of slumping and undercut banks with minimal vegetation or very steep banks". Degraded riverbanks are defined in this study as riverbanks in the categories "unstable", "high risk" and "cleared vegetation".

### 2.2.2 Byron Shire Local Environmental Plan and conservation zones

Conservation zones are a type of land use zones, which are designated by the NSW Environmental planning instruments (EPIs). The EPIs are State Environmental Planning Policies (SEPPs) and Local Environmental Plans (LEP) under the Environmental Planning and Assessment Act 1979 (*Environmental planning Instruments*, 2020). Prior to December 2021 conservation zones were known as environmental protection ones (E) under which they are sometimes still referred to in LEP of councils which have not updated the terminology (DPE, 2022b). Only the terminology changed with the renaming. There are four conservation zones: National Parks and Nature Reserves (zone C1), Environmental Conservation (zone C2), Environmental Management (zone C3) and environmental Living (C4) (DPE, 2022b). Zone C1 is protected fully under the National Parks and Wildlife Act 1974 (2022). Although environmental protection works are permitted in zones C2 and C3, restoration projects still need to undergo an application process (Byron LEP 2014, 2022). These areas therefore need to be avoided to prevent major bureaucracy.

The Byron LEP 2014 layer was obtained through PFCML who had access to the 2021 ArcGIS compatible layer. Direct access to a more recent version was requested from Byron Bay Council, however the access to the map exceeded the project budget.

The Byron LEP 2014 Version 2021 contains zones C1, C2 and C3, which are labelled as Environmental Protection Zones E1, E2 and E3 (*Byron LEP 2014 GIS layer*, 2021). The map also contains areas labelled "deferred matter", which have not been assigned a specific land-use zone. The location C1 zones within the Byron LEP 2014 were compared with the NSW National Parks and Wildlife Estate version 3 map (2022), to confirm no differences between the location of the zones.

### 2.2.3 Byron Shire Council areas

The Byron Shire conducts multiple restoration works, often in close cooperation with community groups such as Brunswick Valley Landcare (BVL) (Byron Shire Council, 2020). The restoration areas are mapped on the council's online mapping tool, and direct access was requested, but as with the Byron LEP 2014, the pricing exceeded the project budget. However, two Byron Shire council Shapefile layers were obtained from PCFML. These layers included mapping of 2019 BVL Dune Work areas and 2021 Byron Shire council bush regeneration zones (*Bush regeneration zones GIS layer*, 2021; Ratcliffe, 2019) The bush regeneration zones are areas where the council is undertaking restoration or maintenance, or where restoration and/or maintenance works are planned (*Bush regeneration zones GIS layer*, 2021). These areas are not limited to bushland.

### 2.2.4 NSW Blue carbon potential priority areas

Lal and Rogers (2021) conducted a spatial analysis study for the NSW Department of Primary Industries (DPI) Fisheries to assess the blue carbon priority areas where preservation, permanence generation and storage are high along the NSW south and north coasts. They assessed data in the context of land-use activities that either contribute to a deterioration of blue carbon or promotes delivery of blue carbon services to provide an indication of the blue carbon potential (Lal & Rogers, 2021b). As a main output, they mapped the NSW blue carbon potential priority areas, which was created to aid with choosing future restoration areas (Lal & Rogers, 2021a). The layer was accessed via the Central Resource for Sharing and Enabling Environmental Data in NSW (SEED).

Priority areas were assigned one out of the following five blue carbon potential levels: "high", "moderately high", "moderate", "moderately low" and "low" (Lal & Rogers, 2021b). The higher the generation, preservation, permanency, and storage of an area, the higher the assigned level of blue carbon potential. Lal and Rogers (2021) defined the terms generation, preservation, permanency, and storage in their study, which have been summarised below for clarity (see table 1).

***Table 1:*** *Definition of the terms generation, preservation, permanency and storage according to Lal and Rogers (2021) as used within their study 'A coastal wetland restoration first pass prioritisation for blue carbon and co-benefits in NSW'*

| Term | Definition by Lal and Rogers (2021) |
|---|---|
| Generation | The capacity of existing mangrove forests and saltmarshes to contribute to carbon additionality from dead organic material, living biomass, and soil carbon. |
| Preservation | The capacity for coastal blue carbon decomposition to be inhibited for long-term sequestration within soils, due to saline anaerobic conditions. |
| Permanency | The capacity for carbon to be preserved and not reworked under higher hydrodynamic energy conditions associated with tides and storms. |
| Storage | The volume of blue carbon within coastal Quaternary sediments. |

# 3 Materials and Methodology

## 3.1 Vegetation and carbon stock

The base methodology for the mangrove carbon stock was taken from Kauffman and Donato (2012), simplified, and adjusted for a non-invasive measurement and inclusion of a general vegetation survey, as described in the following sections. The following components were surveyed: vegetation and cover, dead and downed wood, pneumatophores, and soil texture. These components were surveyed for a pre-restoration recording of the site. Surveyed and analysed for the carbon stock were trees, and dead and downed wood. In addition, the root carbon stock was analysed through the gathered tree data. No carbon stock was estimated for pneumatophores and soil, as these require laboratory analysis and field sampling equipment, which was not available. Understory vegetation (seedlings, herbs, litter) was not analysed for carbon stock as the contribution to the total ecosystem carbon stock is minimal and requires laboratory analysis (Kauffman & Donato, 2012).

### 3.1.1 Study area

The mangrove carbon stock estimation and vegetation survey was conducted on a 200 m inner bank stretch after Mullumbimby. The area is geographically located between 28°32’48.8” S and 153°30’28.2” E, and 28°32’52.8” S and 153°30’30.5” E (see figure 2).

The survey site is situated on private farming land, which is primarily used for cattle farming. As there is no fencing, the cattle have unrestricted access to the Brunswick River. Due to the cattle access, removal of riparian vegetation and previous floods the site is mostly degraded and bare, except on the most southern side, where few mangrove clusters have grown in the intertidal area (see image 3).

The crest area is dominated by pasture grasses with no or few trees (see image 4). Most of the intertidal area is bare or loosely vegetated. The crest area forms a river cliff to the intertidal area, which has slid down in some areas due to riverbank undercut, except on the point bar of the slip-off slope where deposition has occurred creating an even transition. The survey site was visually assessed from the river by kayak and on land before the sampling design was commenced.


***Figure 2:*** *Map of the mangrove carbon stock and vegetation survey area on the Brunswick River NSW*

***Image 3:*** *Intertidal area, towards the southern end of the survey area. A few mangroves are growing on the intertidal area, with the crest area forming a cliff, where the start of undercutting is visible.*

***Image 4:*** *View onto the survey site from on the river in kayaks. The dominating grasses, undercut riverbank can clearly be seen. On the left side few trees are visible on the crest and intertidal area.*

### 3.1.2 Sampling design

A total of 10 quadrant plots of 25 $m^2$ each were surveyed. Along the 200 m stretch, the ten plots were plotted from the crest area down to the intertidal area in 15 m intervals (see figure 3). All plots had sides of 5 x 5 m and were measured using open reel fibreglass tape measures. The corners were pinned with wooden poles and yellow coloured string was used to outline the plots for better visibility. The quadrant shape was chosen to accommodate the intertidal and crest area. In each plot a microplot of 50 x 50 cm was plotted using a wooden folding ruler, for the measurements of pneumatophores. For the measurement of dead and downed wood, two transects, each with an average length of 7 m were laid out from opposite corners in each plot. The sampling time was planned around low tide, for safety and for the exposure of pneumatophores, dead and downed wood, seedlings, and the trunk base of mangroves.

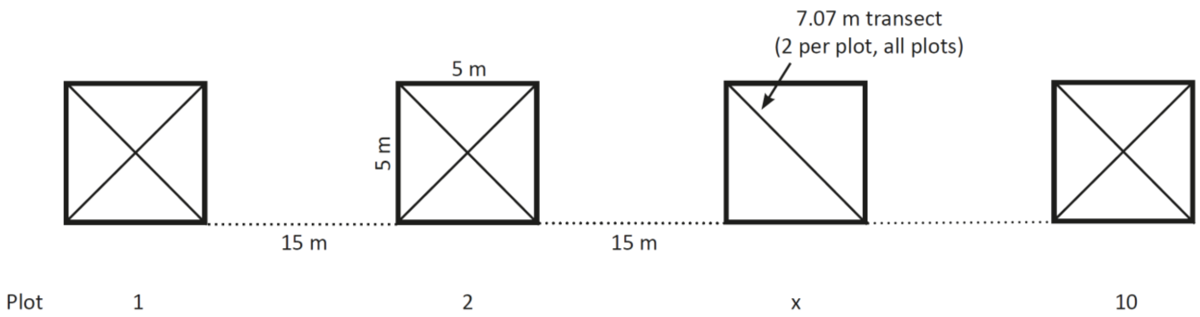


*Figure 3: Sampling plot design for vegetation and carbon stock survey conducted on a 200 m degraded riverbank stretch on the Brunswick River NSW. X = plots three to nine.*

### 3.1.3 Field procedures

The main data collection was conducted over two days. The first four plots were surveyed on the 3.11.2022 and the remaining 6 plots on the 7.11.2022. For each plot, the altitude, coordinates and precision, crew members, date, dead and downed wood, plot number, pneumatophores, a site description, soil texture, tree measurements, vegetation, and vegetation cover were recorded in a field book by pen. The altitude, coordinates, and precision were recorded with the GPS Coordinates app, version 5.07 (108) on an iPhone X (iOS Version 16.11). Photographs were taken from every plot. On the 6.12.2022 another field trip was conducted to specifically identify previously unidentifiable or uncertain plant species. As these were mostly trees, they could easily be located using plot location, height, and notes from the first two field trips.

### Dead and downed wood

All dead and downed wood pieces that had fallen within 2 m of the ground surface and intersected the transects were measure in each plot. For all pieces, the diameter, and length were recorded. The diameter was measured in millimetres using a Craftright 150 mm digital calliper. The length was measured in centimetres with a wooden folding ruler or, if too long, using an open reel fibreglass tape measure. The decay status of each piece was also recorded: sound (knife bounces off or only sinks in slightly when struck) or rotten (knife sinks in deeply and wood is crumbly with significant loss). The decay status is only necessary for large pieces, but was recorded for all pieces, as size class classification was completed after the field surveys (Kauffman & Donato, 2012).

### Pneumatophores

In each microplot each pneumatophore was counted, and the individual height measured. The height was measured in centimetres using a wooden folding ruler. For each plot, the percentage of pneumatophore cover was estimated.

### Trees and seedlings

For all trees (>1.37 m) and seedlings (<1.37 m) the species was identified using the methods described in the vegetation and cover section below. Trees and seedlings were included in the survey if at least 50% of the main stem was rooted inside the plot.

For all trees, the species the height, circumference at 1.37 m above ground level and the status of the tree were recorded. If the circumference measurement at 1.37 m above ground level was not possible, due to the growth habit, the diameter at 30 cm above ground level (diam30) was measured. The diam30 was recorded using a tape measure and a Craftright 150 mm digital calliper. Alternatively, a tape measure was used where the diameter was too large for the digital calliper. The circumference was measured with a tape measure.

The height was estimated in metres using the yardstick method as described by Dr. Coble (2015) from the Arthur Temple College of Forestry and Agriculture.

Decaying or dead standing trees were given one of three statuses: status 1 describing a recently dead tree with no leaves, but all twigs and branches attached, status 2 describing a tree with no twigs or small branches, and status 3 describing a tree with the standing stem only (Kauffman & Donato, 2012). For status 3 the diameter at the base of the tree was also recorded. If the tree was alive, it was recorded as such.

For seedlings the species, height, circumference, or if possible, diam30 and status were recorded. The height was measured using tape measures or wooden folding rulers. The, diam30and status were recorded the same as for trees.

**Soil texture**

The topsoil of each plot was classified into sand, silt, clay, or a mixture using the ribbon method as described by the DPI (2014).

**Vegetation and cover**

For each plot, all species of plants were identified, and species cover, plant canopy cover (if applicable), total canopy cover and total vegetation cover were estimated in percentages. Plant identification was conducted with the plant identification books from Duke (2006), Holliday (2003), Stephens and Sharp (2009), and Logan River Branch SGAP (Qld Region) Inc. (2002). For faster identification the Apps iNaturalist Version 3.2.6, Pl@ntNet Version 3.13.2, and Flora Incognita Version 3.3 were used to delimit the plant families and genus (Cirad et al., 2022; iNaturalist & California Academy of Sciences, 2022; TU Ilmenau, 2022). All species were double-checked for identification and probability of occurrence in the area using PlantNET (2022). The species and total vegetation cover were estimated by taking the average estimate of two to four people estimates per plot. The plant canopy cover and total canopy cover were estimated for all trees and shrubs, also by two to four people per plot.

### 3.1.4 Data review and analysis

After the field measurements were taken, the data was digitalised and reviewed in Microsoft Excel for Microsoft 365 MSO version 2210. All plant species were checked again for probability, assigned to their families, and noted as native or naturalised using PlantNET (2022) and the threatened biodiversity profile search from the NSW DPE (2022). To check if naturalised species were invasive to the area, the NSW WeedWise page from the NSW DPI (2022) was used.

To calculate species diversity, a separate, Excel file was created with the plot-specific cover of each species. This species file was then exported to a CSV., and used to generate a cross table with the aid of Stefan Widmer's R Script (see appendix). The data was analysed using R, Rstudio Version 2022.12.0 Build 353 and the 'vegan' R package by (Oksanen et al., 2020). For species diversity, the species richness, Shannon-index, and species evenness were calculated for each plot.

For the calculations of the mangrove carbon stock estimations, Excel for Microsoft 365 MSO version 2211 was used. Usually, allometric equations are developed for site- and species-specific estimation of the mangrove biomass. Because this was not possible, as no laboratory was available, existing allometric equations for mangroves were used. The carbon mass is to be presented for the survey site, as well as scaled to per-hectare basis to report carbon pool estimates (Kauffman & Donato, 2012). In the following sections, the calculations for the assessed carbon pools are described.

### Dead and downed wood carbon pool ($C_{d\&dWood}$)

First, the diameter of all pieces was converted from millimetres to centimetres. All pieces were then sorted into four size classes according to their diameter: fine (<0.64 cm), small (0.65-2.54 cm), medium (2.55-7.6 cm), and large (>7.60 cm) (Kauffman & Cole, 2010). The use of the quadratic mean diameter (QMD) of wood particles is recommended to calculate volume rather than the mean diameter of a given wood class (Brown & Roussopoulos, 1974; Curtis & Marshall, 2000). The QMD was calculated for each size class with the following equation (see equation 1):

$$QMD\ [cm] = \sqrt{\frac{\sum d_i^2}{n}}$$

***Equation 1:*** *Quadratic mean diameter (QMD). Where d = diameter of each sampled piece in the size class [cm], and n = count of pieces sampled in the size class (Kauffman & Donato, 2012).*

The total volume of each size class was then calculated with the recommended equations from Kauffman & Donato (2012). For size classes “fine”, “small”, and “medium” one equation was used (see equation 2) (Brown, 1971; Van Wagner, 1968). For the size class “large” and status rotten, another equation was applied (see equation 3).

$$Volume\ [m^3 ha^{-1}] = \pi^2 \left( \frac{n_1 \times QMD_i^2}{8 \times L} \right)$$

***Equation 2:*** *Equation to determine the volume of fine, small, and medium dead and downed wood size classes. $n_i$ = count of pieces sampled in the size class i, QMD = quadratic mean diameter of size class i [cm], L = total transect length [m] (Brown, 1971; Van Wagner, 1968).*

$$Volume\ [m^3 ha^{-1}] = \pi^2 \left( \frac{\sum_{k=1}^{n} d_k^2}{8 \times L} \right)$$

***Equation 3****: Equation to determine the volume of large dead wood. $d_k$ = diameter of large dead wood [cm], L = total transect length [m] (Brown, 1971; Van Wagner, 1968).*

Next, the wood biomass [kg] of each size class was calculated by multiplying the volume by the specific gravity. As the specific gravity for each size class from a survey site is calculated through laboratory analysis, existing values for each size class were researched.

As no specific gravity for the different size classes were found for the existing mangrove species on the Brunswick River, the  data for other Australian mangrove species was used from Kauffman and Donato (2012), who adapted the data to the given size classes from Kauffman and Cole (2010). The specific gravity ± standard error (SE) used for each size class were: fine 0.48 ± 0.01, small 0.64 ± 0.02, medium 0.71 ± 0.01, large 0.69 ± 0.02 (Kauffman & Cole, 2010).

The wood biomass of each size class in kilogram was then converted to wood biomass in Megagram per hectare, by dividing by the wood biomass [kg] by the total plot area (250 $m^2$) and multiplied by ten. To calculate the carbon mass, the accepted default value of 50% of the wood biomass was used (Kauffman & Donato, 2012). The total carbon pool of dead and downed wood [$Mg\ ha^{-1}$] was calculated by adding up the carbon mass of each size class.

## Tree carbon mass

For trees, the above ground tree carbon pool ($C_{treeAG}$) as well as the below ground carbon pool ($C_{treeBG}$) were calculated for mangroves *Avicennia marina* and *Aegiceras corniculatum*. The use of species-specific equations for tree biomass, developed in the region, is highly recommeneded for preciser estimates if the development of site-specific equations is not possible (Kauffman & Donato, 2012). A study conducted in NSW found that the same allometric equation can be applied to both *Avicennia marina* and *Aegiceras corniculatum*, as no significant difference existed between the biomass calculated with species specific allometric equations (Owers et al., 2018). Therefore, the same equations can be applied to both species. Comley and McGuinness (2005) developed a tree biomass and root biomass allometric equation for *Avicennia marina* in Australia. These allometric equations were applied to both *Avicennia marina* and *Aegiceras corniculatum*. The equation use the dbh of the species, thus where necessary the circumference measured at 1.37 m was converted to the dbh, by dividing the circumference by pi. Where the measurement of dbh was not possible, the diam30 was used in the equations. This was the case for the majority of *Aegiceras corniculatum*. In the following sections, the $C_{treeAG}$ and $C_{treeBG}$ are further desribed.

### *Above ground tree carbon pool ($C_{treeAG}$)*

The biomass of each individual alive tree was estimated using the following equation (see equation 4):

$$Above\ ground\ tree\ biomass\ [kg] = 0.30dbh^{2.11}$$

***Equation 4:*** *Allometric equation to determine the above ground biomass of individual grey or river mangroves. Dbh = diameter at breast height [cm] (Comley & McGuinness, 2005).*

For status 1 trees, the same equation was applied minus a constant of 2.5% of the above ground biomass estimate of the tree in representation of the leaves, as recommended by Kauffman and Donato (2012). Trees of status 2 or 3 require different calculations, which can be found in the report by Kauffman and Donato (2012).

The individual tree biomass was then summed up for each status of each species, and converted to Megagram per hectare. As the carbon concentration for living wood is below 50% and approximately 50% for dead wood, the biomass was converted to carbon mass by multiplying by 0.46 for live trees and 0.5 for status 1 trees, as suggested by Kauffman and Donato (2012). For the $C_{treeAG}$ the carbon mass of all species and statuses was summed up.

### *Root carbon pool ($C_{treeBG}$)*

The root biomass of each individual tree, alive and status 1, was estimated using the following equation (see equation 5):

$$Root\ biomass\ [kg] = 1.28dbh^{1.17}$$

***Equation 5****: Allometric equation to determine root biomass of individual grey or river mangroves. Dbh = diameter at breast height [cm] (Comley & McGuinness, 2005).*

For status 1 trees, the same equation was applied, as it was presumed the root biomass was not influenced if the tree was still standing and intact except for missing leaves. No known allometric equation exists for the root biomass calculation of status 2 and 3 trees. The individual root biomass was then summed up for each status of each species, and converted to Megagram per hectare. The biomass was converted to carbon mass by multiplying by 0.39 as recommended by Kauffman and Donato (2012). For the $C_{treeBG}$ the carbon mass of all species and statuses was summed up.

### 3.1.5 Total carbon stock and $CO_2$ equivalent ($CO_2e$)

The total mangrove carbon stock was estimated by adding all the carbon pools together (see equation 6):

$$Total\ carbon\ stock\ [Mg\ ha^{-1}] = C_{treeAG} + C_{treeBG} + C_{d\&dWood}$$

***Equation 6:*** *Calculation for the total mangrove carbon stock [Mg ha$^{-1}$]. $C_{treeAG}$ = aboveground tree carbon pool [Mg ha$^{-1}$], $C_{treeBG}$ = belowground tree carbon pool [Mg ha$^{-1}$], $C_{d\&dWood}$ = dead and downed wood carbon pool [Mg ha$^{-1}$]*

To calculate the $CO_2e$, the total carbon stock multiplied by 3.67. This is the ratio between carbon [12] and carbon dioxide [44] (Kauffman & Donato, 2012).

### 3.1.6 Uncertainties

For each carbon pool measured, the uncertainty of the estimates was set to a 70% confidence interval (CI).

The 70% CI was calculated for below- and aboveground the carbon mass of each tree species, and each dead and downed wood size class. By adding up all carbon masses, the 70% CI for each carbon pool was calculated. The total mangrove carbon stock was then calculated using an adjusted error propagation equation (see equation 7) (IPCC, 2000; Kauffman & Donato, 2012).

$$Total\ 70\%\ CI = \sqrt{70\%^2_{C_1} + 70\%^2_{C_2} + \ldots + 70\%^2_{C_n}}$$

***Equation 7:*** *Error propagation equation for the uncertainty of the total carbon pool and total carbon stock, at 70% CI. CI = confidence intervals, c = 70% CI of the individual parameters (species, size classes) or carbon pools. Adjusted from IPCC (2000) and Kauffman and Donato (2012).*

## 3.2 Potential restoration sites

For the survey of potential restoration sites, a criteria catalogue was developed, and relevant geodata were researched for each criterion (see table 2). The criteria catalogue was developed in cooperation with PCFML.
For restoration to avoid major bureaucracy, council work areas, national parks, nature reserves, other conservation zones and settlement areas must be avoided. In addition, the riverbanks must be in a degraded state (see table 2). Furthermore, the restoration areas should include blue carbon potential.

Research for relevant geodata was conducted on state and council level on platforms such as the Central Resource for Sharing and Enabling Environmental Data in NSW (SEED), Fisheries NSW Spatial Data Portal and Byron Shire Council's Online Mapping tool. In addition, Byron shire council and PCFML, were contacted directly for access to relevant maps. If multiple maps were with similar information were found, the data were cross-compared and the more recent data was chosen. Detail and background information on the used data can be found in section 2.2. For geoprocessing and mapping ArcGIS Pro Version 3.0.2 was used on a Microsoft Surface Book 2 Intel® Core™ i5-8350U CPU @ 1.70Ghz, 8GB RAM.

***Table 2**: Criteria catalogue for the search of potential restoration sites on the Brunswick River.*

| Criteria | Description |
|---|---|
| On degraded riverbanks | Riverbank stability must be classified either “high risk”, “unstable” and/or “cleared vegetation” |
| Not within council work areas | Avoiding council restoration areas, including bush regeneration, dune work and other regeneration works. |
| Not in national parks | Avoiding sanctuary zones of the Cape Byron Marine Park (conservation zone C1) |
| Not within nature reserves | Avoiding Brunswick Heads Nature Reserve and Mullumbimby Heritage Park |
| Not within conservation areas | Avoiding conservation zones: Environmental Conservation (C2), Environmental Management (C3) and Environmental Living (C4). |
| Not in settlement areas | Avoiding river stretches which flow directly though Mullumbimby and Brunswick Heads |
| Include blue carbon potential | Including areas which show a potential for supporting blue carbon ecosystems. |

### 3.2.1 Data cleansing and preparation

First data cleaning on the provided riverbank stability data from PCFML, Byron Shire Council maps and NSW blue carbon potential priority areas was conducted. Loose lines, and empty inputs were removed from the files before they were further used. To minimise the data extent geographically, a square perimeter was drawn over the whole Brunswick River area and saved as a feature class (see figure 4, 'Brunswick Area'). The NSW blue carbon potential priority areas, LEP 2014, and BVL areas were then clipped to this perimeter, to only include relevant data for the analysis and avoid major data processing.

**Extent of Brunswick River**

The extent of the Brunswick River water flow (crest area to crest area) was needed for the exclusion of the settlement area. For the extent, the Brunswick River was extracted from the 'Tweed Brunswick River catchment Wetlands Inventory' Shapefile provided by the DPE (2011) on SEED. As the data was from 2011, the width and flow of the river did not represent the current extent, due to the past flooding events. The width and location of the river was thus manually adjusted to the ArcGIS Ersi World imagery base map from 2022. The extent of the river was always adjusted to the visual crest area of the riverbank.

### 3.2.2 Geoprocessing

A ModelBuilder was constructed for the geoprocessing steps applied for the analysis of potential restoration sites (see figure 4).

In a first step, the riverbank data from after the floods in 2022 were extracted from the PCFML riverbank stability layer and saved as a feature class ('Post flood riverbanks'). As the riverbanks were only labelled numerically for the riverbank categories, the labels "stable", "unstable", "high risk", "cleared vegetation" and "artificial stabilisation" were added in a new field with a short python code (see appendix). From this layer, all degraded riverbanks were extracted and saved as a new feature class ('Post flood banks selection').

In a second step, a project perimeter was created from the extent of the Brunswick River polygon layer by first clipping the polygon after Mullumbimby Heritage Park and before the Brunswick Heads boat harbour. Secondly, the polygons on either side were removed, resulting in the layer only containing the new polygon layer of the Brunswick River between Mullumbimby and Brunswick Heads. Lastly, a 20 m buffer was created around the polygon to incorporate riparian area and riverbank data ('Brunswick Buffer'). Through this process, the settlement area was avoided. In addition, the sanctuary zones of Cape Byron Marine Park were also automatically excluded, as confirmed with comparison of the current Cape Byron Marine Park zoning map by the DPI (2020).

Thirdly, the ‘Post flood bank selection’ layer was clipped to the ‘Brunswick Buffer’, so only riverbank data within the defined project perimeter was included (‘Post flood clip’). As the riverbank data is a line feature class, a 20 m buffer on the respective riparian area side was created, to make any further analysis possible.

In a next step the conservation zones were extracted from the Byron LEP 2014 layer by select by attribute E1, E2, E3 (equivalent of conservation zones C1, C2, C3) and saved as a new feature class (conservation zones’). No zone C4 were in the Byron LEP 2014. A 20 m buffer was created around the polygon areas, to avoid any potential bureaucracy with conducting restoration close to the zones (‘conservation zone w buffer’). The same buffer distance was applied to the Byron Shire restoration and Landcare Dune work polygon layers for the same reason (‘Council restoration areas buffer’ and ‘Landcare Dune Work Areas Buffer’ respectively).
These areas were then erased from the ‘degraded banks w buffer’ (‘restore2’). Additionally, the ‘conservation zones w buffer’ were erased from the ‘restore2’ resulting in a polygon layer of degraded riverbanks which avoid national parks, council work areas, nature reserves, conservation area and settlement areas (‘Restoration areas w/o major bureaucracy’).

Lastly, the NSW blue carbon potential area was clipped to the ‘restoration areas w/o major bureaucracy’ layer and saved as a feature class ‘Restoration areas with blue carbon potential’, which describes the content of the layer.


***Figure 4:*** *ArcGIS ModelBuilder for finding potential restoration sites on the Brunswick River NSW. Two main outputs are given as a result: restoration areas without major bureaucracy areas, and with blue carbon potential.*

# 4 Results

## 4.1 Mangrove carbon stock and vegetation

### 4.1.1 Mangrove carbon stock

A total mangrove carbon stock of 50.84 ± 2.41 Mg $ha^{-1}$ was estimated for degraded riverbanks of the Brunswick River. The carbon dioxide concentration was estimated to 185.59 $CO_2$e. The total carbon stock of the 250 $m^2$ survey area was estimated to 1271.03 ± 60.26 kg.
The aboveground carbon pool total was estimated to a total of 44.28 ± 2.39 Mg $ha^{-1}$, and the total belowground carbon pools to 6.56 ± 0.31 Mg $ha^{-1}$. Tree carbon pool contributed the highest fraction towards the total mangrove carbon stock, with an estimated 44.09 ± 2.40 Mg $ha^{-1}$ (see table 3).

Approximately 96% of the carbon stock is stored in the species *Avicennia marina*, with 43.40 ± 2.00 Mg $ha^{-1}$ (≈85%) stored above ground and 5.68 ± 0.31 Mg $ha^{-1}$ (≈11%) below-ground in the roots. *Aegiceras coniculatum* was estimated to store 0.69 ± 0.01 Mg $ha^{-1}$ above ground and 0.88 ± 0.00 Mg $ha^{-1}$. The carbon mass of dead and downed wood was estimated to 0.19 ± 0.01 Mg $ha^{-1}$, where the carbon mass of the size class fine was only estimated in low quantities (traces).

In total, five alive trees and one status 1 tree specimen of *Avicennia marina* were found. Of *Aegiceras coniculatum* the diam30 of 20 alive specimens were recorded (see appendix). No dead specimen of *Aegiceras coniculatum* were found. The mean dbh of all *Avicennia marina* was 28.54 cm with min 13.99 cm and max 43.29 cm. The mean diam30 of *Aegiceras coniculatum* was 1.86cm with min. 0.04 cm and max. 5.86 cm.

A total of 198 pieces of dead and downed wood were measured (see appendix). In the size class fine 79 pieces were measured. In size class small 81 pieces, in size class medium 32 pieces and 6 large rotten pieces were measured. No sound pieces of the large size class were found.

The measurement of the diam30 applied to the majority of *Aegiceras corniculatum* (river mangroves) due to their basitony growth habit.

*Table 3: Total mangrove carbon stock and carbon mass of individual carbon pools on a degraded riverbank on the Brunswick River NSW. For each carbon mass the uncertainty of a 70% confidence interval is given. T = trace (carbon mass of the component was in low quantities).*

| | **Carbon mass [Mg ha$^{-1}$]** | **Carbon mass project area [kg/250m$^{2}$]** |
|---|---|---|
| Trees | | |
| *Aegiceras corniculatum* alive | 0.69 ± 0.01 | 17.29 ± 0.33 |
| *Avicennia marina* alive | 43.36 ± 2.39 | 1084.08 ± 59.76 |
| *Avicennia marina* status 1 | 0.04 ± 0.00 | |
| Total trees | 44.09 ± 2.40 | 1102.35 ± 60.09 |
| Dead and downed wood | | |
| fine (Ø < 0.64cm) | T | 0.03 ± 0.00 |
| small (Ø 0.65-2.54cm) | 0.02 ± 0.00 | 0.51 ± 0.03 |
| medium (Ø 2.55-7.6cm) | 0.08 ± 0.01 | 1.97 ± 0.13 |
| large - rotten (Ø >7.6cm) | 0.09 ± 0.01 | 2.25 ± 0.22 |
| Total dead and downed wood | 0.19 ± 0.01 | 4.76 ± 0.25 |
| **Total aboveground carbon pools** | 44.28 ± 2.39 | 1107.11 ± 59.76 |
| Roots | | |
| *Aegiceras corniculatum* alive | 0.88 ± 0.00 | 21.88 ± 0.09 |
| *Avicennia marina* alive | 5.67 ± 0.31 | 141.76 ± 7.72 |
| *Avicennia marina* status 1 | 0.01 ± 0.00 | 0.27 ± 0.00 |
| Total roots | 6.56 ± 0.31 | 163.92 ± 7.81 |
| **Total belowground carbon pools** | 6.56 ± 0.31 | 163.92 ± 7.72 |
| **Total mangrove carbon stock** | **50.84 ± 2.41** | **1271.03 ± 60.26** |
| **$CO_2$e of total carbon stock** | **185.59 $CO_2$e** | **4664.70 $CO_2$e** |

### 4.1.2 Vegetation

A total of 27 different plants were found on the survey site. Of these, 25 species from 19 different families could be fully identified. 15 species were native and 10 naturalised (see appendix). A native fine-leaved Tuckeroo (*Lepiderema pulchella*) was found on plot eight, which is listed as "vulnerable" on the conservation status NSW.
Of the naturalised species, four were identified as invasive. The invasive species found were Camphor laurel (*Cinnamomum camphora*), Coastal morning glory (*Ipomoea cairica*), Mickey Mouse Plant (*Ochna serrulate*) and Glossy nightshade (*Solanum Americanum*). Of the Camphor laurel, one specimen was found on plot 1 (see appendix).
Coastal morning glory was found in plots 1, 4, 9 and 10. Once specimen of the Mickey Mouse Plant was found in plot 3, and one specimen of Glossy nightshade in plot 2.

*Avicennia marina* was found in two different plots (plots 3 and 8) and *Aegiceras corniculatum* in seven different plots (plots 2, 3, 4, 7, 8, 9, 10). The average tree height of alive *Avicennia marina* was 10.77 m. The average tree height of alive *Aegiceras corniculatum* was 3.05 m. Of *Aegiceras coniculatum* 56 seedlings were recorded, of which 53 were found in plot 8, No seedlings of *Avicennia marina* were found (see appendix).

From the found plants, two could not be identified to species level. One plant was identified to the genus (*Sida* spp.), and one plant could not be identified at all (small flax leaved plant). From both *Sida* spp., and the small flax leaved plant, only one specimen was found in plot three and ten respectively.

On average, the species richness was 7 per plot. The mean Shannon-index was 1.338 and the mean evenness 0.802 (see appendix). The highest species richness was found in plots two, three and four, with a richness of 10. The lowest species richness of 1 was in plot six. Plot two had the highest Shannon-Index of 1.977. The highest evenness of 0.944 was found in plot 7.

### 4.1.3 Pneumatophores and soil texture

Pneumatophores were found in seven of the ten plots. In nine plots, the cover of pneumatophores was below 10% (see table 4). The highest cover of 22% was found in plot four.

The soil texture varied across all plots. Sand texture was found in four plots, located on, or next to, the point-bar of the slip-off slope on the survey site. Seven plots were recorded to have a component of silt texture, and five plots had components of clay texture (see table 1).

***Table 4:*** *Plot specific soil textures and pneumatophore cover [%] on the degraded riverbank stretch on the Brunswick River. If soil textures are mixed, the texture with the higher component in the soil is written first.*

| Plot Nr. | Soil texture | Pneumatophore cover [%] |
|---|---|---|
| 1 | clay | 0 |
| 2 | Clay-silt | 1 |
| 3 | sand | 3 |
| 4 | Silt-sand | 22 |
| 5 | sand | 7 |
| 6 | Sand-silt | 8 |
| 7 | Silt-clay | 2 |
| 8 | silt | 0 |
| 9 | Silt-clay | 5 |
| 10 | Clay-silt | 0 |

## 4.2 Potential restoration sites

Multiple potential restoration sites without major bureaucracy exist on the Brunswick River (see figure 5). The potential restoration sites are located between Mullumbimby and the Pacific Highway Bridge. No potential restoration sites exist after the Pacific Highway Bridge. Around the Brunswick Heads Nature Reserve, all potential restoration sites have 'unstable' riverbanks, except two riverbanks of 'high risk' on opposite banks (left banks in direction of river flow) from the reserve (see figure 6).

The potential restoration sites with "high risk" banks are located on outside banks of the river (see figure 6). Only one site exists with cleared vegetation (see figure 6, 'close up before Kings creek'). This site also has riverbanks in the category 'high risk'. Further upstream from the cleared vegetation, a larger stretch of potential restoration sites with 'high risk' riverbanks exists, after which an unstable riverbank stretch follows (see figure 6, close up before Kings Creek).

Most of the potential restoration sites without bureaucracy contain blue carbon potential priority areas. All blue carbon potential priority levels occur in patches (see figure 7). The levels 'moderate' and 'moderately high' occur the most on the river. Only small patches of 'high' levels are found (see figure 7, close-ups). Areas with 'low' blue carbon potential are scarce, with the biggest patch situated between two 'moderately low' patches (see figure 7, close up after Kings Creek). Upstream from the tight river bend, where the Mullumbimby Rugby League Football club is located, most blue carbon potential priority areas are 'moderately low' (see figure 7). Most of the mangrove carbon stock survey area does not contain any blue carbon potential priority areas. The only blue carbon potential priority area is 'moderately low' within the survey area.

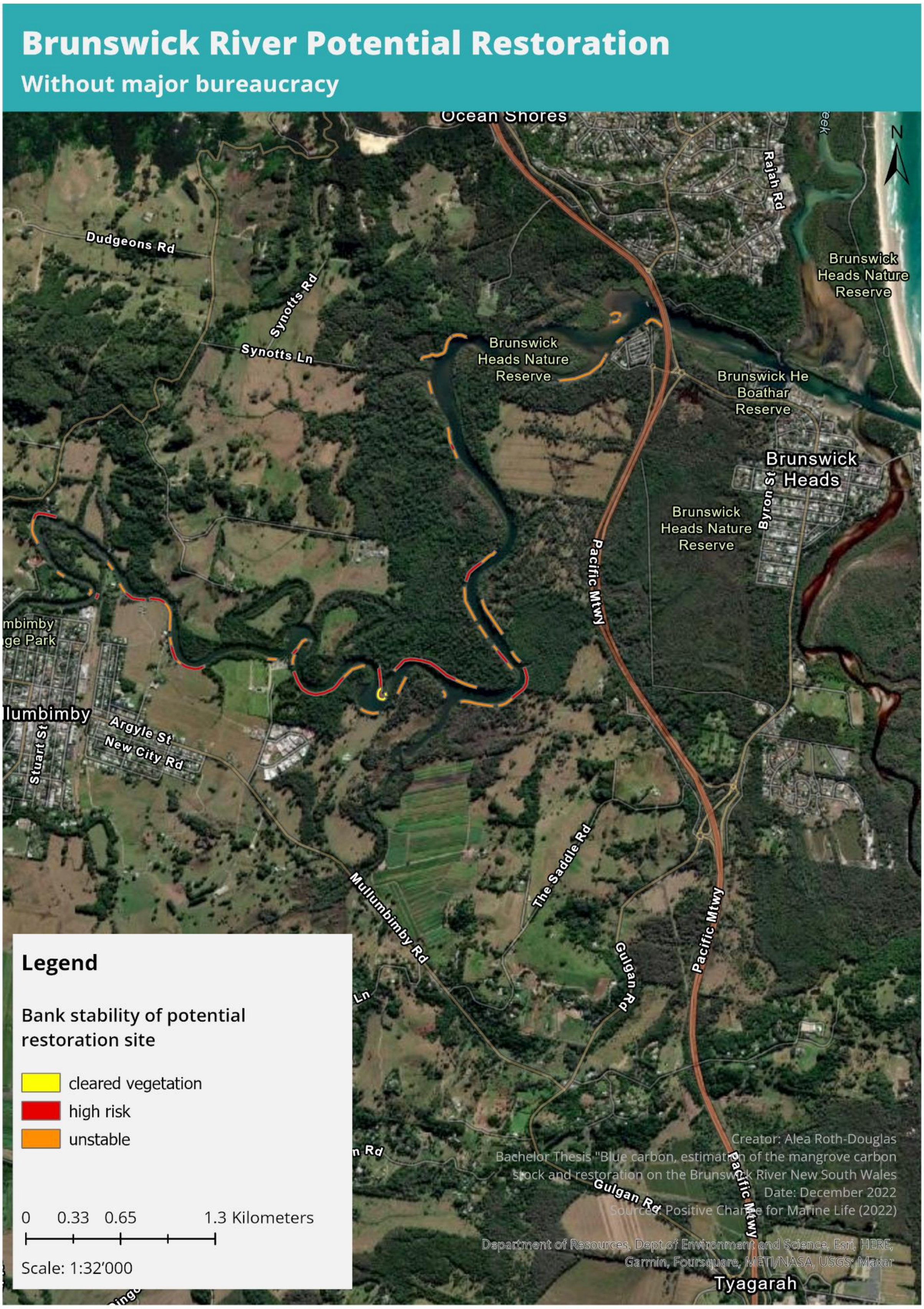


***Figure 5:*** *Potential restoration sites on the Brunswick River NSW, which do not involve major bureaucracy, sorted to the bank stability.*

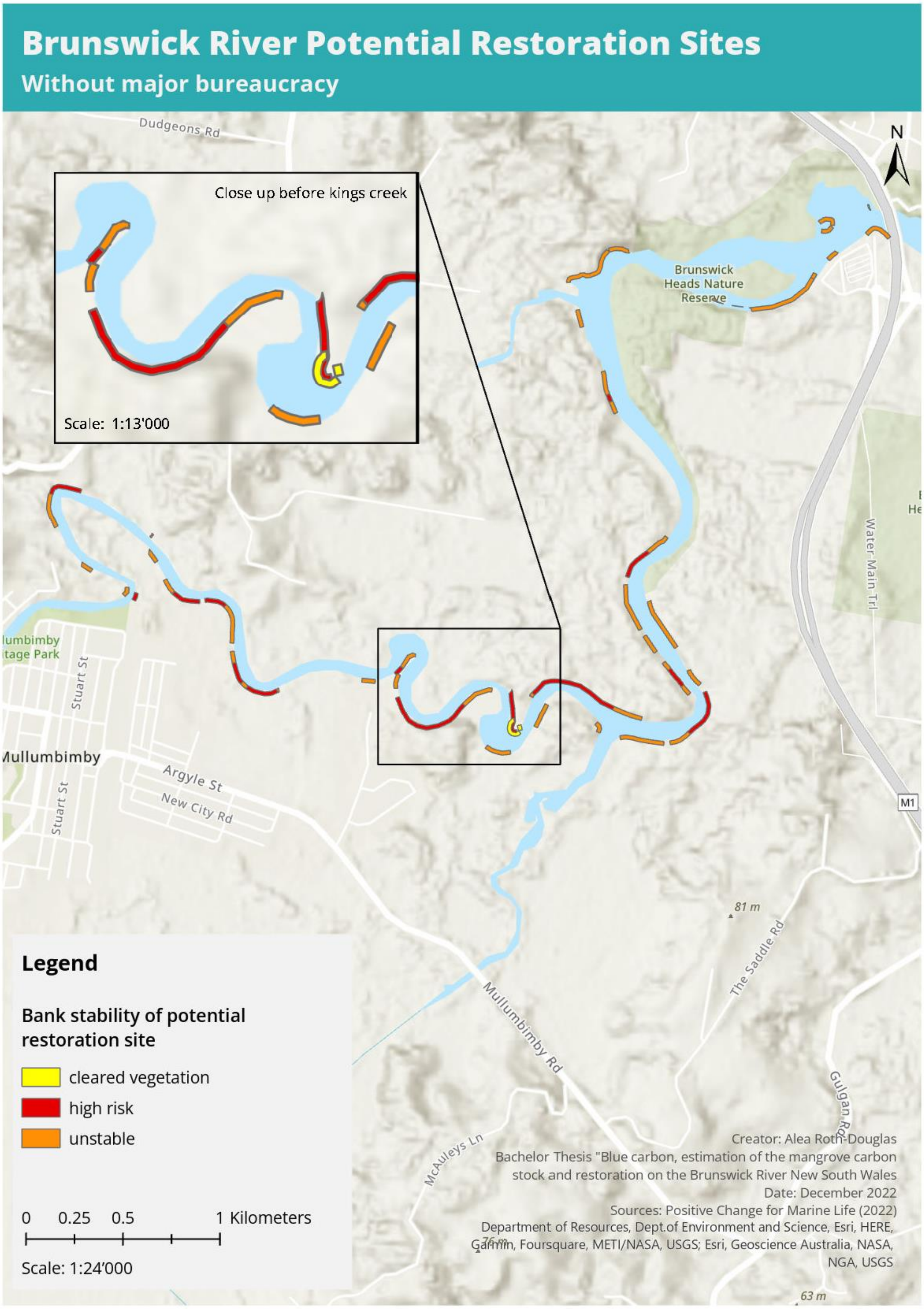


***Figure 6:*** *Potential restoration sites on the Brunswick River NSW, which do not involve major bureaucracy, sorted to the bank stability. Only on one section of the river a riverbank of category high risk with cleared vegetation was found. Around Brunswick Heads Nature Reserve, the potential restoration sites have unstable banks.*

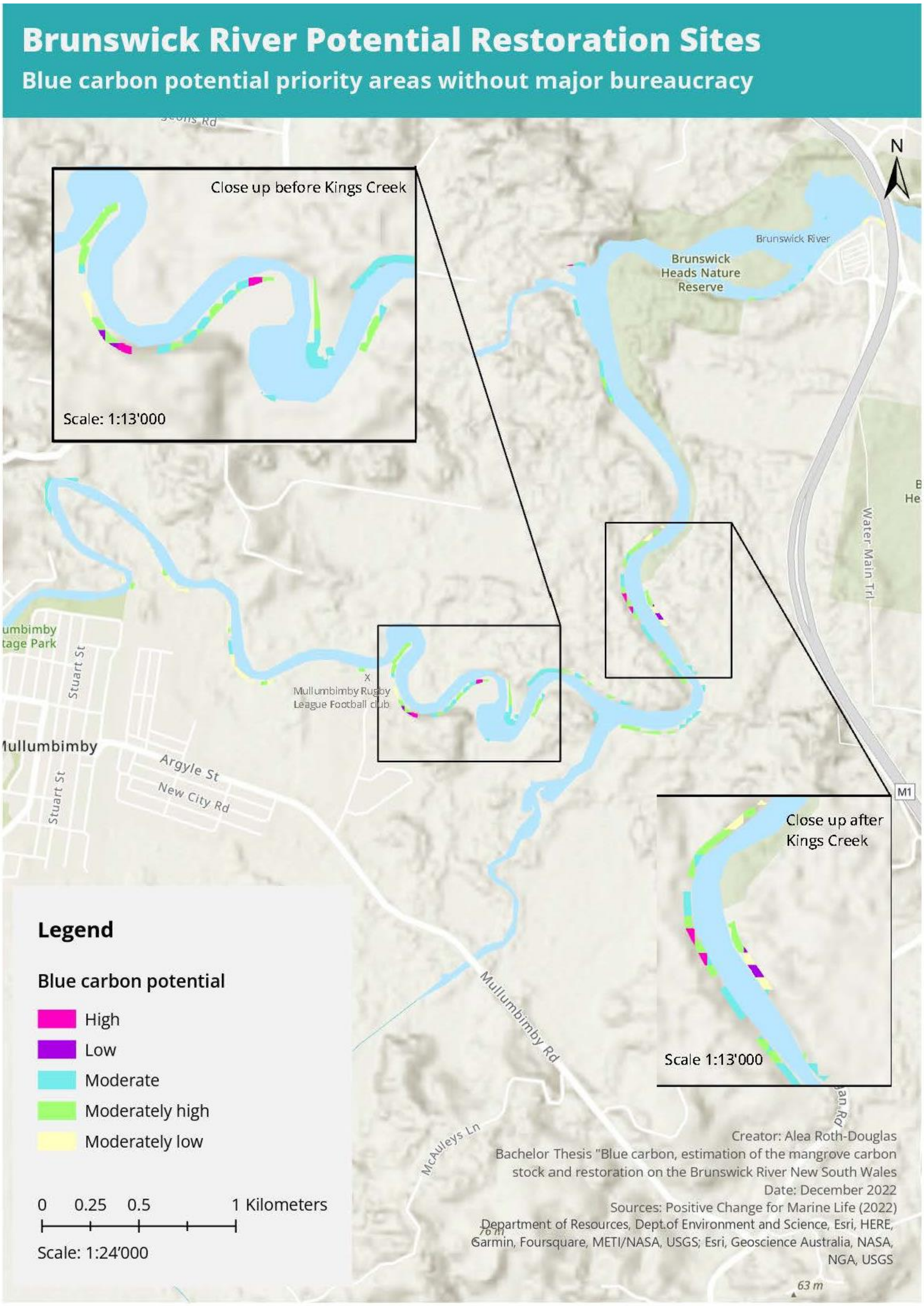


***Figure 7****: Potential restoration sites on the Brunswick River, with blue carbon potential and without major bureaucracy.*

# 5 Discussion

There are three main results of the thesis: the developed methodology for the carbon stock estimation of the mangrove species *Avicennia marina* and *Aegiceras corniculatum*, the estimated mangrove carbon stock of 50.84 ± 2.41 Mg $ha^{-1}$ of a degraded riverbank stretch on the Brunswick River, and maps showing where on the Brunswick River potential restoration sites without major bureaucracy, and potential restoration sites without major bureaucracy and blue carbon potential are located.

The total estimated mangrove carbon stock of 50.84 ± 2.41 Mg $ha^{-1}$ on the Brunswick River, is low compared to the estimated carbon stock of 662-2139 Mg $ha^{-1}$ for mangrove forests in Australia by Alongi (2018). However, this does not come surprisingly as the carbon stock was estimated on degraded riverbanks. The estimates in this thesis mainly give a representation of the aboveground carbon pools, as direct data was only collected for these. Alongi (2012) estimated that on average, 92% of carbon is vested belowground in the soil and roots. Therefore, the results only show a small proportion of the potential carbon stored in the area. For a closer estimation of the total carbon stock, the soil would need to sampled and analysed in a laboratory.

The estimation on the degraded riverbank was highly influenced by the occurrence of six *Avicennia marina* specimens. Without their presence on the survey area, the total carbon stock estimate would only be 1.81 Mg $ha^{-1}$, as they accounted for 96% of the total carbon stock. Therefore, species composition within a survey area and plots, is a large influence of the total carbon stock estimate of a site. Studies found that mangrove carbon sequestration and carbon stocks vary both on local and regional spatial scales (Rovai et al., 2018; Sanderman et al., 2018; Simard et al., 2019). It is therefore advised that the results from this thesis are not used as a general estimate of the carbon stock of degraded riverbanks on the Brunswick River.

The relatively small carbon stock *of Aegiceras corniculatum* compared to *Avicennia marina*, despite 20 specimens being recorded, and carbon mass calculated for, could be due to multiple factors. For one, the aboveground carbon mass was calculated using the diam30 instead of dbh. Secondly, not every diam30 from each single stem within a cluster from the species was measured. Due to the basitony growth form of *Aegiceras corniculatum*, the dbh measurement was not possible and measurements of each single stem would have been very time intensive and impossible in some clusters. Gehring et al. (2008) found that the diam30 is better suited for biomass estimations than dbh for small- to mid-sized vegetation. There therefore is the need for the development of an allometric equation for *Aegiceras corniculatum* in Australia which uses the diam30 instead of the dbh for a closer estimation of the carbon mass.

If the provided methodology is applied again for another carbon stock estimate with *Aegiceras corniculatum* specimens, the measurement of as many stems within a cluster is recommended.

Most of the dead and downed wood pieces most likely did not belong to mangroves, but other trees and shrub species found on the Brunswick. As the survey site is located towards the end of the estuary, woody debris pieces from further upstream most likely belong to other species found along the Brunswick River, such as Tuckeroos or Sheoak species. However, as the contribution to the total carbon stock was such a small proportion (0.19 ± 0.01 Mg $ha^{-1}$), the use of non-species-specific wood specific gravity most likely did not impact the result greatly.

Normally, a confidence interval of 95% is recommended and common practise for the carbon stock estimates (IPCC, 2000; Kauffman & Donato, 2012). However, such a high confidence interval could not be accounted for in the carbon stock estimates of this thesis. Therefore, a confidence interval of 70% was calculated. The 70% CI was chosen for the following reasons: potential inaccuracy in field measurements due to the team's inexperience with carbon stock measurements, usage of simplified field survey and analysis methodologies, using existing allometric equations instead of species- and/or site-specific equations, using specific mean gravities of dead and downed wood size classes from different species and accounting for the existing uncertainties of these, usage of diam30 instead of dbh for *Aegeiceras corniculatum* carbon mass estimate, and using default values for the conversion of biomass to carbon mass instead of species- and/or site-specific values as these were either not available require intrusive methods for calculation.

The generated maps allow a quick overview of the potential restoration sites, which avoid major bureaucracy. As the Byron LEP 2014 map used was from 2021, it is not the most recent version and does not include all conservation zones. The layer contained multiple areas labelled "deferred matter", which were not included in the analysis. Some of these areas have been zoned to conservation zones in 2022 (Byron Shire Council, 2022). Chosen restoration areas therefore still need to be compared to current Byron LEP maps, to avoid areas which have been assigned a zone in the meantime. This can be done via the Byron Shire Council online mapping tool (2022). The same applies to the BVL Dune Work areas and council bush regeneration zones. Even though further research into selected restoration areas still needs to be conducted, to confirm avoidance of major bureaucracy, the maps still give a general overview of where Byron Shire Council previously was not active. Furthermore, the maps highlight where urgent restoration is necessary based on the riverbank instability.

The map of potential restoration sites with blue carbon potential priority areas is useful if a project includes the criteria to restore a degraded riverbank with blue carbon potential. It needs to be highlighted here that this map only includes riverbank and riparian areas where mainly mangroves are located, and thus any blue carbon potential found in the waters of the river, or beyond the 20 m buffer are not included. This includes any potential seagrass and salt- and tidal marshes. Therefore, the potential blue carbon habitats on the Brunswick River are not limited to the extent of the map generated in this thesis.

The vegetation survey is mainly of use for an overview of existing plants which occur on the degraded riverbank stretch. This data can be useful for comparison to intact riverbank areas on the Brunswick River and/or for a pre-restoration assessment of the site. For the data to be significant for restoration projects implemented on the site in the future, it is recommended that vegetation surveys are also conducted post-restoration. This allows for a statistical comparison of the species richness, Shannon-index, and evenness. Alternatively, a vegetation survey of an intact riverbank stretch on the Brunswick River can be conducted and compared to the data in this thesis.

In conclusion, the thesis gives an overview of blue carbon and the mangrove ecosystems, provides a methodology for the non-intrusive mangrove carbon stock estimate, which has been applied to a degraded riverbank stretch on the Brunswick River, and highlights the potential restoration sites based on their feasibility to avoid major bureaucracy and including blue carbon potential. The research questions have therefore been answered and the aim of the thesis achieved. Further studies and inputs from trained experts in the field of carbon stock measurements are recommended to fine tune and confirm the developed methodology. In addition, the creation of a potential restoration site map with more recent data is recommended.

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## Appendix A: R code for species diversity

```
#________________________________________________________________
# Vegetation analysis for Bachelor Thesis
# Species diversity on a degraded riverbank
# Alea Roth-Douglas
# 12.2022
#________________________________________________________________

#Set working directory
setwd("C:/Users/alear/OneDrive - ZHAW/ZHAW/Bachelorarbeit/Data/R")
getwd()

# Read data
?read.csv
#Add header data csv. from plots
Veg1 <- read.csv("Site1_Plant_Species.csv", sep = ";", dec = ".", stringsAsFactors = T)
str(Veg1)

#Calculate diversity in R ------------------------
veg2 <- read.delim("Site1_Species2.csv", sep=";", , row.names = 1)

# install package vegan (if its not installed already)
if(!require(vegan)){install.packages("vegan")}
library(vegan)
#Check citation
citation("vegan")

# Change data format-----------------------------
# replace NAs with 0
veg2[is.na(veg2)] <-0
# transpose species list to matrix
veg2 <- t(veg2)
summary(veg2)
veg2

# Calculate richness, shannon, eveness
richness <- specnumber(veg2)
shan <- diversity(veg2, "shannon")
even <- shan/log(richness)

# Add diversity data to the dataframe (df) of the header data
Veg1$Richness <- richness
Veg1$Shannon <- shan
Veg1$Eveness <- even
summary(Veg1)
```

## Appendix B: Python code for riverbank stability classification

```
BankStabil = state(!BankState!)
def state(bk):
   if bk==1:
      return "stable"
   elif bk==2:
      return "unstable"
   elif bk==3:
      return "high risk"
   elif bk==4:
      return "artificial stabilisation"
   elif bk==5:
      return "cleared vegetation"
   elif bk==6:
      return "other"
   else: "other"
```

## Appendix C: Species list with cover per plot

*Species found on the Brunswick river and their cover [%] in plots 1-10.*

| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| Aegiceras corniculatum | 0 | 2 | 1 | 2 | 0 | 0 | 53 | 25 | 22 | 25 |
| Ageratum conyzoides | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ageratum houstonianum | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0.5 |
| Austrosteenisia blackii | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 | 0 | 0 |
| Avicennia marina | 0 | 0 | 8 | 0 | 70 | 0 | 0 | 0 | 0 | 0 |
| Banksia robur | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Calochlaena dubia | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Casuarina cunninghamiana | 0 | 0 | 0 | 0 | 15 | 0.2 | 0 | 12 | 18 | 46 |
| Centella asiatica | 1 | 1 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cinnamomum camphora | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cupaniopsis anacardioides | 0 | 0 | 22 | 0 | 20 | 0 | 0 | 35 | 40 | 0 |
| Cuphea carthagenensis | 2 | 3 | 0.5 | 0 | 0.5 | 0 | 0 | 0 | 0 | 2 |
| Cynodon dactylon | 8 | 8 | 9 | 10 | 0 | 0 | 0 | 0 | 2 | 0 |
| Ficinia nodosa | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fimbristylis dichotoma | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Ipomoea cairica | 4 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 6 | 11 |
| Juncus usitatus | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Lepiderema pulchella | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 0 | 0 |
| Ochna serrulata | 0 | 0 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Paspalum dilatum | 2 | 5 | 7 | 16 | 0 | 0 | 0 | 0 | 0 | 0 |
| Paspalum distichum | 8 | 4 | 2 | 5 | 0 | 0 | 0 | 0 | 5 | 4 |
| Paspalum urvillei | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 7 | 10 |
| Sida spp. | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sida cordifolia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 1 |
| Solanum americanum | 0 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| unidentified flax leaf | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Verbena bonariensis | 0 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

# Appendix D: Vegetation survey digitalised from field notes

*Digitalised and summarised field notes from the vegetation survey from the Brunswick River*

| English name | Family | Species | cover [%] | canopy cover [%] | plot | native/ naturalised | Invasive | Conservation status NSW |
|---|---|---|---|---|---|---|---|---|
| River mangrove | *Primulaceae* | *Aegiceras corniculatum* | 2 | | 2 | native | | |
| River mangrove | *Primulaceae* | *Aegiceras corniculatum* | 1 | | 3 | native | | |
| River mangrove | *Primulaceae* | *Aegiceras corniculatum* | 1 | 2 | 4 | native | | |
| River mangrove | *Primulaceae* | *Aegiceras corniculatum* | | 53 | 7 | native | | |
| River mangrove | *Primulaceae* | *Aegiceras corniculatum* | | 25 | 8 | native | | |
| River mangrove | *Primulaceae* | *Aegiceras corniculatum* | | 22 | 9 | native | | |
| River mangrove | *Primulaceae* | *Aegiceras corniculatum* | | 25 | 10 | native | | |
| Goatweed | *Asteraceae* | *Ageratum conyzoides* | 1 | | 2 | naturalised | | |
| Blue billy goat weed | *Asteraceae* | *Ageratum houstonianum* | 3 | | 4 | naturalised | | |
| Blue billy goat weed | *Asteraceae* | *Ageratum houstonianum* | 0.5 | | 10 | naturalised | | |
| Blood vine | *Fabaceae* | *Austrosteenisia blackii* | | 30 | 7 | native | | |
| Grey mangrove | *Acanthaceae* | *Avicennia marina* | 2 | 8 | 3 | native | | |
| Grey mangrove | *Acanthaceae* | *Avicennia marina* | 10 | 70 | 5 | native | | |
| Swamp Banksia | *Proteaceae* | *Banksia robur* | 2 | | 1 | native | | |
| Rainbow fern | *Dicksoniaceae* | *Calochlaena dubia* | 2 | | 2 | native | | |
| River Sheoak | *Casuarinaceae* | *Casuarina cunninghamiana* | 3 | 15 | 5 | native | | |
| River Sheoak | *Casuarinaceae* | *Casuarina cunninghamiana* | | 12 | 8 | native | | |
| River Sheoak | *Casuarinaceae* | *Casuarina cunninghamiana* | | 18 | 9 | native | | |
| River Sheoak | *Casuarinaceae* | *Casuarina cunninghamiana* | | 46 | 10 | native | | |
| River Sheoak | *Casuarinaceae* | *Casuarina cunninghamiana seedlings* | 0.2 | | 6 | native | | |
| Indian Pennywort | *Apiaceae* | *Centella asiatica* | 1 | | 2 | native | | |
| Indian Pennywort | *Apiaceae* | *Centella asiatica* | 1 | | 1 | native | | |
| Indian Pennywort | *Apiaceae* | *Centella asiatica* | 0.5 | | 3 | native | | |
| Indian Pennywort | *Apiaceae* | *Centella asiatica* | 0.5 | | 4 | native | | |
| Camphor laurel | *Lauraceae* | *Cinnamomum camphora* | 4 | | 1 | naturalised | yes | |
| Tuckeroo | *Sapindaceae* | *Cupaniopsis anacardioides* | 3 | 22 | 3 | native | | |
| Tuckeroo | *Sapindaceae* | *Cupaniopsis anacardioides* | 3 | 20 | 5 | native | | |
| Tuckeroo | *Sapindaceae* | *Cupaniopsis anacardioides* | | 35 | 8 | native | | |
| Tuckeroo | *Sapindaceae* | *Cupaniopsis anacardioides* | | 40 | 9 | native | | |
| Columbian waxweed | *Lynthraceae* | *Cuphea carthagenensis* | 3 | | 2 | naturalised | | |
| Columbian waxweed | *Lynthraceae* | *Cuphea carthagenensis* | 2 | | 1 | naturalised | | |
| Columbian waxweed | *Lynthraceae* | *Cuphea carthagenensis* | 0.5 | | 3 | naturalised | | |
| Columbian waxweed | *Lynthraceae* | *Cuphea carthagenensis* | 0.5 | | 5 | naturalised | | |
| Columbian waxweed | *Lynthraceae* | *Cuphea carthagenensis* | 2 | | 10 | naturalised | | |
| Bermudagrass | *Poaceae* | *Cynodon dactylon* | 8 | | 2 | native | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Bermudagrass | *Poaceae* | *Cynodon dactylon* | 8 | | 1 | native | | |
| Bermudagrass | *Poaceae* | *Cynodon dactylon* | 9 | | 3 | native | | |
| Bermudagrass | *Poaceae* | *Cynodon dactylon* | 10 | | 4 | native | | |
| Bermudagrass | *Poaceae* | *Cynodon dactylon* | 2 | | 9 | native | | |
| Knobbly club-rush | *Cyperaceae* | *Ficinia nodosa* | 1 | | 4 | native | | |
| Common Fringe-sedge | *Cyperaceae* | *Fimbristylis dichotoma* | 1 | | 5 | native | | |
| Costal morning glory | *Convol-vulaceae* | *Ipomoea cairica* | 4 | | 1 | naturalised | yes | |
| Costal morning glory | *Convol-vulaceae* | *Ipomoea cairica* | 1 | | 4 | naturalised | yes | |
| Costal morning glory | *Convol-vulaceae* | *Ipomoea cairica* | 6 | | 9 | naturalised | yes | |
| Costal morning glory | *Convol-vulaceae* | *Ipomoea cairica* | 11 | | 10 | naturalised | yes | |
| Common rush | *Juncaceae* | *Juncus usitatus* | 1 | | 4 | native | | |
| Fine-leaved Tuck-eroo | *Sapindaceae* | *Lepiderema pulchella* | | 15 | 8 | native | | vulnerable |
| Mickey Mouse Plant | *Ochnaceae* | *Ochna serrulata* | 0.5 | | 3 | naturalised | yes | |
| Paspalum | *Poaceae* | *Paspalum dilatum* | 5 | | 2 | naturalised | | |
| Paspalum | *Poaceae* | *Paspalum dilatum* | 2 | | 1 | naturalised | | |
| Paspalum | *Poaceae* | *Paspalum dilatum* | 7 | | 3 | naturalised | | |
| Paspalum | *Poaceae* | *Paspalum dilatum* | 16 | | 4 | naturalised | | |
| Water Couch | *Poaceae* | *Paspalum distichum* | 4 | | 2 | native | | |
| Water Couch | *Poaceae* | *Paspalum distichum* | 8 | | 1 | native | | |
| Water Couch | *Poaceae* | *Paspalum distichum* | 2 | | 3 | native | | |
| Water Couch | *Poaceae* | *Paspalum distichum* | 5 | | 4 | native | | |
| Water Couch | *Poaceae* | *Paspalum distichum* | 5 | | 9 | native | | |
| Water Couch | *Poaceae* | *Paspalum distichum* | 4 | | 10 | native | | |
| Vasey grass | *Poaceae* | *Paspalum urvillei* | 4 | | 4 | naturalised | | |
| Vasey grass | *Poaceae* | *Paspalum urvillei* | 7 | | 9 | naturalised | | |
| Vasey grass | *Poaceae* | *Paspalum urvillei* | 10 | | 10 | naturalised | | |
| | *Malvaceae* | *Sida spp.* | 1 | | 3 | | | |
| Cuban jute | *Malvaceae* | *Sida cordifolia* | 4 | | 9 | native | | |
| Cuban jute | *Malvaceae* | *Sida cordifolia* | 1 | | 10 | native | | |
| Glossy nightshade | *Solanaceae* | *Solanum americanum* | 0.5 | | 2 | naturalised | yes | |
| | | *unidentified flax leaf* | 1 | | 10 | | | |
| Purpletop | Verbe-naceae | *Verbena bonariensis* | 0.5 | | 2 | naturalised | | |

## Appendix E: Tree measurements

| Species | cirfumference [cm] | dbh [cm](1.37m) | height [cm] | height [m] | status | Plot |
|---|---|---|---|---|---|---|
| *Avicennia marina* | 105 | 33.42 | 1260 | 12.6 | alive | 5 |
| *Avicennia marina* | 83 | 26.42 | 1075 | 10.75 | alive | 5 |
| *Avicennia marina* | 136 | 43.29 | 1040 | 10.4 | alive | 5 |
| *Avicennia marina* | 99 | 31.51 | 995 | 9.95 | alive | 5 |
| *Avicennia marina* | 71 | 22.60 | 1014 | 10.14 | alive | 3 |
| *Avicennia marina* | 43.95 | 13.9897195 | 225 | 2.25 | 1 | 2 |

| Species | dbh [mm](30cm) | Diam30 | dbh [cm](1.37m) | height [cm] | height [m] | status | Plot |
|---|---|---|---|---|---|---|---|
| *Aegiceras corniculatum* | 15 | 1.5 | | 320 | 3.2 | alive | 10 |
| *Aegiceras corniculatum* | 21 | 2.1 | | 190 | 1.9 | alive | 10 |
| *Aegiceras corniculatum* | 14 | 1.4 | | 250 | 2.5 | alive | 10 |
| *Aegiceras corniculatum* | 17 | 1.7 | | 240 | 2.4 | alive | 10 |
| *Aegiceras corniculatum* | 23 | 2.3 | | 450 | 4.5 | alive | 10 |
| *Aegiceras corniculatum* | 25 | 2.50000 | | 375 | 3.75 | alive | 10 |
| *Aegiceras corniculatum* | 20 | 2 | | 310 | 3.1 | alive | 9 |
| *Aegiceras corniculatum* | 15 | 1.5 | | 310 | 3.1 | alive | 9 |
| *Aegiceras corniculatum* | 23 | 2.3 | | 310 | 3.1 | alive | 9 |
| *Aegiceras corniculatum* | 37.8 | 3.78 | | 430 | 4.3 | alive | 8 |
| *Aegiceras corniculatum* | 58.61 | 5.861 | | 430 | 4.3 | alive | 8 |
| *Aegiceras corniculatum* | 29.12 | 2.912 | | 430 | 4.3 | alive | 8 |
| *Aegiceras corniculatum* | 37.7 | 3.77 | | 430 | 4.3 | alive | 8 |
| *Aegiceras corniculatum* | 0.42 | 0.042 | | 230 | 2.3 | alive | 7 |
| *Aegiceras corniculatum* | 3.71 | 0.371 | | 260 | 2.6 | alive | 7 |
| *Aegiceras corniculatum* | 3 | 0.3 | | 170 | 1.7 | alive | 7 |
| *Aegiceras corniculatum* | 1.9 | 0.19 | | 195 | 1.95 | alive | 7 |
| *Aegiceras corniculatum* | 2.48 | 0.248 | | 195 | 1.95 | alive | 7 |
| *Aegiceras corniculatum* | 2.69 | 0.269 | | 195 | 1.95 | alive | 7 |
| *Aegiceras corniculatum* | | | 2.13 | 390 | 3.9 | alive | 4 |

## Appendix F: Species richness, Shannon-index, and evenness

*Species richness, Shannon-index, and evenness for all sampled plots. The mean species richness was 6.7, Shannon-index was 1.338 and the mean evenness 0.802.*

| plot | richness | shannon | evenness |
|---|---|---|---|
| 1 | 8 | 1.869 | 0.899 |
| 2 | 10 | 1.977 | 0.859 |
| 3 | 10 | 1.643 | 0.714 |
| 4 | 10 | 1.811 | 0.787 |
| 5 | 5 | 0.935 | 0.581 |
| 6 | 1 | 0.000 | NaN |
| 7 | 2 | 0.654 | 0.944 |
| 8 | 4 | 1.301 | 0.938 |
| 9 | 8 | 1.693 | 0.814 |
| 10 | 9 | 1.500 | 0.683 |
| **mean** | **6.7** | **1.338** | **0.802** |

## Appendix G: Dead and downed wood field survey notes summarised

| Diameter [mm] | Diameter [cm] | decay status | length [cm] | Note | Plot Nr. | Size Class | Diameter^2 [cm] |
|---|---|---|---|---|---|---|---|
| 130.51 | 13.051 | rotten | | | 1 | large | 170.3286 |
| 94.86 | 9.486 | rotten | 165 | | 1 | large | 89.9842 |
| 130.51 | 13.051 | rotten | 165 | | 1 | large | 170.3286 |
| 102.1 | 10.21 | rotten | 72 | | 3 | large | 104.2441 |
| 124.83 | 12.483 | rotten | 33 | | 3 | large | 155.8253 |
| 76.39 | 7.639 | rotten | 53 | | 4 | large | 58.3543 |
| 59.68 | 5.968 | rotten | 80 | | 1 | medium | 35.6170 |
| 28.23 | 2.823 | rotten | 3.4 | | 2 | medium | 7.9693 |
| 31.33 | 3.133 | sound | 31 | | 3 | medium | 9.8157 |
| 30.71 | 3.071 | rotten | 33 | | 3 | medium | 9.4310 |
| 42.43 | 4.243 | sound | 79 | | 3 | medium | 18.0030 |
| 27.96 | 2.796 | rotten | 13 | | 3 | medium | 7.8176 |
| 46.07 | 4.607 | rotten | 24 | | 3 | medium | 21.2244 |
| 27.73 | 2.773 | rotten | 34 | | 3 | medium | 7.6895 |
| 46.84 | 4.684 | rotten | 32 | | 3 | medium | 21.9399 |
| 36.58 | 3.658 | sound | 110 | | 3 | medium | 13.3810 |
| 65.95 | 6.595 | sound | 16 | | 3 | medium | 43.4940 |
| 26.04 | 2.604 | rotten | 22 | | 3 | medium | 6.7808 |
| 59.55 | 5.955 | sound | 23.5 | | 4 | medium | 35.4620 |
| 60.48 | 6.048 | rotten | 25 | | 4 | medium | 36.5783 |
| 49.93 | 4.993 | rotten | 119 | | 5 | medium | 24.9300 |
| 40.21 | 4.021 | rotten | 402 | | 5 | medium | 16.1684 |
| 40.21 | 4.021 | rotten | 402 | | 5 | medium | 16.1684 |
| 33.47 | 3.347 | rotten | 205 | | 5 | medium | 11.2024 |
| 33.65 | 3.365 | sound | 57 | | 5 | medium | 11.3232 |
| 74.14 | 7.414 | rotten | 402 | | 5 | medium | 54.9674 |
| 26.74 | 2.674 | rotten | 40 | | 6 | medium | 7.1503 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 30.48 | 3.048 | rotten | 11 | 6 | medium | 9.2903 |
| 71.65 | 7.165 | rotten | 69 | 6 | medium | 51.3372 |
| 29.45 | 2.945 | rotten | 55 | 6 | medium | 8.6730 |
| 27.9 | 2.79 | rotten | 12 | 6 | medium | 7.7841 |
| 29.84 | 2.984 | sound | 68.5 | 7 | medium | 8.9043 |
| 42.07 | 4.207 | rotten | 10 | 7 | medium | 17.6988 |
| 37.42 | 3.742 | rotten | 80 | 8 | medium | 14.0026 |
| 26.58 | 2.658 | rotten | 35 | 8 | medium | 7.0650 |
| 53.89 | 5.389 | rotten | 28 | 8 | medium | 29.0413 |
| 32.88 | 3.288 | sound | 74 | 8 | medium | 10.8109 |
| 73.2 | 7.32 | rotten | 34 | 8 | medium | 53.5824 |
| 59.68 | 5.968 | rotten | 80 | 1 | medium | 35.6170 |
| 28.23 | 2.823 | rotten | 3.4 | 2 | medium | 7.9693 |
| 31.33 | 3.133 | sound | 31 | 3 | medium | 9.8157 |
| 30.71 | 3.071 | rotten | 33 | 3 | medium | 9.4310 |
| 42.43 | 4.243 | sound | 79 | 3 | medium | 18.0030 |
| 27.96 | 2.796 | rotten | 13 | 3 | medium | 7.8176 |
| 46.07 | 4.607 | rotten | 24 | 3 | medium | 21.2244 |
| 27.73 | 2.773 | rotten | 34 | 3 | medium | 7.6895 |
| 46.84 | 4.684 | rotten | 32 | 3 | medium | 21.9399 |
| 36.58 | 3.658 | sound | 110 | 3 | medium | 13.3810 |
| 65.95 | 6.595 | sound | 16 | 3 | medium | 43.4940 |
| 26.04 | 2.604 | rotten | 22 | 3 | medium | 6.7808 |
| 59.55 | 5.955 | sound | 23.5 | 4 | medium | 35.4620 |
| 60.48 | 6.048 | rotten | 25 | 4 | medium | 36.5783 |
| 49.93 | 4.993 | rotten | 119 | 5 | medium | 24.9300 |
| 40.21 | 4.021 | rotten | 402 | 5 | medium | 16.1684 |
| 40.21 | 4.021 | rotten | 402 | 5 | medium | 16.1684 |
| 33.47 | 3.347 | rotten | 205 | 5 | medium | 11.2024 |
| 33.65 | 3.365 | sound | 57 | 5 | medium | 11.3232 |
| 74.14 | 7.414 | rotten | 402 | 5 | medium | 54.9674 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 26.74 | 2.674 | rotten | 40 | 6 | medium | 7.1503 |
| 30.48 | 3.048 | rotten | 11 | 6 | medium | 9.2903 |
| 71.65 | 7.165 | rotten | 69 | 6 | medium | 51.3372 |
| 29.45 | 2.945 | rotten | 55 | 6 | medium | 8.6730 |
| 27.9 | 2.79 | rotten | 12 | 6 | medium | 7.7841 |
| 29.84 | 2.984 | sound | 68.5 | 7 | medium | 8.9043 |
| 42.07 | 4.207 | rotten | 10 | 7 | medium | 17.6988 |
| 37.42 | 3.742 | rotten | 80 | 8 | medium | 14.0026 |
| 26.58 | 2.658 | rotten | 35 | 8 | medium | 7.0650 |
| 53.89 | 5.389 | rotten | 28 | 8 | medium | 29.0413 |
| 32.88 | 3.288 | sound | 74 | 8 | medium | 10.8109 |
| 73.2 | 7.32 | rotten | 34 | 8 | medium | 53.5824 |
| 2.38 | 0.238 | sound | 5 | 1 | fine | 0.0566 |
| 1.79 | 0.179 | sound | 115 | 1 | fine | 0.0320 |
| 2.25 | 0.225 | sound | 16 | 1 | fine | 0.0506 |
| 3.23 | 0.323 | sound | 52 | 1 | fine | 0.1043 |
| 4.62 | 0.462 | sound | 47 | 1 | fine | 0.2134 |
| 3.43 | 0.343 | sound | 36.2 | 1 | fine | 0.1176 |
| 5.86 | 0.586 | sound | in ground | 1 | fine | 0.3434 |
| 3.56 | 0.356 | sound | 15 | 1 | fine | 0.1267 |
| 3.5 | 0.35 | sound | 25.2 | 1 | fine | 0.1225 |
| 4.23 | 0.423 | sound | 38 | 1 | fine | 0.1789 |
| 4.3 | 0.43 | sound | 48 | 1 | fine | 0.1849 |
| 0.5 | 0.05 | rotten | 11 | 1 | fine | 0.0025 |
| 3.05 | 0.305 | sound | 50 | 2 | fine | 0.0930 |
| 2.93 | 0.293 | sound | 14 | 2 | fine | 0.0858 |
| 4.93 | 0.493 | sound | 17 | 2 | fine | 0.2430 |
| 5.03 | 0.503 | sound | 51 | 2 | fine | 0.2530 |
| 6.57 | 0.657 | sound | 35 | 3 | fine | 0.4316 |
| 2.86 | 0.286 | sound | 16 | 3 | fine | 0.0818 |
| 4.4 | 0.44 | sound | 17 | 4 | fine | 0.1936 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 4.58 | 0.458 | sound | 72 | 4 | fine | 0.2098 |
| 3.2 | 0.32 | sound | 45 | 4 | fine | 0.1024 |
| 1.96 | 0.196 | sound | 9 | 5 | fine | 0.0384 |
| 2.27 | 0.227 | sound | 10 | 5 | fine | 0.0515 |
| 2.15 | 0.215 | sound | 11 | 5 | fine | 0.0462 |
| 1.64 | 0.164 | sound | 5 | 5 | fine | 0.0269 |
| 1.62 | 0.162 | sound | 4 | 5 | fine | 0.0262 |
| 1.98 | 0.198 | rotten | 11 | 5 | fine | 0.0392 |
| 1.68 | 0.168 | rotten | 8 | 5 | fine | 0.0282 |
| 5.45 | 0.545 | rotten | 12 | 5 | fine | 0.2970 |
| 4.67 | 0.467 | sound | 12 | 5 | fine | 0.2181 |
| 3.27 | 0.327 | sound | 4 | 5 | fine | 0.1069 |
| 3.19 | 0.319 | sound | 9 | 5 | fine | 0.1018 |
| 2.81 | 0.281 | rotten | 14 | 5 | fine | 0.0790 |
| 4.25 | 0.425 | sound | 18 | 5 | fine | 0.1806 |
| 3.9 | 0.39 | sound | 18 | 5 | fine | 0.1521 |
| 3.55 | 0.355 | sound | 4 | 5 | fine | 0.1260 |
| 2.59 | 0.259 | sound | 18 | 5 | fine | 0.0671 |
| 3.23 | 0.323 | sound | 31 | 5 | fine | 0.1043 |
| 2.94 | 0.294 | sound | 6.5 | 5 | fine | 0.0864 |
| 4.91 | 0.491 | sound | 27 | 5 | fine | 0.2411 |
| 4.07 | 0.407 | rotten | 27 | 5 | fine | 0.1656 |
| 2.88 | 0.288 | sound | 23 | 5 | fine | 0.0829 |
| 6.45 | 0.645 | sound | 66 | 5 | fine | 0.4160 |
| 5.45 | 0.545 | sound | 90 | 5 | fine | 0.2970 |
| 1.98 | 0.198 | rotten | 9 | 6 | fine | 0.0392 |
| 2.48 | 0.248 | sound | 19 | 6 | fine | 0.0615 |
| 2.46 | 0.246 | sound | 17 | 6 | fine | 0.0605 |
| 2.22 | 0.222 | rotten | 7 | 6 | fine | 0.0493 |
| 2.41 | 0.241 | sound | 41 | 6 | fine | 0.0581 |
| 2.77 | 0.277 | sound | 37 | 6 | fine | 0.0767 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 5.27 | 0.527 | sound | 12 | 6 | fine | 0.2777 |
| 4.53 | 0.453 | rotten | 22 | 6 | fine | 0.2052 |
| 4.81 | 0.481 | sound | 75 | 7 | fine | 0.2314 |
| 4.65 | 0.465 | sound | 14 | 7 | fine | 0.2162 |
| 4.09 | 0.409 | sound | 29 | 7 | fine | 0.1673 |
| 4.55 | 0.455 | sound | 10 | 7 | fine | 0.2070 |
| 4.22 | 0.422 | sound | 85 | 7 | fine | 0.1781 |
| 4.4 | 0.44 | sound | 90 | 7 | fine | 0.1936 |
| 4.47 | 0.447 | sound | 31 | 7 | fine | 0.1998 |
| 4.9 | 0.49 | sound | 37 | 7 | fine | 0.2401 |
| 5.55 | 0.555 | sound | 27 | 7 | fine | 0.3080 |
| 2.69 | 0.269 | sound | 29 | 7 | fine | 0.0724 |
| 3.98 | 0.398 | sound | 45.5 | 7 | fine | 0.1584 |
| 5.8 | 0.58 | sound | 74 | 8 | fine | 0.3364 |
| 5.51 | 0.551 | sound | 69 | 8 | fine | 0.3036 |
| 6.18 | 0.618 | rotten | 25 | 8 | fine | 0.3819 |
| 3.41 | 0.341 | sound | 12 | 8 | fine | 0.1163 |
| 5.14 | 0.514 | sound | 36 | 8 | fine | 0.2642 |
| 2.42 | 0.242 | rotten | 19 | 9 | fine | 0.0586 |
| 2.45 | 0.245 | sound | 39 | 9 | fine | 0.0600 |
| 4.75 | 0.475 | rotten | 68 | 9 | fine | 0.2256 |
| 6.56 | 0.656 | sound | 30 | 9 | fine | 0.4303 |
| 3.3 | 0.33 | sound | 32 | 9 | fine | 0.1089 |
| 5.44 | 0.544 | sound | 35 | 9 | fine | 0.2959 |
| 3.64 | 0.364 | sound | 45 | 9 | fine | 0.1325 |
| 6.5 | 0.65 | sound | 43 | 9 | fine | 0.4225 |
| 1.9 | 0.19 | rotten | 49 | 10 | fine | 0.0361 |
| 4.55 | 0.455 | sound | 24 | 10 | fine | 0.2070 |
| 4.11 | 0.411 | sound | 45 | 10 | fine | 0.1689 |

## Appendix H: Story Map

The story map can be accessed via: https://storymaps.arcgis.com/stories/9b4379bb352f44959dd7726bb76d62c2

# Blue carbon, estimation of the carbon stock and restoration

On the Brunswick River Northern New South Wales Australia

**By Alea Roth-Douglas,**
12 January 2023