BLUE AND TEAL CARBON ASSESSMENT AT A LOCAL SCALE

Western Australia

September 2023

Blue Carbon Lab

DEAKIN UNIVERSITY

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About Deakin's Blue Carbon Lab

Deakin University's Blue Carbon Lab offers innovative research solutions for helping to mitigate climate change and improve natural capital, while also contributing to jobs, economic growth, capacity building and community wellbeing.

Acknowledgement of Country

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

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

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Glossary and Acronyms

Term	Acronym	Definition
Australian carbon credit units	ACCUs	
Blue carbon	-	Carbon captured and stored by marine and coastal ecosystems.
Carbon	C	
Carbon cccumulation rates	AR	The speed at which carbon is sequestered and stored by the vegetation and soils of an ecosystem
Carbon dioxide equivalent	CO_2e	Unit of measurement used to standardise the climate effects of various greenhouse gases. The conversion factor 3.67 is used for organic carbon, which represents the molecular weight ratio between CO_2 and C.
Carbon stocks	CS	The amount of carbon that is stored in the vegetation, roots and soils of an ecosystem
Environmental Economic Accounting	EEA	A way of evaluating ecosystem assets, flows, and services in physical and monetary terms that enable comparison with other goods and services
Greenhouse gases	-	Gases that absorb and emit radiant energy within the thermal infrared range, which can cause the greenhouse effect [e.g., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N2O)]
IPCC		The United Nations body for assessing the science related to climate change
Nitrogen	N	
Nitrogen stocks	NS	The amount of nitrogen that is stored in the vegetation, roots and soils of an ecosystem
United Nations System of Environmental Economic Accounting	UN SEEA	International statistical framework for environmental economic accounting
Soil organic carbon	SOC	Organic carbon stored within the soil/sediment. Values reported in ton C ha^{-1}. SOC is usually reported down to a specific depth (e.g., 100 cm depth).
Western Australia	WA	A state of Australia and the location of this study.

Executive Summary

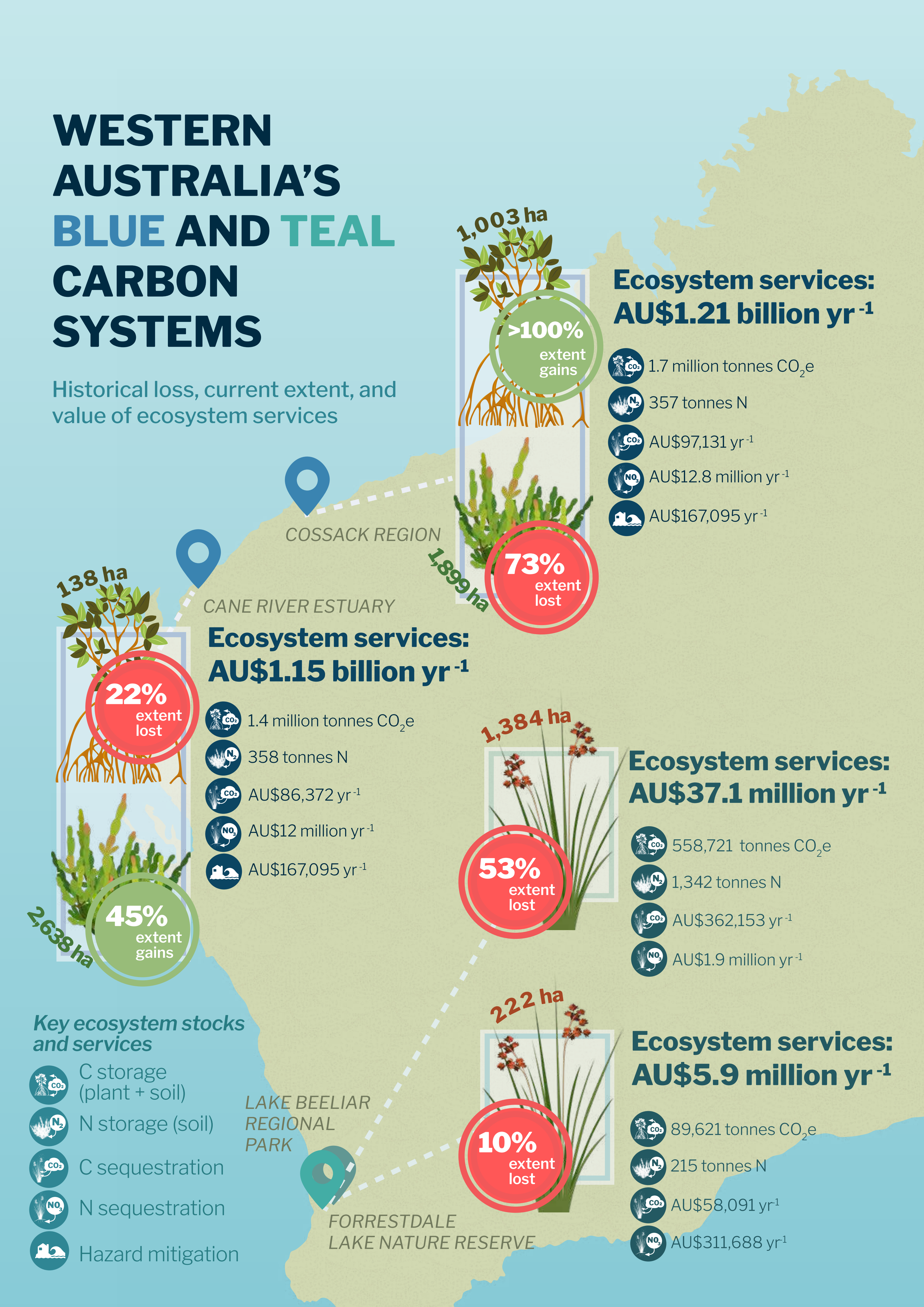
Wetlands are recognised globally for their ability to mitigate climate change by sequestering and storing carbon in their plants and soils. This is why coastal wetlands have been nicknamed 'blue carbon ecosystems', with their freshwater counterparts being referred to as 'teal carbon ecosystems'. The immense value of these systems is enhanced by the multitude of co-benefits they provide for communities and nature.

This study quantifies and values the ecosystem services provided by two coastal (Cane River estuary and Cossack region) and two freshwater wetlands (Beeliar Regional Park and Forrestdale Lake Nature Reserve) in Western Australia (WA), specifically carbon and nitrogen storage and sequestration as well as water quality improvement through nitrogen removal, and coastal hazard mitigation.

We conducted a literature review to identify local or regional-scale datasets quantifying ecosystem services from wetlands across WA. We identified 43 relevant studies, most of which focused on seagrass ecosystems (60%) or quantifying carbon stocks (67%). Using the best available data, we estimated changes in the distribution of mangroves, saltmarshes, and tidal mudflats from their pre-European status. We combined local and regional-scale data with global estimates to develop ecosystem service tables for each study area using environmental economic accounting (EEA) principles.

We found that coastal wetlands in the Cane River estuary provide 2,786 tonnes CO_2e yr^{-1} of carbon sequestration and 231 tonnes N yr^{-1} of nitrogen sequestration services with a total ecosystem service value of AU$1.15 billion per year including potential coastal hazard mitigation (AU$167,095). Mangroves, saltmarshes, and tidal mudflats in the Cossack region provide 3,133 tonnes CO_2e yr^{-1} of carbon sequestration and 247 tonnes N yr^{-1} of nitrogen sequestration services with a total ecosystem service value of AU$1.21 billion per year including potential coastal hazard mitigation (AU$167,095). The freshwater wetlands of Beeliar Regional Park provide 11,682 tonnes CO_2e yr^{-1} of carbon sequestration and 37 tonnes N yr^{-1} of nitrogen sequestration services with a combined value of AU$37.1 million. Forrestdale Lake Nature Reserve freshwater wetlands provide ecosystem services valued at AU$5.9 million including sequestration of 1,874 tonnes CO_2e yr^{-1} and 6 tonnes N yr^{-1}.

Further studies and local datasets from WA are needed to improve our capacity to predict and understand the value of wetlands in the state. However, this first-pass assessment highlights the broad benefits of wetlands for nature and communities whilst highlighting knowledge gaps that will shape future research and wetland policy in WA.



WESTERN AUSTRALIA'S BLUE AND TEAL CARBON SYSTEMS
Historical loss, current extent, and value of ecosystem services
1,003 ha
>100% extent gains
Ecosystem services: AU$1.21 billion yr -1
1.7 million tonnes CO2e
357 tonnes N
AU$97,131 yr -1
AU$12.8 million yr -1
AU$167,095 yr -1
COSSACK REGION
1,899 ha
73% extent lost
138 ha
CANE RIVER ESTUARY
Ecosystem services: AU$1.15 billion yr -1
22% extent lost
1.4 million tonnes CO2e
358 tonnes N
AU$86,372 yr -1
AU$12 million yr -1
AU$167,095 yr -1
1,384 ha
Ecosystem services: AU$37.1 million yr -1
53% extent lost
558,721 tonnes CO2e
1,342 tonnes N
AU$362,153 yr -1
AU$1.9 million yr -1
2,638 ha
45% extent gains
222 ha
Ecosystem services: AU$5.9 million yr -1
Key ecosystem stocks and services
C storage (plant + soil)
N storage (soil)
C sequestration
N sequestration
Hazard mitigation
LAKE BEELIAR REGIONAL PARK
10% extent lost
89,621 tonnes CO2e
215 tonnes N
AU$58,091 yr1
AU$311,688 yr1
FORRESTDALE LAKE NATURE RESERVE

Introduction

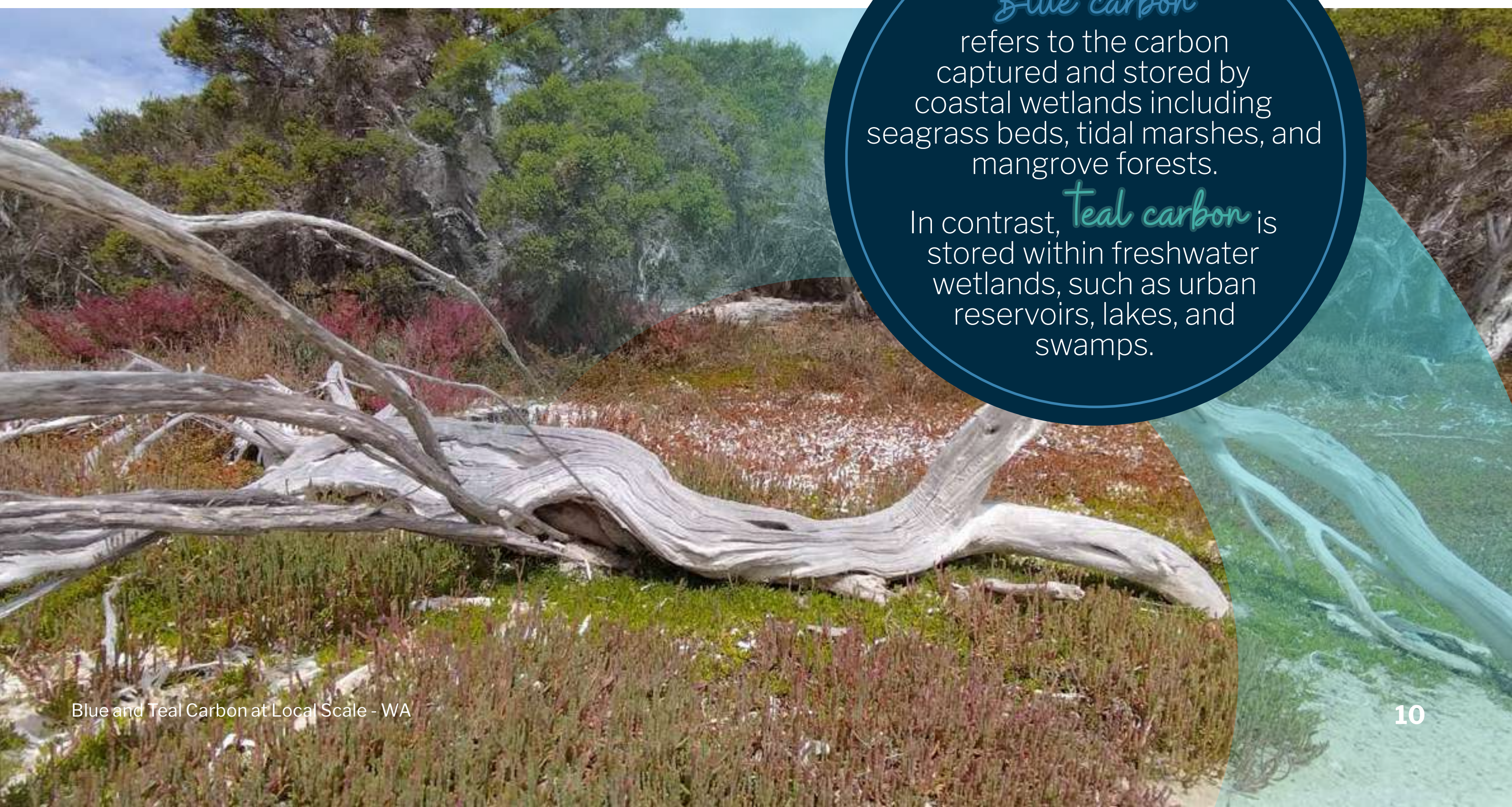
Coastal and freshwater wetlands are globally important ecosystems helping communities mitigate and adapt to climate change.

Wetlands act as natural carbon sinks capturing carbon emissions and storing it in the soil over millennia, thereby playing a crucial role in mitigating climate change (McLeod et al., 2011; Nellemann et al., 2009). Further, they offer a wide range of co-benefits that enhance biodiversity, reduce flood risk, improve water quality, and enhance people's wellbeing and livelihood (Constanza et al., 1997; Finlayson et al., 2005; Baker et al., 2020; Friess et al., 2020). As the world faces pressing environmental challenges, it is critical to quantify and value the significance of coastal and freshwater wetlands to ensure their conservation and restoration.

Wetlands can store up to 4 times more carbon and sequester up to 40 times faster than any other ecosystem (Duarte et al., 2005; Bridgham et al., 2006; McLeod et al., 2011; Carnell et al., 2018) thanks to their strategic location between land and water, high productivity, and relatively slow decomposition of organic carbon. However, if degraded they can often turn from carbon sinks to carbon sources, exacerbating climate change through the release of ancient carbon in the form of greenhouse gases (Pendleton et al., 2012). In addition to carbon sequestration, wetlands provide a wide range of ecosystem services to humans and nature. For example, wetlands increase flood resilience by storing excess water during heavy rainfall events and reducing soil erosion (Ramachandra et al., 2012; Marsooli et al., 2016). They also enhance local biodiversity by hosting a wide array of plant and animal species as well as improve water quality by cycling nutrients

Blue carbon refers to the carbon captured and stored by coastal wetlands including seagrass beds, tidal marshes, and mangrove forests.

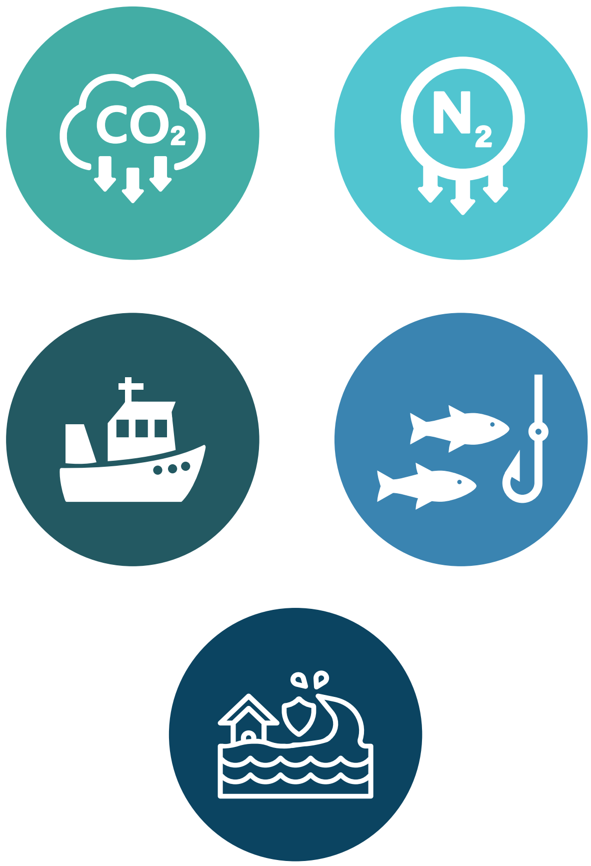
In contrast, *teal carbon* is stored within freshwater wetlands, such as urban reservoirs, lakes, and swamps.



and filtering sediments (Verhoeven et al., 2006; Finlayson et al., 2005). Further, wetlands hold significant recreational, cultural, and spiritual values, making them essential not only for ecological purposes, but also for the wellbeing and enjoyment of local communities (Clarke et al., 2021; Moore et al., 2022).

Wetlands possess significant economic value on a global scale (Barbier et al., 2011; Constanza et al., 2014; Barbier et al., 1997; Gardner & Finlayson, 2018), with the annual value of global wetland ecosystem services estimated at US$47.4 trillion (Davidson et al., 2019). Despite their critical ecological importance and high economic value, wetlands are among the most threatened ecosystems globally. With a net loss of 21% of global wetlands since 1700 (Fluet-Chouinard et al., 2023), wetland conservation and restoration is one of the most promising natural climate solutions to reach net-zero emissions (Nellemann et al., 2009; Serrano et al., 2019; Kelleway et al., 2017; Macreadie et al., 2017; McLeod et al., 2011).

Western Australia (WA) is endowed with highly valuable natural assets, including 2.5 million hectares of nationally significant wetlands across the state (5% of WA's land area). Both coastal and freshwater wetlands extend across a wide range of climatic, geomorphic and hydrological settings, creating a mosaic of ecosystems with distinct characteristics, functions and services (Bucher & Saenger, 1991; Geoscience Australia,



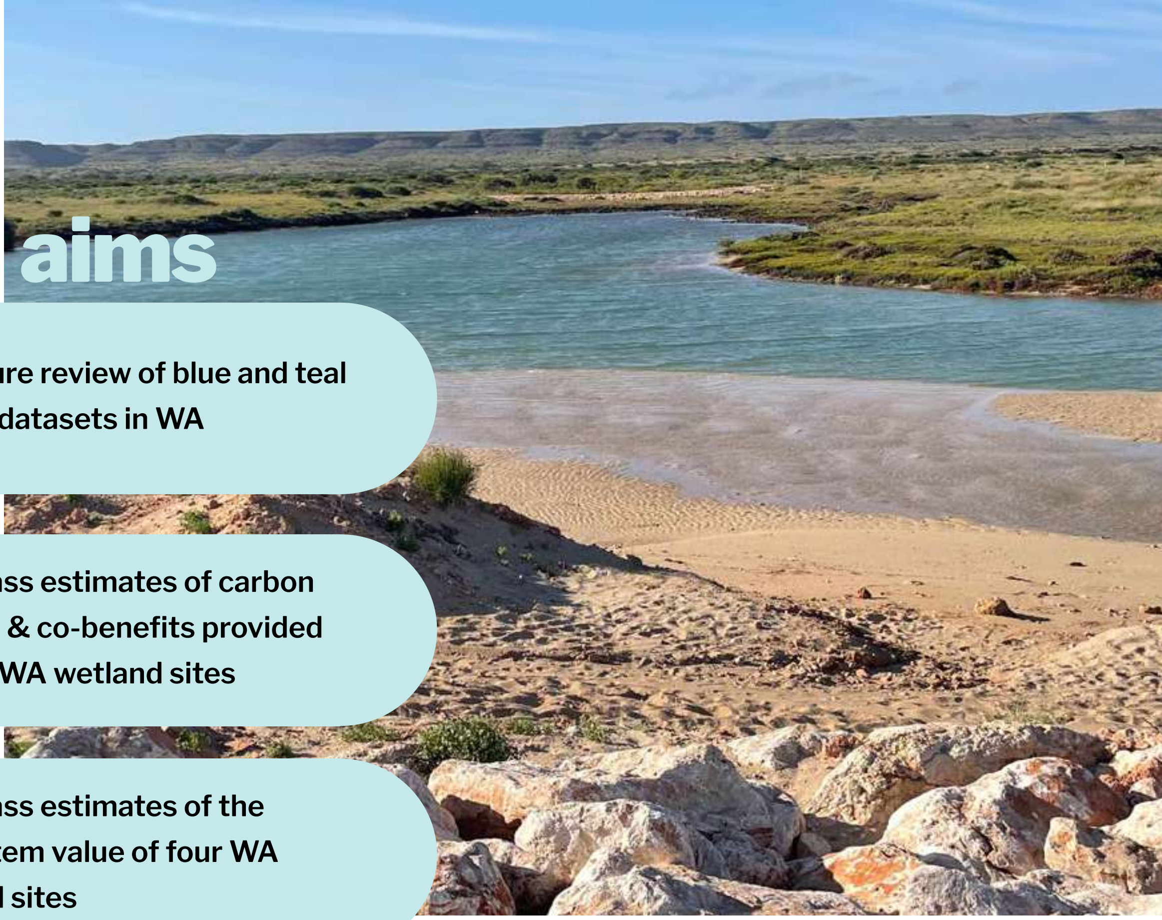
Although blue carbon ecosystems provide a wider range of ecosystem services (e.g., biodiversity enhancement, cultural values, recreation, eco-tourism), the lack of available data prevents us from including the full set of ecosystem services in our analysis.

2004). Available studies in WA suggest coastal wetlands alone store approximately 451 million tonnes of carbon (Serrano et al., 2019). However, in recent years, the state has experienced significant wetland loss due to human activities such as urbanisation, agriculture, and mining. At least 80% of the wetlands have already been lost (Hercock, 1997; Fairbridge, 1950; Department of Environmental Protection 2004). Therefore, protecting and restoring these vital ecosystems is critical for ensuring the long-term environmental and socioeconomic sustainability of WA.

Ecosystem services serve as the connecting concept between ecosystem assets and the production and consumption activity of businesses, households, and governments. Ecosystem services are defined as: "*the contributions of ecosystems to the benefits that are used in economic and other human activity*" (United Nations, 2021). These contributions extend beyond marketed goods, such as timber and fish, and include services such as water purification, global climate regulation and recreation-related services. Commonly, these types of services are supplied to communities outside markets. The focus of accounting for ecosystem services is to provide a clear description of the range of these services, the spatial heterogeneity of their delivery, and the local to global beneficiaries of these services.

Benefits are the goods and services that are used and enjoyed by people and society. As applied in ecosystem accounting, a benefit will reflect a gain or positive contribution to well-being arising from the use of ecosystem services. As it is possible to measure ecosystem services in physical terms (kg of fish), so too it is possible to measure them in monetary terms (value of catch), which allows us to understand the total scale of value produced by an ecosystem, as well as understand the relative scale of the many ecosystem services that an ecosystem produces. Importantly though, measuring ecosystem services does not provide a complete assessment of the relationship between ecosystems and people. While the scope of ecosystem services is broad, there are a range of other benefits that are difficult to capture, for example relational and intrinsic values. Nonetheless,

Project aims



- **Literature review of blue and teal carbon datasets in WA**
- **First-pass estimates of carbon storage & co-benefits provided by four WA wetland sites**
- **First-pass estimates of the ecosystem value of four WA wetland sites**

a focus on ecosystem services does provide an important piece of information in describing our use of, and dependence on ecosystems.

Understanding the economic value of wetlands is essential for future management and conservation of these ecosystems. The aim of this study was to develop a first-pass evaluation on the economic value of the ecosystem services provided by WA wetlands. Overall, such information can inform future applications of environmental economic accounting frameworks in the region. Focused on WA, this project aims to quantify and value the ecosystem services of two freshwater wetlands including Beeliar Regional Park and Forrestdale Lake wetlands, as well as two coastal wetlands including Cane River estuary and Cossack region (Point Samson). To achieve this, we first performed a literature review to identify on-ground datasets quantifying the ecosystem services from wetlands across the state. We then used local data found during the literature review (or global estimates, if local or regional data was unavailable) to estimate the ecosystem services provided by the four wetland sites and their potential economic value. By understanding the magnitude and value of these wetlands, we can better advocate for their local conservation and wise management to ensure a the longevity of ecosystem services and increase climate resilience in coastal communities.

Methods

Literature review

We identified studies on Western Australia's teal and blue carbon ecosystems and the services they provide by conducting a search of peer-reviewed and grey literature (theses and reports) from 1901 to November 2021 in Google Scholar and Web of Science. Using boolean logic (AND, *, OR, $) we limited our search to studies that included three terms related to the location (Table 1; Term #1), the ecosystem (Table 1; Term #2), and the services (Table 1; Term #3). The initial search of scientific documents yielded 331 results. However, most studies were excluded from the review as they: (1) were incorrectly identified (e.g., took place in a different state), (2) did not specify the presence and type of wetland vegetation (e.g., research took place in an estuary, but there was no mention of the presence of mangroves, seagrass or saltmarsh in the area), (3) did not provide data that could be used to quantify ecosystem services (i.e., provided fish lists, but not fish density or biomass), (4) did not report data in a way that could be extracted, transformed or analysed (e.g., reported summary data within text), or (5) provided duplicate datasets already included elsewhere (e.g., review papers that did not report new data).

Table 1: Search criteria used to identify relevant scientific literature. Search conducted on 17-11-2021.

Term	Category	Search
#1	Location	Western Australia
#2	Ecosystem	mangrov* OR seagrass* OR marsh* OR "vegetated coastal ecosystem*" OR estuar* OR wetland* OR freshwater OR Ramsar OR lacustrine OR riverine OR "aquatic ecosystem*" OR swamp*
#3	Services and Values	"ecosystem service*" OR "water security" OR "water purif*" OR "nutrient cycl*" OR "nitrogen cycl*" OR "economic value" OR "ecosystem valuation" OR "ESV" OR "Ecosystem Services Valuation" OR "SEEA" OR "System of Environmental Economic Accounting" OR "blue carbon" OR "teal carbon" OR "soil carbon" OR "soil organic carbon" OR "vegetation carbon" OR "aboveground" OR "belowground" OR "plant biomass" OR "carbon sequestration" OR "carbon stock*" OR "carbon storage" OR "carbon content" OR "SOC" OR "sediment carbon" "carbon drawdown" OR "carbon sink" OR "carbon cycl*" OR "carbon source" OR "carbon emission*" OR "carbon dioxide" OR "methane" OR "fish biomass" OR "fish productivity" OR "stable isotope" OR "fish harvest*" OR "fish catch*" OR fishing OR recreation* OR birdwatch* OR "touris*" OR "artisanal fishing" OR visitation OR "willingness to pay" OR "travel cost" OR "flood damage" OR "flood control" OR "avoided damage" OR "property damage" OR "coastal protection" OR "erosion prevention" OR "wave energy" OR "erosion control" OR "loss of life"

Estimating wetland ecosystem services at local scale

A. Study sites

Coastal wetlands in Western Australia span approximately 1.6 million ha of coastline and include ~666,000 ha of seagrasses, ~630,000 ha of saltmarshes and ~290,000 of mangroves (Lucieer et al., 2019). Mangroves were recently estimated to cover an area of approximately 276,000 ha distributed along 4,000 km of coastline (Hickey & Radford 2022). These ecosystems play a crucial role in shoreline stabilisation, erosion control, and nutrient cycling, while also serving as nurseries and feeding grounds for fish (Jänes et al., 2020; Jänes et al., 2020a; Unsworth et al., 2019), protecting coastlines (Arkema et al., 2013; Friess et al., 2020; Temmerman et al., 2013), reducing nutrients and suspended sediments runoff (Nelson & Zavaleta, 2012), and enhancing biodiversity (Carugati et al., 2018; Duffy, 2006).

In contrast, freshwater wetlands in Western Australia cover approximately 632,000 ha (Department of Biodiversity, Conservation and Attractions, 2021b). Wetlands found within or adjacent to cities and towns play a crucial role in enhancing the liveability, resilience, and sustainability of urban areas. The scale and potential ecosystem services of teal carbon ecosystems makes them an important consideration in this valuation study.

In this study, we quantified and valued the ecosystem services of two freshwater wetlands and two coastal wetlands (Table 2, Figures 1 and 2). We used existing data on the distribution of coastal (Hickey & Radford, 2022; Lucieer et al., 2019) and freshwater (Department of Biodiversity, Conservation and Attractions, 2021b) wetlands to estimate their distribution within each study area (Table 2). Furthermore, we used the modelled pre-1750 vegetation distribution dataset available for WA (Beard et al., 2013) to estimate the potential gains and losses in the distribution of wetlands within each site. Spatial analyses were undertaken in ArcGIS Pro 2.4.3 (ESRI, 2011) and R version 3.6.1 statistical software (R Core Team, 2019).

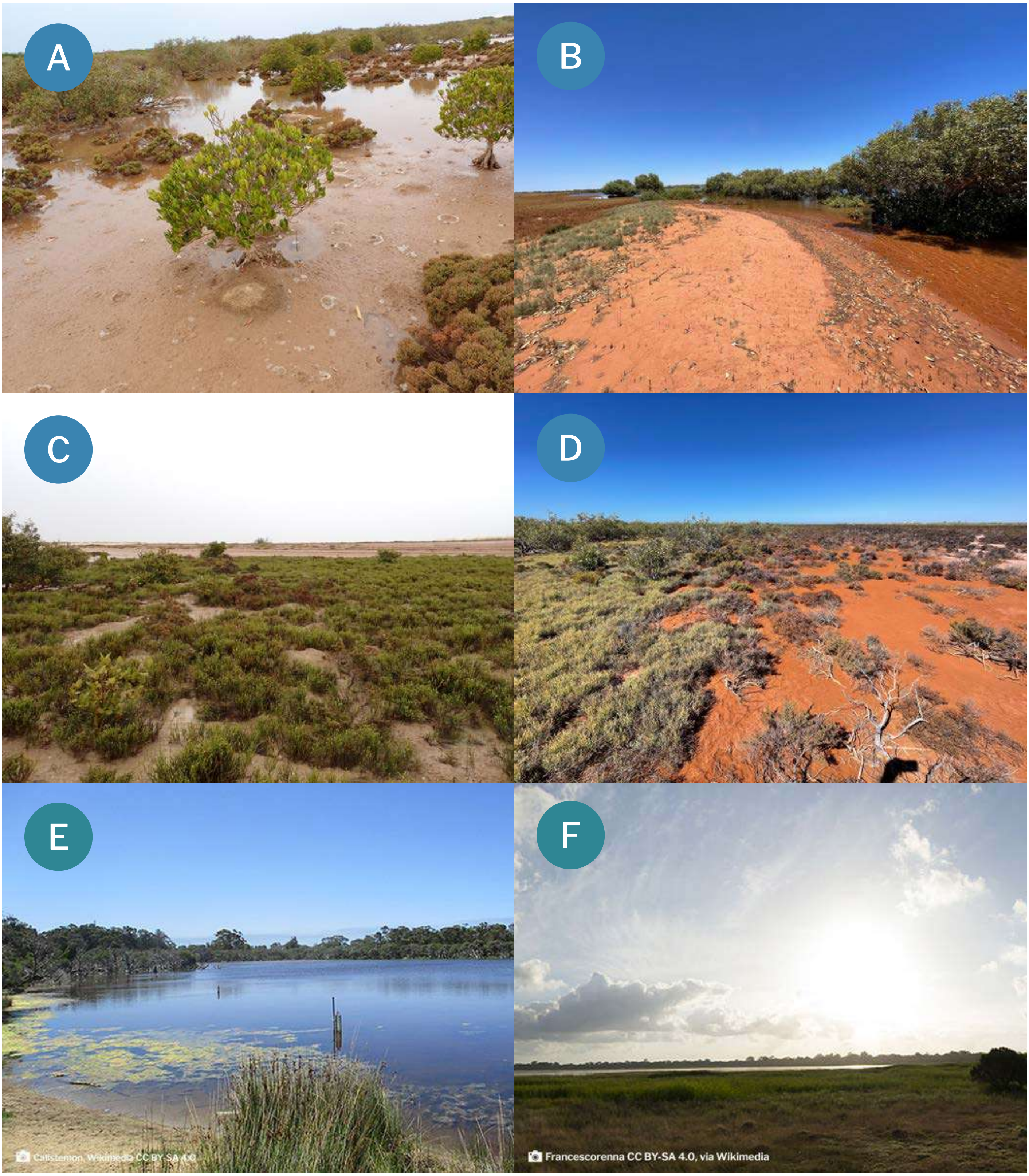


Figure 1: Sites and habitats included in this study. Mangroves (A) in Cane River estuary and (B) Cossack region. Saltmarsh in (C) Cane River estuary and (D) Cossack region. Freshwater wetlands in (E) Beeliar Regional Park and (F) Forrestdale Lake Nature Reserve.

Table 2: Summary information for each site included in this study. Ecosystem distribution was based on Hickey & Radford, (2022) and Lucieer et al. (2019) for coastal wetlands and the Department of Biodiversity, Conservation and Attractions (2021b) for freshwater wetlands.

Characteristics	Coastal Wetlands		Freshwater Wetlands	
	Cane River estuary	**Cossack Region**	**Beeliar Regional Park**	**Forrestdale Lake Nature Reserve**
Site description	Located in the Pilbara region, WA. The river flows in a north-westerly direction through the Cane River Conservation Park and over the Onslow Coastal Plain. It discharges into the Indian Ocean near Yardie Landing approximately 35 km north- east of Onslow (Figure 1). The region supports a wide range of fauna and flora species with a large proportion of endemic species. The boundaries for the Cane River estuary were delimited following the Western Australia Coastal Waterways Geomorphic Habitat Mapping, Version 2 (Dyall et al., 2017).	The Cossack region, including the coastal town of Point Samson and the mouth of the Harding River, is located 1,480 km north of Perth and within the Pilbara coast of Western Australia (Figure 1). Cossack is an important cultural site for the Ngarluma Peoples and is located on Butcher Inlet (also called Butcher's Inlet) at the mouth of the Harding River. The river mouth remains an important location for fishing and hunting traditional foods to the Ngarluma Peoples.	Beeliar Regional Park, located in the southern suburbs of Perth, Western Australia, is a significant and diverse natural area that offers a haven for biodiversity and outdoor recreation (Figure 1). Encompassing approximately 3,600 hectares, the park is home to a range of distinct ecosystems, including wetlands, lakes, woodlands, heathlands, and coastal dunes. These diverse habitats provide critical refuge for a variety of birdlife and water-dependent species, while holding cultural and spiritual significance to the Nyoongar people, who used these wetlands for camping, ceremonies and to seek food. Given its location in a highly populated area on the City of Cockburn, the Beeliar Regional Park serves as an important recreational space for the local community, providing opportunities for outdoor education, birdwatching, picnicking, and relaxation (City of Cockburn, 2021; Department of Biodiversity, Conservation and Attractions, 2021). The limits for the Beeliar Regional Park were delimited following the Regional Parks layer (Department of Biodiversity, Conservation and Attractions, 2021 c).	Forrestdale Lake Nature Reserve is a seasonal lake that has been designated as a RAMSAR site in 1990. It is located in the southeastern suburbs of Perth, Western Australia, is a significant wetland conservation area renowned for its ecological importance and biodiversity (Figure 1). The Reserve is situated on the Swan Coastal Plain (City of Armadale) and is one of the most important conservation areas in southwestern Australia. The wetland is recognized for its critical role in supporting a wide range of migratory waterbird species, as well as providing habitat for threatened and endangered species, such as the Carnaby's black-cockatoo, the Western swamp tortoise, two species of short-tongued native bees (Department of Biodiversity, Conservation and Attractions, 2021). The limits for the Forrestdale Lake Nature Reserve were delimited following the layer describing the WA's RAMSAR sites (Department of Biodiversity, Conservation and Attractions, 2017).
Region	Pilbara	Pilbara	Perth metropolitan	Perth metropolitan
Climatic Region	Tropical	Tropical	Temperate	Temperate
Coordinates	-21.55, 115.38	-20.69, 117.18	-32.13, 115.83	-32.17, 115.93
Wetland extent	Saltmarshes and salt flats are widely distributed in the region covering 2,638 ha, with mangrove forests only present across 138 ha.	Coastal wetlands in the region are composed of mangrove forests and saltmarshes covering 1,003 ha and 1,899 ha, respectively.	Freshwater wetlands extend across 1,384 ha within the Beeliar Regional Park.	Forrestdale Lake Nature Reserve has approximately 222 ha of freshwater wetlands, with the reserve including a Ramsar-listed wetland of international significance (Department of Biodiversity, Conservation and Attractions, 2017).

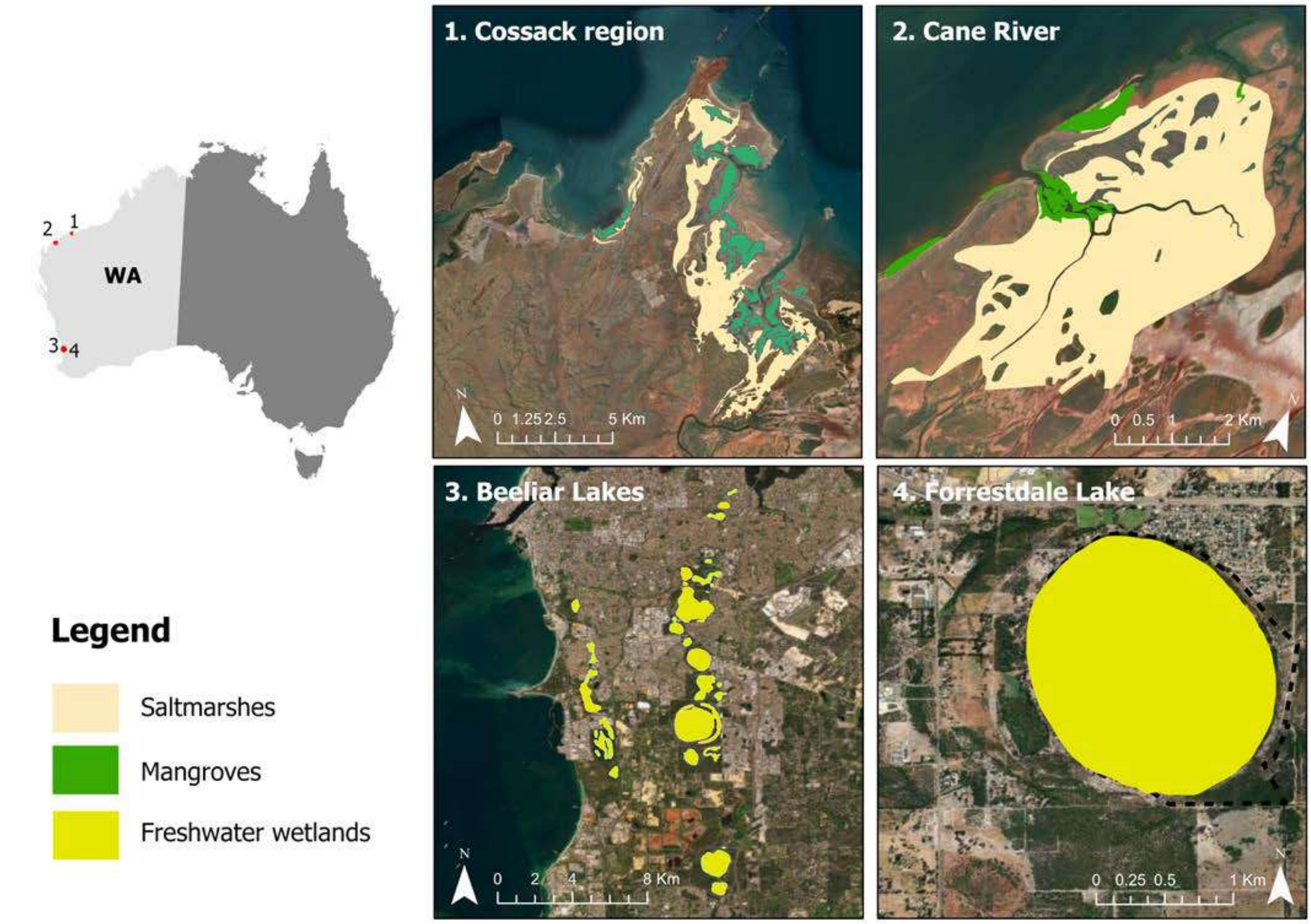


Figure 2: Map of Western Australia including the four sites included in this study: Cossack region (including Point Samson and the mouth of the Harding River), Cane River estuary, Beeliar Regional Park, and Forrestdale Lake Nature Reserve. Ecosystem distribution was based on Hickey & Radford (2022) and Lucieer et al. (2019) for coastal wetlands and the Department of Biodiversity, Conservation and Attractions (2021a) for freshwater wetlands. An interactive map is available on the StoryMap.

B. Ecosystem services and their valuation

Our approach to collating information on ecosystem services provided by blue and teal carbon wetlands extended beyond those values strictly valued within the System for Environmental Economic Accounting – Ecosystem Accounting (United Nations, 2021). This is because we wanted to include the diverse benefits of these ecosystems, such as biodiversity and welfare values (services for which there isn't a market), but still can be valued using different environmental economics approaches.

We used the data extracted from the literature review to quantify the ecosystem services provided by blue and teal ecosystem within each site (Table 2). Since data on ecosystem services provided by wetlands is scarce in WA, we have also extracted data from global (Constanza et al., 2014) and regional estimates (Macreadie et al., 2017; Carnell et al., 2018; Serrano et al., 2019) to help our quantification (Table 3). In the case of the global value of ecosystem services, we corrected the values into 2023-dollar value using an inflation calculator. Then, converted the US$ into AU$ using a conversion rate of US$1=AU$1.49.

In addition to the data extracted from the literature, we also conducted a fieldwork sampling to collect data on nitrogen stocks for blue carbon ecosystems in WA (details in the section '**Measuring nitrogen stocks in Cane River estuary**'). Furthermore, we used unpublished data (Carnell et al., 2019) on the coastal protection (i.e., hazard mitigation) value provided by coastal wetlands to estimate their value within blue carbon ecosystems (details available in the section '**Coastal protection value by WA's blue carbon ecosystems**').

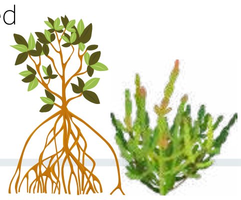
For WA's coastal wetlands, to estimate the annual value of nitrogen sequestration, we assumed a price of AU$52 per kg, based on a previous estimate of approximately €32 per kg (Liekens et al., 2013; Costa et al., 2022). Furthermore, we assumed an average value of AU$31 per tonne (Clean Energy Regulator, 2022) to estimate the value of carbon sequestration by blue carbon ecosystems.

Then, we combined the ecosystem services data with the wetland mapping available for teal (Department of Biodiversity, Conservation and Attractions, 2021b) and blue carbon ecosystems (Hickey & Radford, 2022; Lucieer et al., 2019) to estimate the total services provided by these ecosystems at each site. In this case, ecosystem services were estimated by multiplying service value * by the total area of each ecosystem at a specific site (Table 3).

Table 3: Description of data and sources used in the quantification of ecosystem services provided by coastal and freshwater wetlands. Data was classified as L: local, within WA; R: regional, within other parts of Australia; or G: global. Equations used in the calculations for each service is described, and includes carbon stocks (CS), nitrogen stocks (NS), carbon/nitrogen accumulation rates (AR), and the conversion factor (CF) used in this assessment.

Services quantified based on local/ regional data	MANGROVES	SALTMARSH	FRESHWATER WETLAND	EQUATION	
Carbon storage – PLANT	**224** tonnes ha^{-1} Alongi et al. 2000, 2003; Hickey et al. 2018; Serrano et al. 2019	**70** tonnes ha^{-1} Congdon & McComb 1980, 1981; Serrano et al. 2019	NA	CS_{CO2e} (tonnes ha^{-1}) = area (ha) * CS * CF CF= 3.67	L/R
Carbon storage – SOIL	**574** tonnes ha^{-1} Alongi et al. 2000, 2003; Lovelock et al. 2021	**411** tonnes ha^{-1} Macreadie et al. 2017; Serrano et al. 2019; Gorham et al. 2021	**404** tonnes ha^{-1} Carnell et al. 2018		
Soil nitrogen stocks	**0.11** tonnes ha^{-1} This study	**0.13** tonnes ha^{-1} This study	**0.97** tonnes ha^{-1} Carnell, unpublished data for lacustrine wetlands	NS (tonnes ha^{-1}) = area (ha) * NS	L
Carbon sequestration rates	**1.2** tonnes ha^{-1}y^{-1} Serrano et al. 2019	**1.0** tonnes ha^{-1}y^{-1} Gorham et al. 2021	**8.4** tonnes ha^{-1}y^{-1} Carnell et al. 2018	AR_{CO2e} (tonnes ha^{-1} yr^{-1}) = area (ha) * AR * CF * Price CF= 3.67	L/R
	Carbon price at AU$31 per tonne (Clean Energy Regulator, 2022)				
Nitrogen sequestration rates	**0.089** tonnes ha^{-1}y^{-1} Costa et al., 2022	**0.083** tonnes ha^{-1}y^{-1} Costa et al., 2022	**0.027** tonnes ha^{-1}y^{-1} Carnell, unpublished data	ARN (tonnes ha^{-1} yr^{-1}) = area (ha) * AR * Price	L/R
	Nitrogen price at AU$52 per kg (Liekens et al., 2013; Costa et al., 2022)				
Hazard mitigation	**AU$69,529** yr^{-1}	**AU$97,565** yr^{-1}	No information available	NA	L

Table 3 continued



Services quantified based on global estimates (Constanza et al. 2014)	MANGROVES + SALTMARSH	FRESHWATER WETLAND
Water regulation	NA	AU$16,103 $ha^{-1}yr^{-1}$
Water supply	AU$2,616 $ha^{-1}yr^{-1}$	AU$3,875 $ha^{-1}yr^{-1}$
Waste treatment	AU$348,454 $ha^{-1}yr^{-1}$	AU$1,968 $ha^{-1}yr^{-1}$
Food production	AU$2,388 $ha^{-1}yr^{-1}$	AU$227 $ha^{-1}yr^{-1}$
Recreation	AU$4,713 $ha^{-1}yr^{-1}$	AU$4,641 $ha^{-1}yr^{-1}$
Climate regulation	AU$144 $ha^{-1}yr^{-1}$	NA
Disturbance regulation	AU$11,501 $ha^{-1}yr^{-1}$	NA
Erosion control	AU$8,444 $ha^{-1}yr^{-1}$	NA
Nutrient cycling	AU$97 $ha^{-1}yr^{-1}$	NA
Habitat refugia	AU$36,834 $ha^{-1}yr^{-1}$	NA
Raw materials	AU$769 $ha^{-1}yr^{-1}$	NA
Genetic resources	AU$669 $ha^{-1}yr^{-1}$	NA

EQUATION

Service= Value * area (ha)

Measuring nitrogen stocks in Cane River estuary

We collected soil cores to determine soil nitrogen stocks in mangroves and saltmarshes within the Cane River region, to help us quantify nitrogen removal services at both blue carbon sites. We estimated soil nitrogen content (%) from mangroves and saltmarshes at 20 sites in the Cane River region in two field trips to Onslow (October 2022) and Karratha (December 2022) (Figure 3). At each site, we collected sediment cores (1 m deep or until bedrock was reached) using either a PVC pipe (5 cm internal diameter, 150 cm length) or a Russian peat corer. To account for soil compaction, we measured the distance of the from the top of the pipe to the soil surface outside and inside the PVC pipe (Figure 4) and calculated the compaction factor through the steps:

C1 = total pipe length – compaction in

C2 = total pipe length – compaction out

Compaction Factor = C1/C2

Each sediment core was immediately sub-sampled at the top, middle and bottom sections with a 20 ml syringe through pre-drilled holes on the PVC pipe or from the peat corer. The volume was noted, and samples were stored at 4 °C until transportation to Deakin University (Melbourne, Australia) for processing of bulk density and soil nitrogen stocks.

In the laboratory, the samples were dried at 60 °C until they reached a constant weight (48-72 hours). Then, we recorded their weights to calculate the sediment bulk density (g cm^{-3}) using the following equation:

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

We pulverized and homogenised all samples using a Retsch RM200 mortar grinder (Baldock et al., 2013). Total nitrogen analyses were performed on a LECO elemental analyser, through high-temperature combustion of samples. The total nitrogen stock for each depth strata were calculated using the N percentage and sediment bulk density of the layer using the following formula (Howard et al., 2019):

*Soil N pool (tonnes ha^{-1}) of each depth section = bulk density (g cm^{-3}) * SON%*

For each soil core, we determined the total soil nitrogen stock by summing the nitrogen stocks for all depth sections. In this study, we calculated nitrogen stocks up to 1 m soil depth in line with IPCC guidelines (IPCC, 2014).

Figure 3: Collection of soil cores in Cane River with pre-drilled PVC pipes during October 2022.

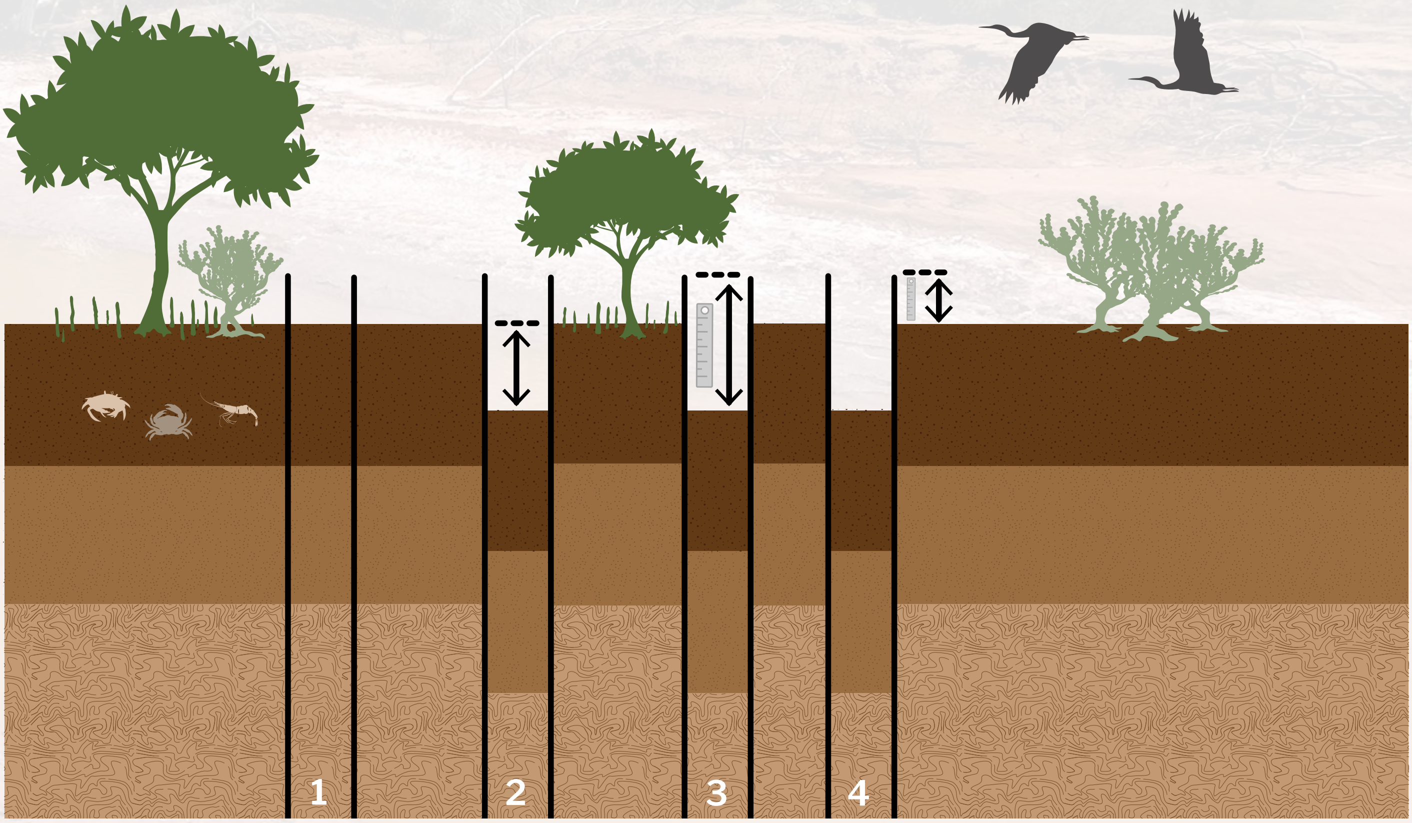
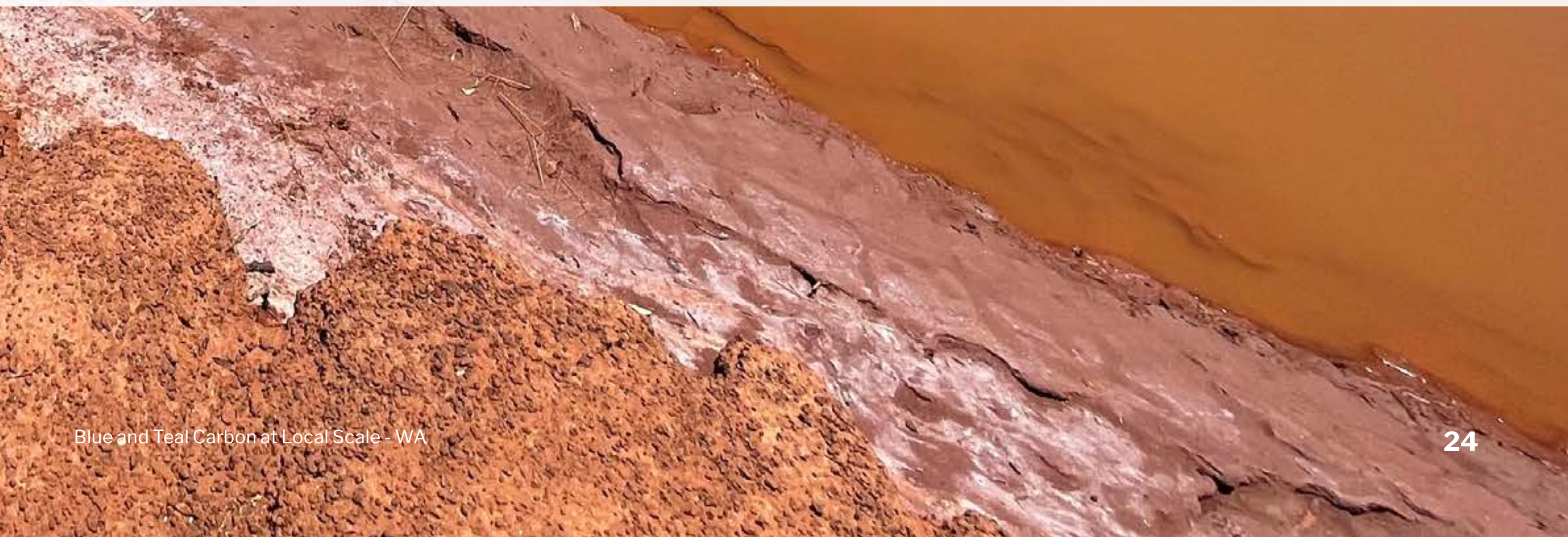


Figure 4: Schematic drawing showing how compaction was measured during the soil sampling: 1= non-compacted core, 2= compacted core, 3= measuring compaction in, and 4= measuring compaction out.



VISIT TO CANE RIVER

Prof Peter Macreadie, director of the Blue Carbon Lab, visited Cane River, WA, in October 2022.

He met with Onslow Indigenous Sea Rangers and local landowners to discuss potential restoration opportunities in the region and assess potential sites for blue carbon projects.

As part of the visit, Peter conducted training on blue carbon sampling, while collecting coastal soil cores from saltmarshes and mangroves. These samples were analysed to quantify nitrogen stocks for this study.

Evaluating the value of coastal hazard mitigation by coastal wetlands

To estimate the value of coastal hazard mitigation by WA's blue carbon ecosystems, we referred to an unpublished assessment of the impact of different climate variables on coastal vulnerability based on the InVEST model (Carnell et al., 2019), which generates an index-based assessment calculated from various physical factors that potentially cause coastal hazards (Sharp et al. 2018). This assessment considered six different scenarios, including:

1. Sea level trend + storm surge potential
2. Sea level trend + cyclone generated surge
3. Sea level changes + cyclone generated surge
4. Sea level 2018 + storm surge 10-year return period
5. Sea level 2100 RCP 2.6 + storm surge 100-year return period
6. Sea level 2100 RCP 8.5 + storm surge 100-year return period

For the purposes of this study, we used the scenario focusing on the sea level trend plus storm surge potential to represent a conservative indication of the role of blue carbon ecosystems to coastal hazard mitigation. In this case, sea level trend represents the long-term rate of sea level rise from the satellite altimetry for the period 1993-2018; while storm surge indicates the cross-shore distance between coastline and the edge of continental shelf.

The InVEST Coastal Vulnerability offered a first-pass assessment of the potential coastal hazard mitigation generated by coastal wetlands at a large scale. The socio-economic value of natural ecosystems was estimated using the difference in population density and total capital stock values exposed to coastal hazards at the county (postcode) level. We estimated the total value of infrastructure and population protected by coastal wetlands in WA and for each of our study sites by extracting the average value of properties within 1 km of the coastline where the presence of blue carbon ecosystems reduced coastal hazards (e.g., inundation, extreme events, erosion). We then transformed the asset value (i.e., total property value) into an annual flow value in line with previous work conducted in Victoria (Costa et al., 2022) and assuming a 7% discount rate over a 25-year timeframe in the following equation:

$$\textit{Annual value} = \frac{\dfrac{\text{Discount rate}}{\text{Present value}}}{1 - (1 + \text{Discount rate})^{-years}}$$

Results

Literature review

We identified WA's teal and blue carbon literature by systematically searching peer-reviewed and grey literature in Google Scholar and Web of Science. Using search terms specific to location ("Western Australia"), ecosystem (e.g., mangrove, wetland), and ecosystem services (e.g., carbon, fisheries), we identified over 300 potential studies. Publications were only included if they specified the presence of a vegetated wetland community and provided detailed data in tables or graphs.

Only 43 studies included relevant quantitative data from WA's wetland ecosystems (Figure 5; Appendix 1). Interest in wetland ecosystems has peaked in recent years, with half of all studies being published within the past 10 years (2011-2021). Research has predominantly focused on coastal wetlands (85% of studies), with most of them being conducted in the extensive seagrass meadows of Shark Bay. Only eight studies reported relevant datasets from freshwater wetlands, with all of them taking place in natural or artificial wetlands around Perth.

Wetland carbon sequestration and storage is the ecosystem service best quantified in WA (65% of studies). Despite numerous fish studies taking place in coastal and freshwater wetlands across the state (over 35 studies), only eight clearly specify the presence of wetland vegetation (e.g., seagrass) and provide data indicative of fish density, biomass, and productivity (e.g., as opposed to isotope or diet studies). There were only two studies relating to wetland nutrient cycling, social values and recreation in WA.

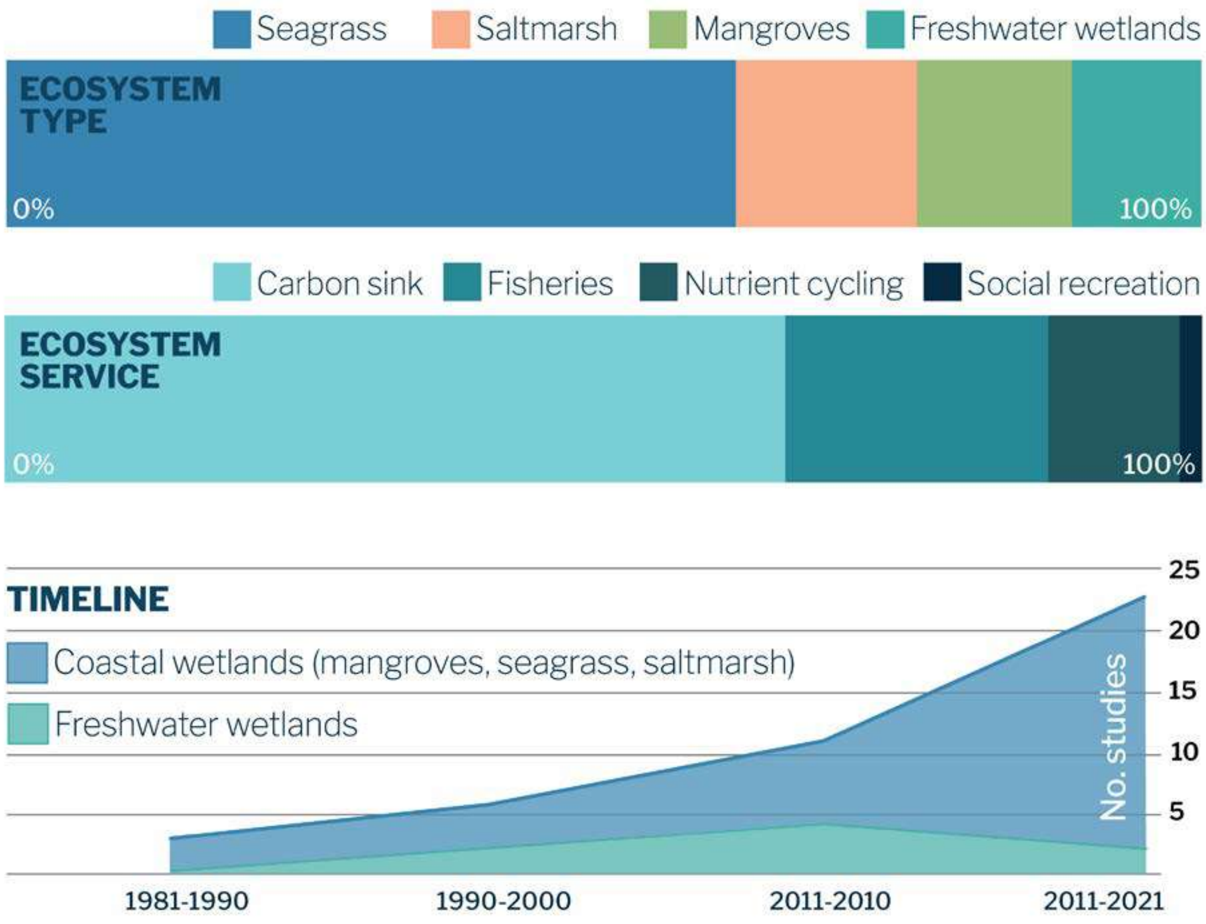


Figure 5: Trends in WA's blue and teal ecosystem literature. The 43 relevant studies identified through this review are classified by (a) ecosystem type, (b) the ecosystem service measured, and (c) date interval. A single study may report datasets for multiple ecosystems or ecosystem services.

Estimating wetland ecosystem services at local scale

Coastal wetlands

Cane River estuary

Before European settlement, the Cane River estuary held approximately 177 ha of mangroves and 230 ha of saltmarshes (Figure 6). The best available information indicates that the region currently holds approximately 138 ha of mangrove forests and 2,638 ha of saltmarshes[1] (Figure 6, Table 4). Although there are some uncertainties associated with the saltmarsh distribution within WA, we estimate that 22% of mangroves were lost in the region, while saltmarshes have potentially increased their distribution. The pre-European vegetation map shows that the region encompassed 1,592 ha of tidal mudflats in combination with 230 ha of saltmarshes. However, it is likely that the spatial dataset used in this study for the current distribution of saltmarsh is classifying both habitats as 'saltmarshes'. We used a conservative approach, combining both habitats to estimate that saltmarshes and mudflats have increased their distribution by approximately 45% along the Cane River estuary.

Ecosystem services

Mangroves and saltmarshes within the Cane River estuary hold approximately 1.4 million tonnes of CO_2e distributed within their living plants and soil (Table 4). In addition, these ecosystems also hold 358 tonnes of nitrogen in their soils. Additional to carbon and nitrogen storage, these ecosystems also provide an array of ecosystem services including carbon and nitrogen sequestration, and coastal hazard mitigation which were quantified in this first-pass assessment.

Overall, carbon sequestration varies from 172 tonnes CO_2e yr^{-1} for mangroves and 2,614 tonnes CO_2e yr^{-1} for saltmarshes. In addition, these ecosystems provide water quality improvement through nitrogen removal varying from 12 tonnes N yr^{-1} for mangroves and 219 tonnes N yr^{-1} for saltmarshes. We valued carbon sequestration services provided by blue carbon ecosystems at AU$86,372 per year and nitrogen sequestration services at AU$12 million per year. We estimated the value of potential coastal hazard mitigation to be AU$167,095 per year. Table 4 shows the detailed ecosystem supply accounting for mangroves and saltmarshes within the Cane Rive estuary.

Using the global average values to estimate the combined value of ecosystem services provided by mangroves and saltmarshes, we found that these ecosystems could provide co-benefits to the value of AU$1.15 billion per year within the Cane River estuary. Table 5 shows the detailed ecosystem service valuation for each co-benefit included in this analysis.

[1] We recognise that the dataset used to estimate saltmarshes in the region is likely overestimating their distribution, which seems to be composed by large areas of tidal mudflats in combination with saltmarshes. This agrees with the WA pre-European vegetation map, which shows an area of 1,592 ha of tidal mudflats in combination with 230 ha of saltmarshes along the Cane River estuary.

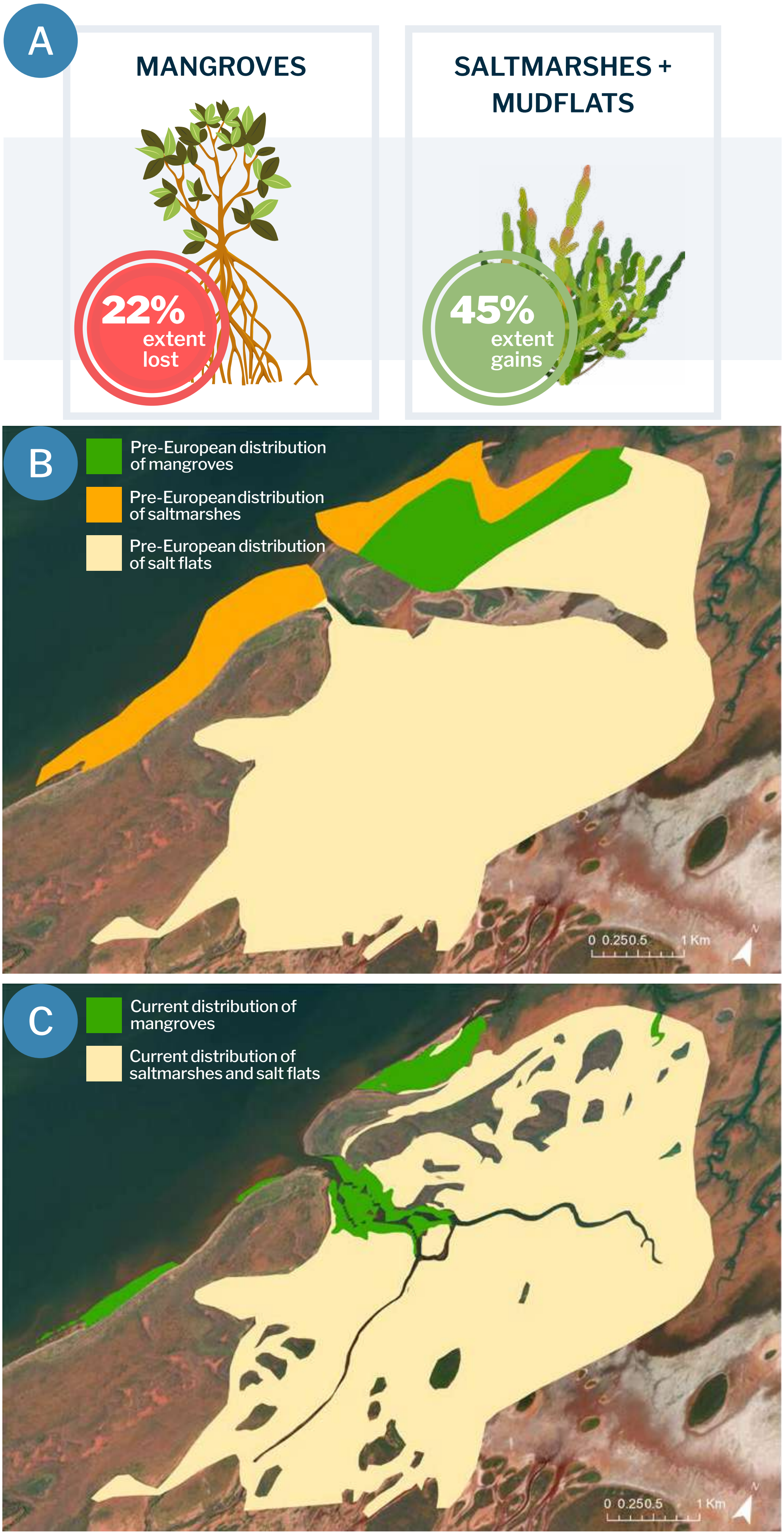


Figure 6: (A) Percentage change in saltmarsh and mangrove cover within the Cane River estuary as well as the past (B) and current (C) distribution of blue carbon ecosystems within the region based on existing spatial data.

Table 4: Ecosystem services supply account in physical and monetary terms for existing mangroves and saltmarshes within the Cane River estuary.

Ecosystem type			Mangroves	Saltmarshes	Total supply
Extent		hectares	138	2,638	**2,776**
Carbon stocks (plant + soil)		tonnes CO_2e	109,902	1.3 million	**1.4 million**
Nitrogen stocks		tonnes N	15	343	**358**
Physical ecosystem services account					
Regulating services	Carbon sequestration	tonnes CO_2e yr^{-1}	172	2,614	**2,786**
	Water purification	tonnes N yr^{-1}	12	219	**231**
Monetary ecosystem services account					
Regulating services	Carbon sequestration	AU$ yr^{-1}	5,338	81,034	**86,372**
	Coastal hazard mitigation		69,529	97,565	**167,095**
	Water purification		638,664	11.8 million	**12 million**

Table 5: Ecosystem service valuation for combined mangroves and saltmarshes within the Cane River estuary based on global estimates (Constanza et al., 2014). We corrected the values into 2023-dollar values using an inflation calculator and converted US$ into AU$ using a conversion rate of US$1=AU$1.49.

	MANGROVES + SALTMARSH (AU$ yr^{-1})
Water supply	$7,262,016
Waste treatment	$967,308,304
Food production	$6,629,088
Recreation	$13,083,288
Climate regulation	$399,744
Disturbance regulation	$31,926,776
Erosion control	$23,440,544
Nutrient cycling	$268,772
Habitat refugia	$102,251,184
Raw materials	$2,134,744
Genetic resources	$1,857,144

Cossack region

Before European settlement, the Cossack region held approximately 5,112 ha of saltmarshes and 299 ha of mangroves (Figure 7). The best available information indicates that the region currently holds approximately 1,003 ha of mangroves and 1,899 ha of saltmarshes (Figure 7, Table 6). Similar to the Cane River estuary, there are some uncertainties associated with the distribution of saltmarshes within WA. The map used in this study likely combines both saltmarshes and tidal mudflats. The pre-European vegetation map shows that the region encompassed 1,965 ha of tidal mudflats in combination with 5,112 ha of saltmarshes. For a conservative approach, we combined both habitats to estimate the potential changes in the ecosystem distribution and found that mangroves widely increased their distribution (>100%) while the distribution of saltmarshes and tidal mudflats decreased by 73% (Figure 7, Table 6).

Ecosystem services

Mangroves and saltmarshes within the Cossack region hold approximately 1.7 million tonnes of CO_2e distributed within their living plants and soil (Table 6). These ecosystems also hold 357 tonnes of nitrogen in their soils. Additional to carbon and nitrogen storage, these ecosystems also provide an array of ecosystem services, which were quantified in this first-pass assessment. These include carbon and nitrogen sequestration as well as coastal hazard mitigation.

Overall, carbon sequestration varies from 1,251 tonnes CO_2e yr^{-1} for mangroves and 1,882 tonnes CO_2e yr^{-1} for saltmarshes. In addition, these ecosystems provide water quality improvement through nitrogen removal varying from 89 tonnes N yr^{-1} for mangroves and 158 tonnes N yr^{1} for saltmarshes. We valued these services at AU$97,131 per year for carbon sequestration and AU$12.8 million per year for nitrogen sequestration.

Table 6: Ecosystem services supply account in physical and monetary terms for existing mangroves and saltmarshes within the Cossack region.

Ecosystem type			Mangroves	Saltmarshes	Total supply
Extent		hectares	1,003	1,899	**2,902**
Carbon stocks (plant + soil)		tonnes CO_2e	798,779	912,982	**1.7 million**
Nitrogen stocks		tonnes N	110	247	**357**
Physical ecosystem services account					
Regulating services	Carbon sequestration	tonnes CO_2e yr^{-1}	1,251	1,882	**3,133**
	Water purification	tonnes N yr^{-1}	89	158	**247**
Monetary ecosystem services account					
Regulating services	Carbon sequestration	AU$ yr^{-1}	38,798	58,333	**97,131**
	Coastal hazard mitigation		69,529	97,565	**167,095**
	Water purification		4.6 million	8.2 million	**12.8 million**

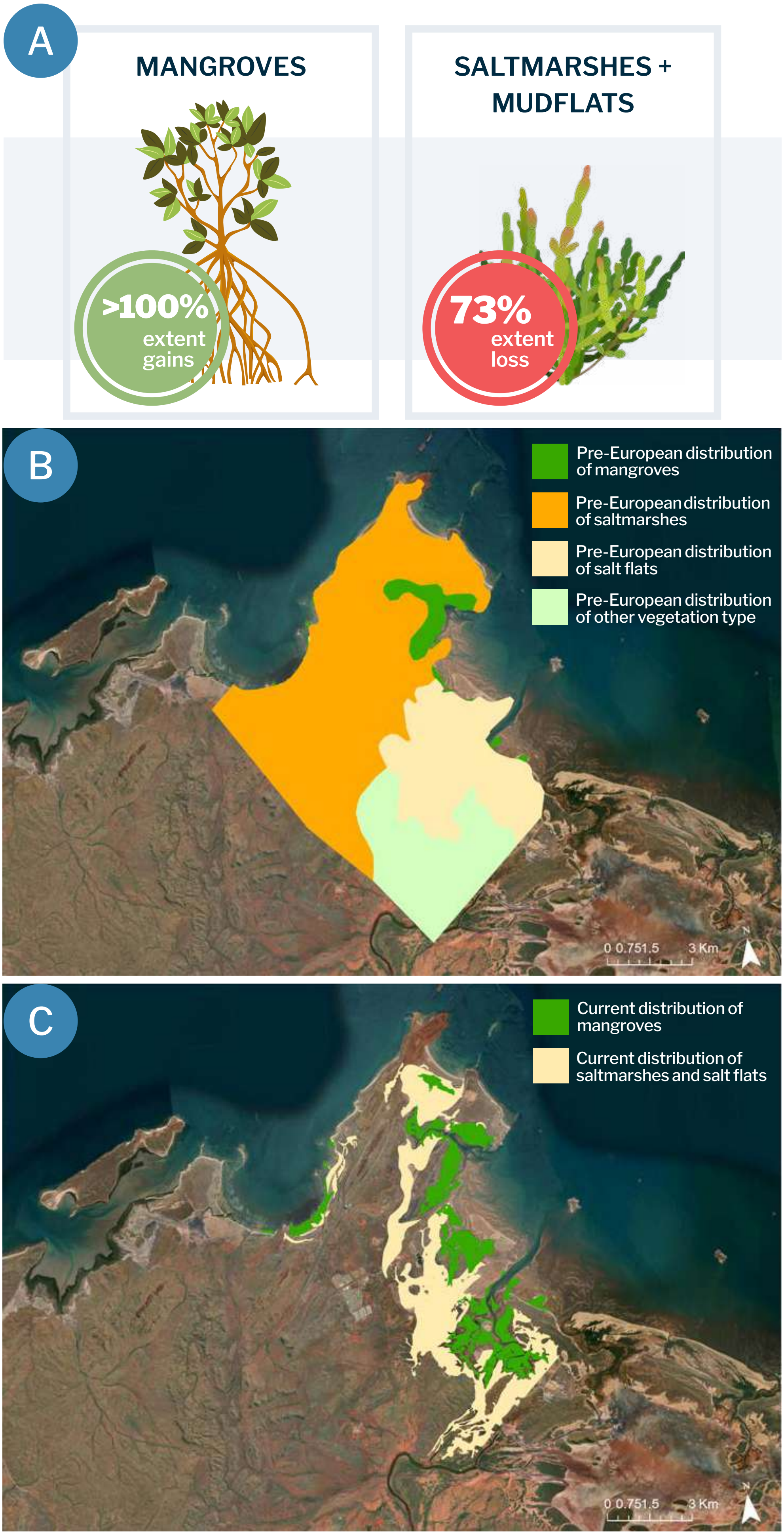


Figure 7: (A) Percentage change in saltmarsh and mangrove cover within the Cane River estuary as well as the past (B) and current (C) distribution of blue carbon ecosystems within the region based on existing spatial data.

We also estimated the value of potential coastal hazard mitigation by coastal wetlands to be AU$167,095 per year. Table 6 shows the detailed ecosystem supply accounting for mangroves and saltmarshes within the Cossack region.

Using the global average values to estimate the combined value of ecosystem services provided by mangroves and saltmarshes, we found that these ecosystems could provide co-benefits to the value of AU$1.21 billion per year within the study region. Table 7 shows the detailed ecosystem service valuation for each co-benefit included in this analysis.

Table 7: Ecosystem service valuation for combined mangroves and saltmarshes within the Cossack region based on global estimates (Constanza et al., 2014). We corrected the values into 2023-dollar values using an inflation calculator and converted US$ into AU$ using a conversion rate of US$1=AU$1.49.

	MANGROVES + SALTMARSH (AU$ yr^{-1})
Water supply	$7,591,632
Waste treatment	$1,011,213,508
Food production	$6,929,976
Recreation	$13,677,126
Climate regulation	$417,888
Disturbance regulation	$33,375,902
Erosion control	$24,504,488
Nutrient cycling	$280,972
Habitat refugia	$106,892,268
Raw materials	$2,231,638
Genetic resources	$1,941,438

Freshwater wetlands

Beeliar Regional Park

Before European settlement, Beeliar Regional Park held 2,921 ha of freshwater wetlands. From this total, 140 ha were sedgelands, 529 ha were freshwater lakes, 25 ha were clay plans, 2,220 ha were woodlands, and 6 ha were scrub-heath (Figure 8). The best available information indicates that the region currently holds approximately 1,384 ha of freshwater wetlands, which include 99 ha of damplands (i.e., basin-shaped, seasonally waterlogged wetlands), 699 ha of freshwater lakes, and 586 ha of sumplands (i.e., basin-shaped wetlands containing surface water seasonally) (Figure 8, Table 8). For the purpose of this study, we will consider all relevant classifications included in pre-European and current vegetation mapping provided by the WA Government as 'freshwater wetlands'. We estimate that freshwater wetlands within Beeliar Regional Park have decreased their distribution by 53% (Figure 8).

Ecosystem services

Freshwater wetlands within Beeliar Regional Park hold approximately 558,721 tonnes of CO_2e distributed within their soils (Table 8). These ecosystems also hold 1,342 tonnes of nitrogen. Overall, carbon sequestration was estimated at 11,682 tonnes CO_2e yr^{-1} and water quality improvement through nitrogen removal was estimated at 37 tonnes N yr^{-1}. We valued carbon sequestration services at AU$362,153 per year and nitrogen sequestration services at AU$1.9 million per year. Table 8 shows the detailed ecosystem supply accounting for freshwater wetlands within Beeliar Regional Park.

Using the global average values to estimate the combined value of ecosystem services provided by freshwater lakes, we found that these ecosystems could provide co-benefits to the value of AU$37.1 million per year within the study region. Table 9 shows the detailed ecosystem service valuation for each co-benefit included in this analysis.

Table 8: Ecosystem services supply account in physical and monetary terms for existing freshwater wetlands within Beeliar Regional Park.

Ecosystem type			Wetlands
Extent		hectares	**1,384**
Carbon stocks		tonnes CO_2e	**558,721**
Nitrogen stocks		tonnes N	**1,342**
Physical ecosystem services account			
Regulating services	Carbon sequestration	tonnes CO_2e yr^{-1}	**11,682**
	Water purification	tonnes N yr^{-1}	**37**
Monetary ecosystem services account			
Regulating services	Carbon sequestration	AU$ yr^{-1}	**362,153**
	Water purification		**1,900,000**

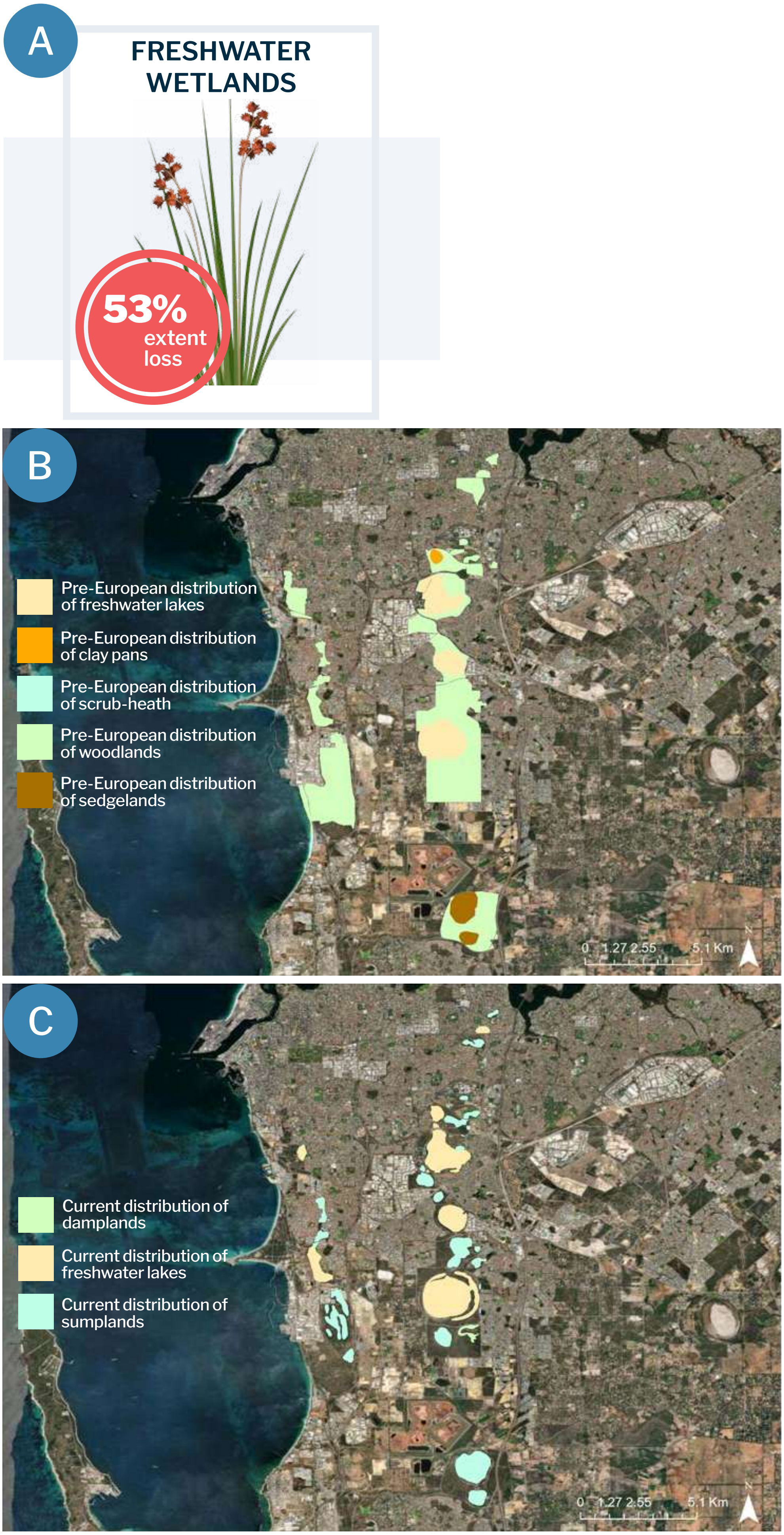


Figure 8: (A) Percentage change in freshwater wetlands cover within Beeliar Regional Park as well as past (B) and current (C) distribution of teal carbon ecosystems within the region based on existing spatial data

Table 9: Ecosystem service valuation for freshwater wetlands (lakes) within Beeliar Regional Park based on global estimates (Constanza et al., 2014). We corrected the values into 2023-dollar values using an inflation calculator and converted US$ into AU$ using a conversion rate of US$1=AU$1.49.

	FRESHWATER WETLANDS (AU$ yr^{-1})
Water regulation	$5,363,000
Water supply	$22,286,552
Waste treatment	$2,723,712
Food production	$314,168
Recreation	$6,423,144

Forrestdale Lake Nature Reserve (Forrestdale Lake)

Before European settlement, the Forrestdale Lake Nature Reserve held approximately 246 ha of freshwater wetlands. This area was constituted by 53 ha of woodlands and Forrestdale Lake (193 ha) (Figure 9). The best available information indicates that the region currently holds approximately 222 ha of lacustrine freshwater wetlands (Figure 9, Table 10). Forrestdale Lake is a seasonal lake that usually starts to fill in June/July and reaches its maximum depth by late September. The lake dries completely by early summer. For the purpose of this study, we will consider all relevant wetland classifications included in the pre-European and current vegetation mapping provided by the WA Government as 'freshwater wetlands'. In this case, we estimate that freshwater wetlands within the Forrestdale Lake Nature Reserve have decreased their distribution by 10% (Figure 9).

Ecosystem services

Freshwater wetlands within the Forrestdale Lake Nature Reserve hold approximately 89,621 tonnes of CO_2e distributed within their soils (Table 10). These ecosystems also hold 215 tonnes of nitrogen. Overall, carbon sequestration was estimated at 1,874 tonnes CO_2e yr^{-1} and water

quality improvement through nitrogen removal was estimated at 6 tonnes N yr $^{-1}$. We valued carbon sequestration services at AUD58,091 per year and nitrogen sequestration services at AU$311,688 per year. Table 10 shows the detailed ecosystem supply accounting for freshwater wetlands within Forrestdale Lake Nature Reserve.

Using global average values to estimate the combined value of ecosystem services provided by freshwater lakes, we found that these ecosystems could provide co-benefits to the value of AU$5.9 million per year within the study region. Table 11 shows the detailed ecosystem service valuation for each co-benefit included in this analysis.

Table 10: Ecosystem services supply account in physical and monetary terms for existing freshwater wetlands within Beeliar Regional Park.

Ecosystem type			**Wetlands**
Extent		hectares	**222**
Carbon stocks		tonnes CO_2e	**89,621**
Nitrogen stocks		tonnes N	**215**
Physical ecosystem services account			
Regulating services	Carbon sequestration	tonnes CO_2e yr $^{-1}$	**1,874**
	Water purification	tonnes N yr $^{-1}$	**6**
Monetary ecosystem services account			
Regulating services	Carbon sequestration	AU$ yr $^{-1}$	**58,091**
	Water purification		**311,688**

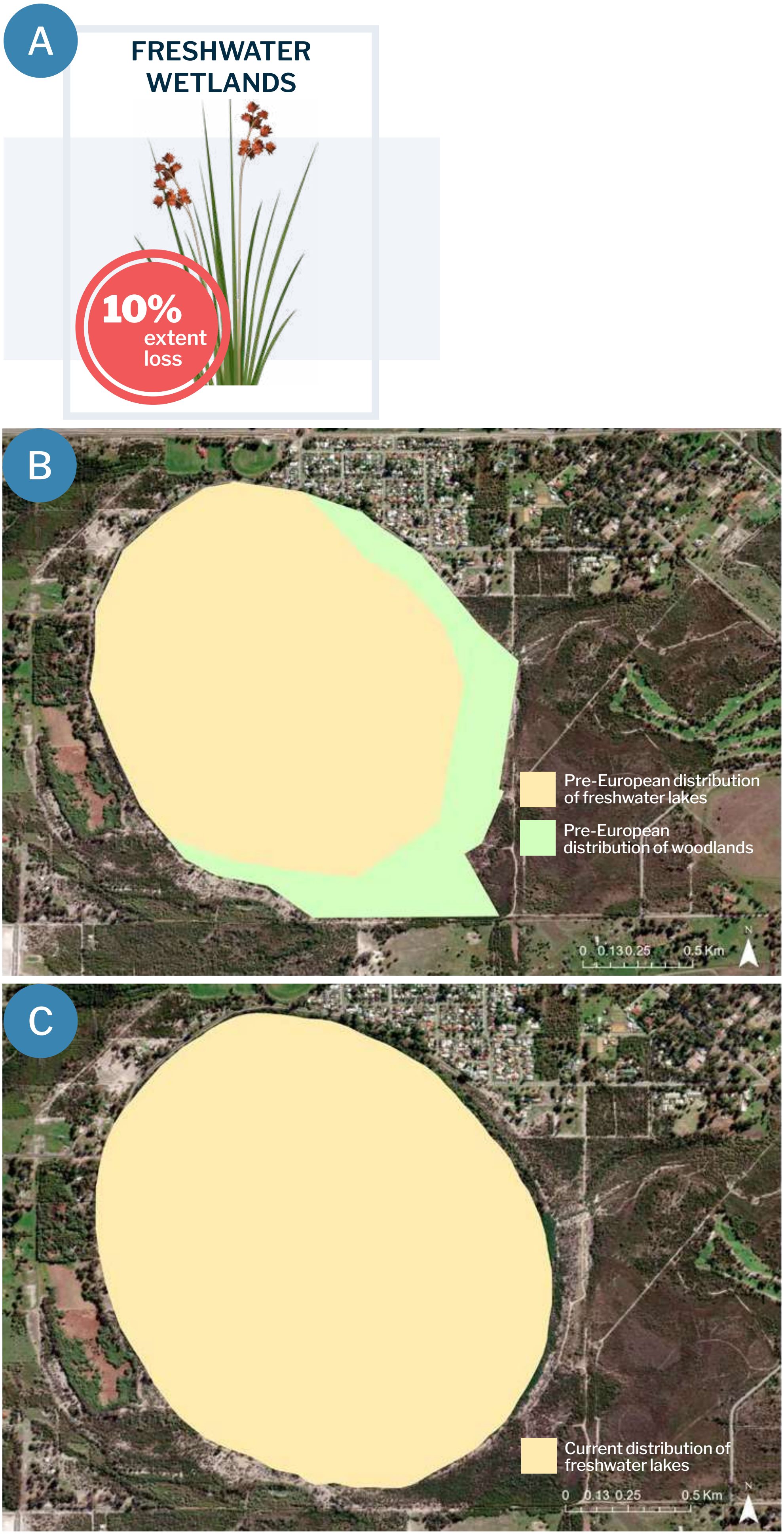
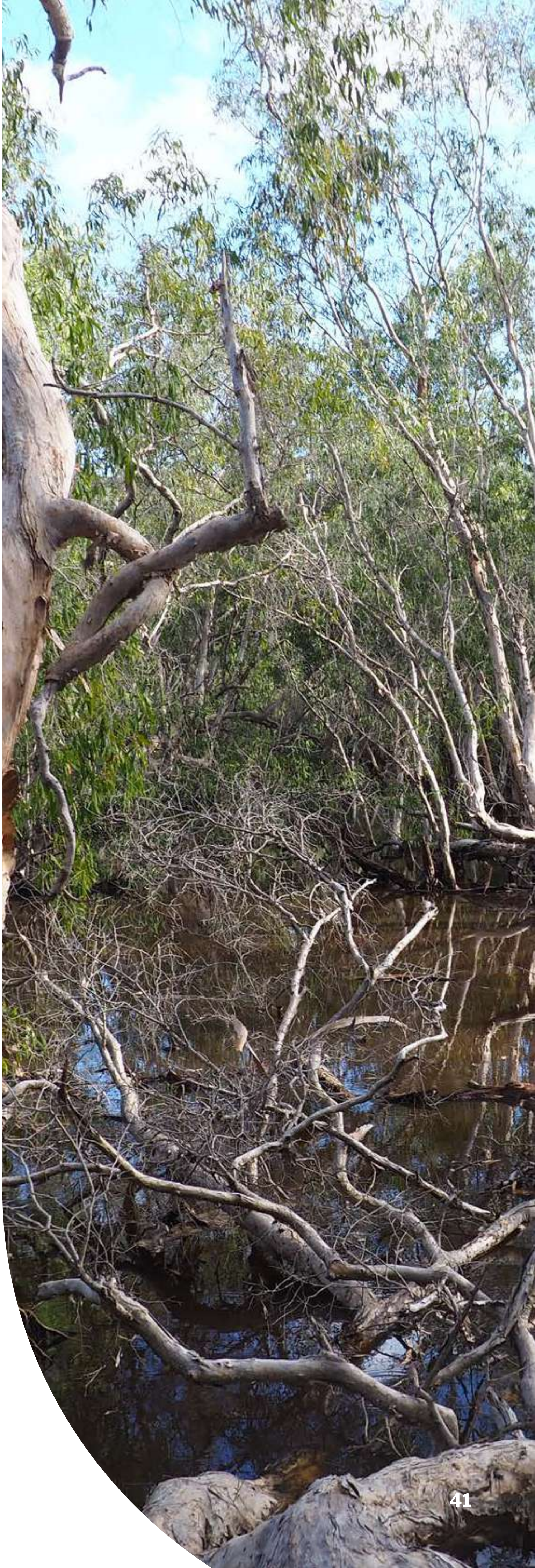


Figure 9: (A) Percentage change in freshwater wetlands cover within Beeliar Regional Park as well as past (B) and current (C) distribution of teal carbon ecosystems within the region based on existing spatial data

Table 11: Ecosystem service valuation for freshwater wetlands (lakes) within Forrestdale Lake Nature Reserve based on global estimates (Constanza et al., 2014). We corrected the values into 2023-dollar values using an inflation calculator and converted US$ into AU$ using a conversion rate of US$1=AU$1.49.

	FRESHWATER WETLANDS (AU$ yr^{-1})
Water regulation	$860,250
Water supply	$3,574,866
Waste treatment	$436,896
Food production	$50,394
Recreation	$1,030,302



CASE STUDY:

Valuing Shark Bay's Seagrass Meadows

Shark Bay, located in Western Australia, is a natural World Heritage site renowned for its exceptional biodiversity and unique seagrass meadows. The bay is home to one of the largest and most diverse seagrass ecosystems globally, covering approximately 430,000 ha (Arias-Ortiz et al., 2018; Serrano et al., 2023).

Shark Bay's seagrass meadows are dominated by seagrass species *Amphibolis* spp. and *Posidonia* spp., which play a vital role in the bay's health by providing critical habitats and nurseries for a variety of marine life (e.g., dugongs, turtles, fishes). Further, they contribute to carbon storage and water filtration while also attracting tourists interested in experiencing its unique marine environment.

Methods

To assess potential ecosystem services provided by seagrasses in WA, we extracted data from the literature on carbon/nitrogen stocks and sequestration rates, fisheries, and coastal protection. Coastal hazard mitigation, carbon and nitrogen data were analysed with the same methods described in the 'Methods' section of this report. For fisheries data, the following approach was taken:

1. A total of 37 publications were found in the literature review that contained relevant data for this study. We conducted a manual screening with the following exclusion criteria:

a. Studies with abundance or biomass data per trap or conducted with 'baited remote underwater video stations' (BRUVS).

b. Isotope studies, due to lack of information for the primary producers in the system (e.g., seagrass, plankton, macroalgae). Furthermore, this type of studies would help us understand the proportional contribution of the ecosystem rather than estimate the biomass enhancement from seagrass ecosystems.

c. Studies that did not specify the presence of seagrass.

d. Studies focusing on fish diet and stomach content.

e. Studies focusing on juvenile fish.

After the manual screening, we identified seven publications that were used to extract abundance data for this study.

2. From these studies, the following data was extracted: study area, fish species (records at genus level were excluded from the analysis), sampling method, mesh size (mm), area per haul or survey (m^2), sampling events, total number of replicates, total area per study site (m^2), and total catch number (individuals' number).

3. We used FishBase.org to extract data on total length (TL) and length-weight relationships for all fish species included in this study to predict fish biomass (W). Here, we assumed that fish weight (W) can be predicted from length (L) through length-weight relationships (LWR) using the formula W= a * L * b, where b indicates isometric growth in body proportions if b ~3, and a is a parameter describing body shape and condition if b ~3 (Froese, 2006). More specifically, b is the slope of a regression line over log-transformed weight-at-length data, while parameter a is the intercept of a regression line over log-transformed weight-at-length data.

Since most of the studies included in this analysis did not report length or size, we assumed that fish size was half of its total length (Eger et al., 2023).

For species with no information on their total length, we used standard length information as a conservative estimate. Finally, we used the LWR equations for each species and the 0.5 maximum TL to convert length into biomass.

4. Fish biomass was transformed to fish production (kg ha^{-1} yr^{-1}) using a validated productivity-biomass relationship (Jenkins, 2015).

5. We conducted a search to find fisheries values for the different species included in this analysis. In this case, we used the 'Status reports of the fisheries and aquatic resources of Western Australia 2020/21' report (Newman et al., 2021) to extract the average price received by commercial fishers for each species in the 2020/21 financial year. For the species not included in the report, we assumed an average price of AU$5.24.

6. The annual fisheries value of seagrasses in WA was estimated by multiplying species-specific productivity values by species-specific market values.

Results

According to local estimates, every hectare of seagrass meadow stores 422 tonnes CO_2e on average (Bedulli et al., 2020; Serrano et al., 2020a; Serrano et al. 2020b; Salinas et al., 2020; Kaal et al., 2019; Serrano et al., 2019; Arias-Ortiz et al., 2018; Rozaimi et al., 2016; Serrano et al., 2016a; Serrano et al., 2016b; Serrano et al., 2016c; Serrano et al., 2014; Fourqurean et al., 2012). Furthermore, seagrasses in Shark Bay sequester an average of 378,744 CO_2e yr^{1} (Gorham et al., 2021; Bedulli et al., 2020; Salinas et al., 2020; Serrano et al., 2020a; Serrano et al., 2020b; Kaal et al., 2019; Serrano et al., 2019; Arias-Ortiz et al., 2018; Macreadie et al., 2017; Rozaimi et al., 2016; Serrano et al., 2016a; Serrano et al., 2016b; Serrano et al., 2016c; Marbá et al., 2015; Serrano et al., 2014). Assuming a carbon price of AU$31 per tonne (Clean Energy Regulator, 2022), we estimate that the carbon sequestration value provided by Shark Bay's seagrasses is approximately AU$11.7 million yr^{-1}.

If we consider nitrogen, seagrasses store approximately 9.7 tonnes N ha^{-1} (Fourqurean et al., 2012; Serrano et al., 2020a). In addition, this ecosystem sequesters approximately 14,190 N yr^{1} on average. Assuming a nitrogen price at AU$52 per kg (Liekens et al., 2013; Costa et al., 2022), we estimate that the nitrogen sequestration value provided by seagrasses in Shark Bay is approximately AU$737.9 million yr^{-1}.

Based on the best available data, we estimate Shark Bay's seagrass meadows provide a combined average value of

AU$758.7 million

in ecosystems services.

Shark Bay is also a hotspot for fish productivity. We estimated that seagrasses in the region support more than 1.8 million kg fish yr^{-1}, valued at approximately AU$8.9 million yr^{-1}. Furthermore, we found that this ecosystem also provides an annual coastal hazard mitigation service worth approximately AU$186,267 yr^{-1}.

Our estimates and valuation highlight the ecological and economic importance of Shark Bay's seagrass meadows and indicate a need to protect this ecosystem. Our analysis also highlights the need to improve our understanding of the distribution of seagrass along WA's coastline for largescale assessments of ecosystem service values in the future.

Discussion

This study provides a first-pass evaluation of the economic value of ecosystem services provided by coastal and freshwater wetlands in Western Australia, focusing on four specific sites: Cane River estuary, Cossack region, Beeliar Regional Park, and Forrestdale Lake Nature Reserve. We conducted a site-specific assessment for each wetland site, which included the distribution of blue and teal carbon ecosystems distribution and estimates of their potential ecosystem services. Furthermore, we estimated the potential monetary value of these ecosystem services following some general principles of environmental economic accounting frameworks[2]. Our results are on a local scale, but the approach can be applied at larger scales and inform future management actions for coastal and freshwater wetlands in WA. Our analysis highlighted the broad benefits of wetlands for nature and communities whilst highlighting knowledge gaps that will shape future research and wetland policy in WA.

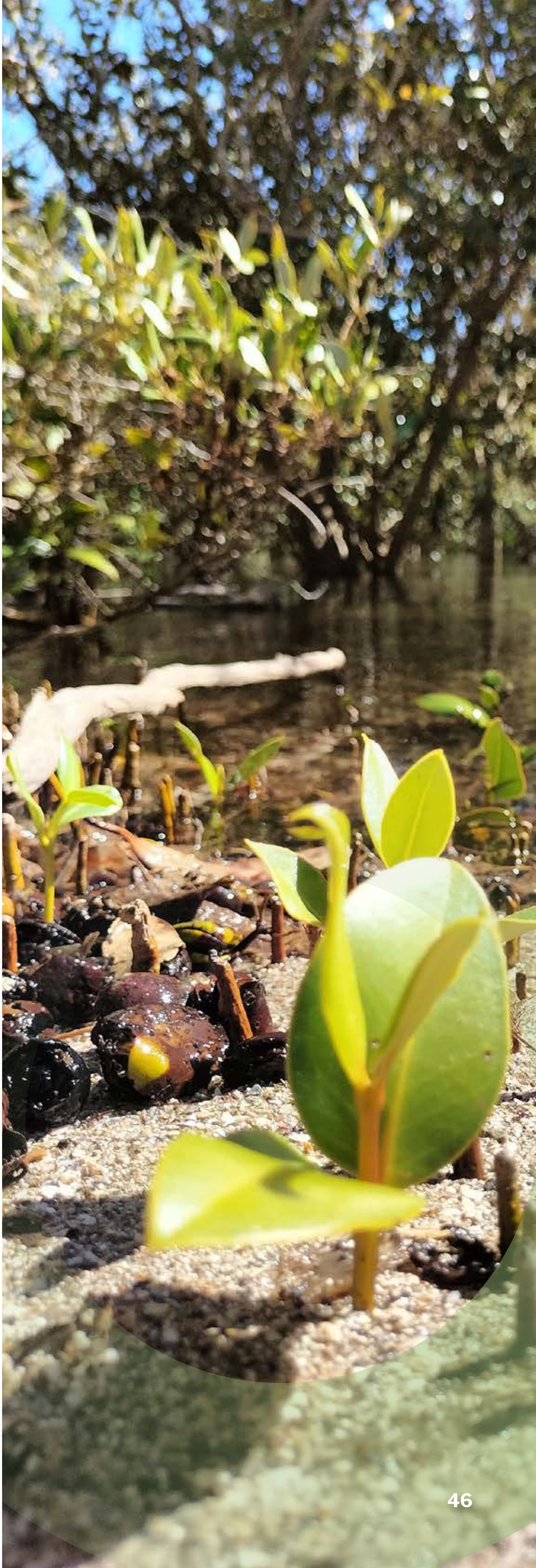
The UN System of Environmental Accounting (UN SEEA) framework provides an internationally verified standard that links ecosystem values to economic and other human activities (United Nations, 2021). This study has estimated the physical and monetary values of four wetlands in Western Australia. However, UN SEEA could be applied to develop spatially explicit, detailed, and replicable environmental economic account (EEA) tables that provide a strong baseline for future assessments and enable the comparison of ecosystem assets, flows and services with other goods and services. This would depend on access to high resolution spatial data that could be used to calculate the extent of different wetlands as well as information about the condition of ecosystem assets (United Nations, 2021). More information about the way each ecosystem is used would also be needed to improve our results.

[2] The monetary value is a representation only since no credits can be collected for existing ecosystems.

Although blue and teal carbon ecosystems provide a wide range of ecosystem services (e.g., biodiversity enhancement, cultural values, recreation, eco-tourism), the lack of available data prevented us from including the full set of ecosystem services in our analysis. For example, it has been estimated that the number of urban wetlands in Perth, within 1.5 km of a property, can significantly increase property prices (Tapsuwan et al., 2009). In this case, it has been suggested that there is a positive relationship between housing density and wetland visitation rates (Syme et al., 2001). More importantly, the value of wetlands to Traditional Owners is not accounted for in this study or in the conventional application of UN SEEA. However, there are potentially substantial cultural values associated with each of the four study systems for the Ngarluma People (Cossack region), Nyoongar People (Beeliar Regional Park), Thalanyji People People (Cane River region), and Whadjuk People (Forrestdale Lake Nature Reserve) (Registered Native Title Bodies Corporate, 2020; The Project Group, 2018; Department of Biodiversity, Conservation and Attractions, 2021; Conservation Committee of Western Australia 2005). These may include culturally significant sites, food resources, and spiritual/cultural emblems (e.g., totems) (Jackson, 2005). It is challenging to compare cultural values with other services because they are circular and holistic in nature (Carnell et al., 2023). However, explicit consideration of Traditional Owner values in wetland valuation is imperative for effective collaborative management of Australian wetlands (Jackson, 2005).

Limitations and knowledge gaps

One major knowledge gap that became exceedingly obvious was the limited availability of spatial data at regional scale for blue and teal carbon ecosystems in Western Australia. In addition to the datasets used in this study, to our knowledge, high resolution wetland mapping is only available for threatened ecological communities such as subtropical and temperate coastal saltmarshes (Department of Biodiversity, Conservation and Attractions, 2022). However, such information is not publicly available. Furthermore, there are important wetlands in other regions of the state that have not been mapped at



a regional or local scale, which makes it challenging to reliably estimate the value they provide in environmental economic accounting processes. Examples include coastal wetlands at the mouth of the Fitzroy and Fraser River systems (Russell Shaw, 2023, personal correspondence). There is a critical need to undertake regional-scale mapping of coastal and freshwater wetlands in priority areas of WA, such as the four sites included in this study.

Despite using the best available spatial information and datasets across the study sites, this study highlighted the lack of a systematic and continuous approach to monitor these ecosystems and account for multidecadal changes in their extent. In recent years, the advancement of new technologies has increased our ability to map and monitor coastal and inland ecosystems at different spatial scales allowing us to better understand changes over time and conditions (Lymburner et al. 2020, Navarro et al. 2020, 2021, Lee et al. 2021, Murray et al. 2022, Dalby et al. 2022; Hickey & Radford, 2022). These studies could be used as examples of an approach that can be applied to different spatial scales and ecosystems within WA. Understanding the distribution of wetlands within these regions will help refine and possibly boost current value estimates for climate regulation, hazard mitigation and other wetland services with potential to both improve and incentivize effective local management.

Our literature review identified large gaps in the studies focusing on the ecosystem services provided by coastal and freshwater wetlands in WA. Overall, information on freshwater studies was severely lacking in the State. We found only eight studies with relevant data, all of which took place in the Greater Perth area. Furthermore, most of the studies on coastal wetlands were focused on seagrasses, with limited information available for tidal marshes and mangroves. These knowledge gaps had a direct influence on our estimates of ecosystem services. This led to the need to apply regional and global data to estimate the co-benefits provided by coastal and freshwater wetlands within our four study sites. To minimise the uncertainties and to fully understand the climate change mitigation capacity of WA teal and blue carbon ecosystems, field studies measuring greenhouse gas fluxes (especially carbon and nitrogen sequestration) are needed across a range of climates and wetland typologies. Future studies should also assess flood mitigation, biodiversity, and non-use values of these ecosystems to ensure their ongoing protection and enable the consideration of relevant services for development and offset proposals.

One of the major assumptions of this study is that the wetlands assessed were in good, functioning

condition at the time of our analysis. This is likely true based on positive ecosystem service values reported in the literature. However, all four study systems are subject to diverse natural and anthropogenic stressors, which have the potential to change wetland condition over time (The Project Group, 2018; Kanchi, 2019; Department of Environment and Conservation, 2012; Conservation Committee of Western Australia 2005). If wetland condition decreases, then the value of affected ecosystems will likely decrease due to loss of ecosystem functions (for example, Imdad et al., 2022). To ensure integrity in wetland value estimates, it is therefore necessary to monitor wetland condition over time.

While our study has focused on four specific sites, the analysis applied here is also relevant for future restoration projects targeting coastal and freshwater wetlands. We currently have one blue carbon method enabling Australian carbon credit units (ACCUs) to be earned through the removal or modification of tidal restrictions, which allows for the restoration of coastal wetlands. However, new methods are also expected to be released in the future for both coastal and freshwater wetlands, which are likely to increase the chances of restoring these ecosystems while also supporting landholders to transition to different land uses. In Australia, there is a growing interest in environmental market-based mechanisms, with the Federal Government currently working on the Nature Repair Market Bill, which aims to create a national framework for a voluntary national market that delivers biodiversity outcomes. More specifically in WA, the State has released the Carbon Farming and Land Restoration Program, which includes AU$15 million to support carbon farming in the State through projects that will deliver environmental, economic and social co-benefits following the WA's Co-benefits Standard 2022-2023.

Further studies and local datasets from WA are needed to improve our capacity to predict and understand the value of wetlands in the state. However, this first-pass assessment highlights the broad benefits of wetlands for nature and communities whilst highlighting knowledge gaps that will shape future research and wetland policy in WA.

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Appendix 1

Table A1: Overview of the 43 studies identified through the literature review that contain relevant datasets on the ecosystem services from coastal and freshwater wetlands in Western Australia. For each publication we specify the ecosystem category (Blue vs Teal), the ecosystem type, the location, and the type of ecosystem service reported (C: carbon storage or sequestration; N: nutrient cycling; F: fisheries; S: social value; R: recreation). A single study may report datasets for multiple ecosystems or ecosystem services.

1. **Teal carbon** sites indicated by **teal coloured** cell, all other sites **blue carbon**

2. Type C= Carbon sink, N= Nutrient cycle, F= Fisheries, S= Social value, R= Recreation

Authors	Year	Title	Ecosystem type[1]	Location within WA	Type[2]
Adyel, T. M., et al	2018	A multi-functional and multi-compartment constructed wetland to support urban waterway restoration	Urban wetland	Cannington -Wharf Street Constructed Wetland (Perth)	N
Alongi et al	2000	Below-ground decomposition of organic matter in forests of the mangroves Rhizophora stylosa and Avicennia marina along the arid coast of Western Australia	Mangrove	Port Headland, Dampier, Mangrove Bay, Bay of Rest	C, N
Alongi et al	2003	Nutrient partitioning and storage in arid-zone forests of the mangroves Rhizophora stylosa and Avicennia marina	Mangrove	Dampier, Port Hedland, Mangrove Bay, Bay of Rest	C
Arias-Ortiz et al	2018	A marine heatwave drives massive losses from the world's largest seagrass carbon stocks	Seagrass	Shark Bay	C
Bedulli et al	2020	Contribution of Seagrass Blue Carbon Toward Carbon Neutral Policies in a Touristic and Environmentally-Friendly Island	Seagrass	Rottnest Island	C
Black, R., et al	1990	Fishes and benthos of near-shore seagrass and sandflat habitats at Monkey Mia, Shark Bay, Western Australia	Seagrass	Shark Bay	F
Blake	2005	Predicting the spatial distribution of organic rich sediments on the Swan Coastal Plain, Western Australia	Flooded woodland	Malaleuca Park and Whiteman Park (Perth)	C
Congdon & McComb	1980	Productivity and nutrient content of Juncus kraussii in an estuarine marsh in south-western Australia	Tidal marsh	Blackwood River Estuary	C
Congdon & McComb	1981	The Vegetation of the Blackwood River Estuary, South-West Australia	Tidal marsh	Blackwood River Estuary	C

Authors	Year	Title	Ecosystem type[1]	Location within WA	Type[2]
Fourqurean et al	2012	Carbon, nitrogen and phosphorus storage in subtropical seagrass meadows: examples from Florida Bay and Shark Bay	Seagrass	Shark Bay	C, N
French, B., et al	2021	The mesh size effect: counting long thin fish in seagrass	Seagrass	Shark Bay and Geographe Bay	F
Gorham, C., et al	2021	Heterogeneous tidal marsh soil organic carbon accumulation among and within temperate estuaries in Australia	Tidal marsh	10 Sites Perth to Esperence	C
Gorham, C., et al	2021	Soil Carbon Stocks Vary Across Geomorphic Settings in Australian Temperate Tidal Marsh Ecosystems	Tidal marsh	10 Sites Perth to Esperence	C
Hickey, S. M., et al	2017	Spatial complexities in aboveground carbon stocks of a semi-arid mangrove community: A remote sensing height-biomass-carbon approach	Mangrove	Mangrove Bay	C
Humphries, P., Potter, I.C., et al	1992	The fish community in the shallows of a temperate Australian estuary – Relationships with the aquatic macrophyte rupia-megacarpa and environmental	Seagrass	Wilson Inlet	F
Hyndes, G.A., Kendrick, A.J., et al	2003	Differences in the species- and size-composition of fish assemblages in three distinct seagrass habitats with differing plant and meadow structure	Seagrass	Owen Anchorage region	F
Hyndes, G.A., et al	1996	Habitat partitioning by whiting species (Sillaginidae) in coastal waters	Seagrass	Cockburn Sound	F
Jackson, G., Ryan, K.L., et al	2016	Assessing the effectiveness of harvest tags in the management of a small-scale, iconic marine recreational fishery in Western Australia	Seagrass	Freycinet Estuary, Shark Bay	R
Kaal et al.	2019	Millennial-scale changes in the molecular composition of Posidonia australis seagrass deposits: Implications for Blue Carbon sequestration	Seagrass	Waychinicup Inlet	C
Kendrick, A.J., and Hyndes, G.A.	2003	Patterns in the abundance and size-distribution of syngnathid fishes among habitats in a seagrass-dominated marine environment	Seagrass	Fremantle	F
Lovelock, C.E., et al	2021	Vulnerability of an arid zone coastal wetland landscape to sea level rise and intense storms	Mangrove	Exmouth Gulf	C
Lund, M.A, et al	2001	Removing filterable reactive phosphorus from highly coloured stormwater using constructed wetlands	Urban wetland	Henley Brook (Perth)	N
MacArthur, L.D., et al	2001	Differential use of seagrass assemblages by a suite of odacid species	Seagrass	Fremantle	F
Macreadie et al.	2017	Carbon sequestration by Australian tidal marshes	Tidal marsh	Wonnerup inlet, Lake Mcleod, Vasse Estuary	C
Marba et al.	2015	Impact of seagrass loss and subsequent revegetation on carbon sequestration and stocks	Seagrass	Oyster Harbour	C

Authors	Year	Title	Ecosystem type[1]	Location within WA	Type[2]
Paling and Mccomb	2000	Autumn biomass, below-ground productivity, rhizome growth at bed edge and nitrogen content in seagrasses from Western Australia	Seagrass	Shoalwater Bay, Point Peron Cockburn South	C
Qiu et al.	2000	Properties of sediment phosphorus in seven wetlands of the Swan Coastal Plain, South-Western Australia	Flooded woodland	Lake Jandabup, Lake Monger, Lake Boorangoon, Murdoch Swamp, North Lake, Lake Banganup, Lake Forrestdale (Perth)	C
Qiu et al.	2003	Nutrient response to soil and litter metabolic activity in a transect across a seasonal wetland	Rush	Thomsons Lake (Perth)	C
Qiu et al.	2012	Leaf Litter Decomposition and Nutrient Dynamics in Woodland and Wetland Conditions along a Forest to Wetland Hillslope	Rush	Thomsons Lake (Perth)	C
Rozaimi et al	2016	Long-term carbon storage and its recent loss in an estuarine Posidonia australis meadow (Albany, Western Australia)	Seagrass	Oyster Harbour	C
Ryder and Horwitz	1995	Seasonal water regimes and leaf litter processing in a wetland on the Swan Coastal Plain, Western Australia	Rush	Lake Jandalup (Perth)	C
Salinas et al.	2020	Seagrass losses since mid-20th century fuelled CO2 emissions from soil carbon stocks	Seagrass	Cockburn Sound	C
Serrano et al.	2014	Influence of water depth on the carbon sequestration capacity of seagrasses	Seagrass	Cockburn Sound	C
Serrano et al.	2016	Key biogeochemical factors affecting soil carbon storage in Posidonia meadows	Seagrass	Cockburn Sound	C
Serrano et al.	2016	Impact of mooring activities on carbon stocks in seagrass meadows	Seagrass	Rottnest Island (Thompson Bay and Stark Bay)	C
Serrano et al.	2016	Location and Associated Carbon Storage of Erosional Escarpments of Seagrass Posidonia Mats	Seagrass	Big Lagoon (Shark Bay), Waychinicup Inlet (Albany), Oyster Harbour (Albany)	C
Serrano et al.	2019	Australian vegetated coastal ecosystems as global hotspots for climate change mitigation	Tidal marsh, Seagrass	Wonnerup inlet, Lake Mcleod, Oyster Harbour, Garden Island, Shark Bay, Rottnest isand	C
Serrano et al.	2020	Organic chemistry insights for the exceptional soil carbon storage of the seagrass Posidonia australis	Seagrass	Oyster Harbour	C
Serrano, O., Lavery, P.S., et al	2020	Impact of seagrass establishment, industrialization and coastal infrastructure on seagrass biogeochemical sinks	Seagrass	Cockburn Sound	C, N
Tapsuwan, S., Ingram, G., Burton, M., et al	2009	Capitalized amenity value of urban wetlands: a hedonic property price approach to urban wetlands in Perth, Western Australia	Urban wetland	Herdsman lake and surroundings (Perth)	S
Travers, M. J. and Potter, I.C.	2005	Factors influencing the characteristics of fish assemblages in a large subtropical marine embayment.	Seagrass	Shark Bay	F

Authors	Year	Title	Ecosystem type[1]	Location within WA	Type[2]
Vanderklift, M.A., Jacoby, C.A.	2003	Patterns in fish assemblages 25 years after major seagrass loss	Seagrass	Cockburn Sound	F
Wernberg, T; Vanderklift, M.A., How, J.; Lavery, P.S.	2006	Export of detached macroalgae from reefs to adjacent seagrass beds	Seagrass	Marmion Lagoon and Jurien Bay	F

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