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Kakadu Sea Country Strategy 2025–2035 Literature Review

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Cover images

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Summary

Kakadu National Park, a UNESCO World Heritage site, is recognised for its exceptional natural and cultural values. It encompasses diverse biomes such as tropical savanna forests, extensive floodplains, coastal estuaries, and marine ecosystems. The Park holds significant ecological importance, supporting numerous threatened species and maintaining critical habitats for a wide range of biodiversity. However, Kakadu's marine and coastal environments remain underrepresented within the Park's boundaries, limiting conservation efforts and necessitating integrated management strategies that extend beyond terrestrial ecosystems.

Despite the ecological and cultural significance of these marine environments, their biodiversity and ecosystem functions are poorly documented, with research gaps in species distribution, habitat connectivity, and ecosystem resilience. This review synthesises literature on Kakadu's marine values, identifying key threats, conservation needs, and research priorities. The primary environmental threats to the region include saltwater intrusion, climate change-induced sea level rise, invasive species, and fire regimes. Additionally, anthropogenic pressures, such as mining activities, recreational fishing, and unsustainable land-use practices, further exacerbate the vulnerability of the Park's ecosystems.

To address these challenges, collaborative and adaptive management approaches are essential. The review highlights the importance of Indigenous-led research and co-management strategies, incorporating Bininj Traditional Owners' knowledge systems to guide conservation planning and decision-making. Strengthening marine ecosystem monitoring, conducting habitat mapping, and enhancing governance frameworks are critical for ensuring the long-term protection of Kakadu's natural and cultural heritage.

This review provides strategic recommendations for future research and conservation efforts, emphasising the need for participatory approaches integrating scientific research, Indigenous knowledge, and sustainable resource management. These insights will contribute to effective policy development, ensuring the resilience and sustainability of Kakadu National Park's marine and coastal ecosystems in the face of climate change and environmental pressure.

1 Introduction

The Indigenous-owned lands of Kakadu National Park are a mixed World Heritage site renowned internationally for their outstanding natural and cultural values (Figure 1) (Claudino-Sales & Claudino-Sales, 2019). The region was formally declared a national park in 1979, covering 1980 km^2 of the Northern Territory, Australia. Kakadu is the largest national park in Australia and contains a range of biomes, ranging from coastal estuaries and extensive seasonally flooded wetlands to vast areas of Eucalyptus-dominated tropical savanna forests and woodlands (Press et al., 1995; Setterfield et al., 2013).

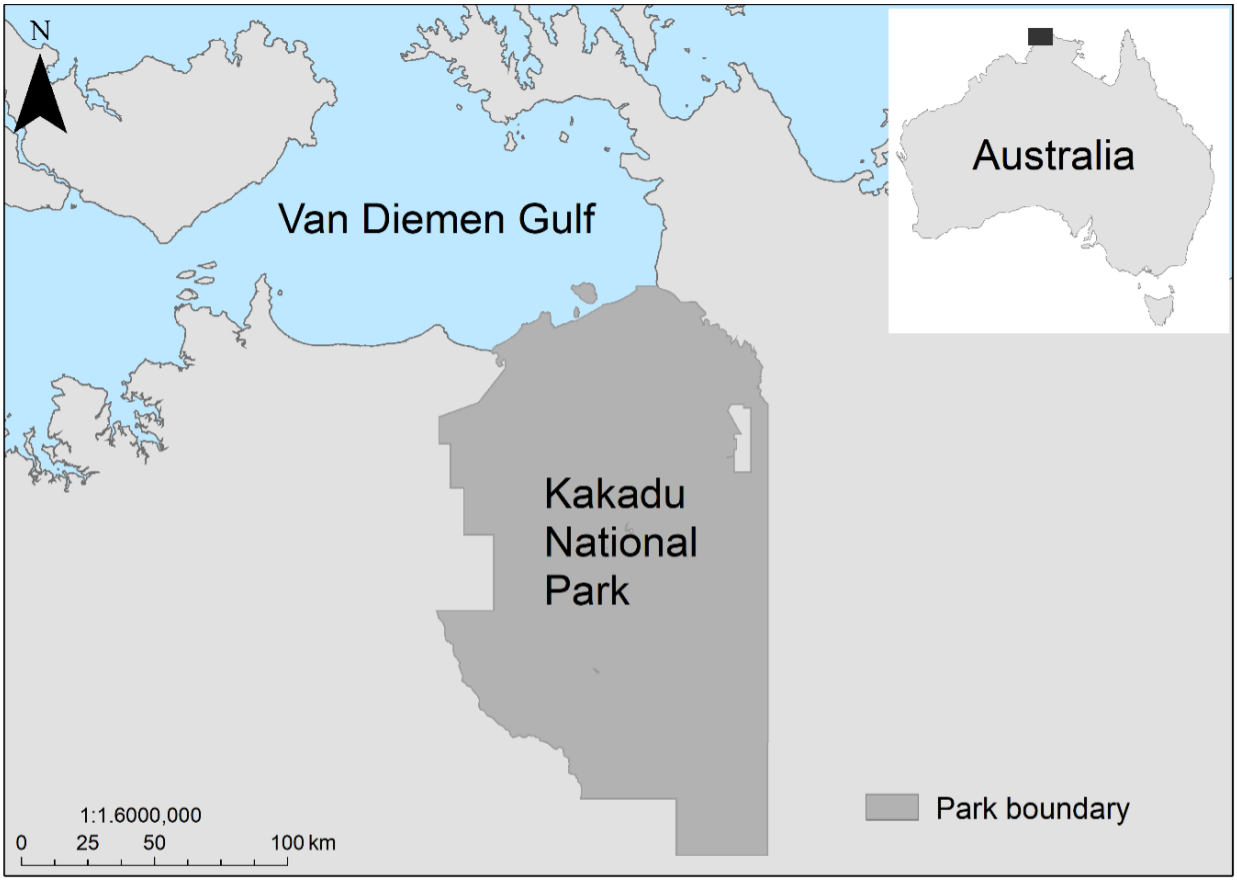

Figure 1. Location of Kakadu National Park. Sources: Esri, Michael Bauer Research GmbH 2022, Australian Bureau of Statistics; The data is supplied to the Commonwealth for compilation by States and Territories of Australia, as well as several large environmental NGOs.

To the local Bininj Aboriginal people of the coastal Country, it is a rich cultural homeland comprised of distinct Countries. Thousands of generations of families have thrived since the ancestral beings created the landscape features, clan boundaries, rules, and relationships. Aboriginal peoples have continuously inhabited the Kakadu region for at least 60,000 years, cultivating a complex cultural heritage encompassing extensive ecological knowledge, oral histories, law, and ceremonial traditions (Claudino-Sales & Claudino-Sales, 2019). The region contains a vast array of cave paintings, rock carvings,

and archaeological sites, which serve as historical records of the lifeways, skills, and traditions of its inhabitants (Marshall et al., 2022). These artistic and archaeological expressions chronicle human-environment interactions from prehistoric times to the present, offering an exceptional cultural and historical archive spanning tens of thousands of years (David et al., 2017).

The coastal and marine fauna associated with Kakadu's ecosystems is diverse, encompassing a range of species from large, ecologically significant taxa – such as estuarine crocodiles, marine turtles, dugongs, sharks, and seabirds – to less conspicuous organisms, including the giant mudskipper, box jellyfish, crabs, worms, and other marine invertebrates (Kyne, 2014; Pusey et al., 2015; Russell & Smith, 2007). The region is recognised as a biodiversity hotspot, supporting over one-third of Australia's bird species, approximately one-quarter of the nation's mammal species, 1,600 identified plant species, 128 reptile species, and an estimated 10,000 insect species (Chatto, 2005; Claudino-Sales & Claudino-Sales, 2019).

Despite the ecological importance and highly diverse marine environment of Van Diemen Gulf, the northern boundary of Kakadu National Park is limited to mean low water. Consequently, marine and coastal ecological values are underrepresented and inadequately protected within the Park's current boundaries, restricting the ability to manage marine activities that may impact these ecosystems effectively (Russell & Smith, 2007). Beyond the intertidal marine waters of Van Diemen Gulf, the Northern Territory Government holds jurisdiction over coastal waters extending up to three nautical miles offshore. As a result, any research initiatives or management activities concerning marine and coastal ecosystems beyond Kakadu's jurisdiction necessitate cooperation with the Northern Territory Government (NTG and other partners, 2019).

While nearly the entire South Alligator River catchment is managed within Kakadu's protected area, its closely linked coastal and marine environments remain outside the Park boundaries (NTG, 2019) and thus lack the same level of conservation oversight. Given the strong ecological interconnectivity between marine and terrestrial environments, there is a clear need for integrated conservation and management strategies that extend beyond Kakadu's coastal boundary to ensure comprehensive ecosystem protection (Kiessling et al., 2008).

The natural and cultural values of Kakadu National Park face multiple threats, which are expected to intensify over time. One of the primary ecological challenges is the proliferation of the invasive aquatic plant Salvinia, *Salvinia molesta*, which continues to spread within the Park's wetlands (Bangalang et al., 2022; Bradshaw et al., 2007). Additionally, fire regimes pose a significant threat, as the wet-dry tropics of the Australian savannas are highly susceptible to fire due to the seasonal nature of rainfall and the accumulation of flammable grassy fuels (Townsend & Douglas, 2004).

Between 1960 and 1980, high densities of feral buffalo caused substantial alterations to the hydrology of the floodplains, facilitating saltwater intrusion and leading to widespread forest dieback (Bradshaw et al., 2007). This process continues today, exacerbated by salinisation linked to sea level rise, driven by climate change (Bowman et al., 2010a). Furthermore, climate change is expected to accelerate erosion in tidal flats and mangrove swamps as rising sea levels increasingly impact coastal environments (Boustead, 2009).

Changes in humidity levels may also occur, potentially leading to a longer dry season and/or reduced precipitation during the wet season, further disrupting Kakadu's delicate ecological balance (Russell-Smith et al., 2017).

To effectively prioritise managing these threats, it is important to bring together existing information and identify what is known and what are the most important gaps to be addressed. This will help synergise efforts between researchers, managers and custodians. The conservation status of many species within the marine environment at both regional and national levels is uncertain due to insufficient survey coverage along the Northern Australian coastline (Roeger & Russell-Smith, 1995). Despite the ecological significance of the Van Diemen Gulf and the Kakadu coast as critical nursery and breeding habitats for species of commercial, cultural, and conservation importance, these marine environments have been relatively understudied (Kiessling et al., 2008).

Existing information on marine values is fragmented and narrowly focused, primarily comprising species lists with limited consideration of spatial and temporal variations in abundance and distribution, habitat associations, or broader ecological dynamics. This lack of information presents a significant hurdle to effectively conserving Kakadu's marine environment. The creation of a greater knowledge base for the marine environment will increase the capacity of the Government and community to manage the impacts of human activity, which are likely to build in range and intensity over the next few decades. The impacts of climate change, including saltwater intrusion, are being recorded, and there are plans for extracting and processing natural gas in and adjacent to Northern Territory waters and demands for increasing commercial fishing.

Management plans may have to be altered to incorporate landscape changes caused by climate change. Managers may have to pay more attention to what is happening in adjacent lands and waters and how they interact with the predicted impacts within Kakadu. This changing environment will profoundly impact the Country, and people may have to think about the most appropriate place to live. As some areas are already impacted, there is an urgency to initiate a precise baseline understanding of biodiversity. With this, we can best monitor any changes and ensure the values of Kakadu National Park will be managed based on the best available evidence and information, including scientific and Indigenous knowledges and values. Recent management approaches have increasingly emphasised the importance of including local communities and the need for transparency in decision-making processes related to management actions and research priorities.

This review assesses and summarises relevant published literature on knowledge of marine values and past scientific research. This approach will identify new ways to interpret and shed light on gaps in previous research. It will identify areas of prior research to prevent duplication of effort, help direct the way forward for further research, and address where new evidence is needed.

2 Methodology

The literature review was conducted through a systematic search and evaluation of academic and technical sources relevant to the marine values of Kakadu National Park. This process involved identifying and analysing peer-reviewed journal articles, books, and technical reports obtained from reputable online databases, including ScienceDirect, Web of Science, and Google Scholar. A structured keyword search strategy was employed to ensure comprehensive coverage of relevant literature. The primary search term "Kakadu National Park" was used in combination with specific ecological and environmental descriptors, including "marine ecosystem," "biodiversity," "mangrove," "saltmarsh," "seagrass," "estuaries," and "mudflats." This approach facilitated the retrieval of scholarly publications and grey literature addressing key aspects of marine and coastal biodiversity within the Park.

In addition to database searches, relevant data and reports were accessed through resources held by Kakadu National Park management. This included locally relevant documentation, management reports, and conservation assessments that may not be readily available in academic databases. The integration of peer-reviewed research and Park-specific resources enabled a holistic assessment of the current knowledge regarding marine ecosystems in Kakadu National Park.

3 Ecological values of the marine environment in Kakadu National Park

3.1 Biodiversity and Threatened species

The marine environment within Kakadu encompasses and interacts with some of the more extensive and ecologically diverse river systems in northern Australia, providing essential habitats for diverse sedentary and migratory species listed under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) (Claudino-Sales & Claudino-Sales, 2019; NTG, 2019). These catchments are among the few extensive estuarine systems largely unaffected by agricultural activity. The area includes nearly the entire South Alligator River catchment, characterised by a funnel-shaped estuary predominantly influenced by tidal dynamics. The estuary extends several kilometres at its mouth and narrows to 80 metres at the upper tidal limit, situated 105 kilometres upstream (Pusey et al., 2015).

The Kakadu marine environment comprises extensive mangroves, wetlands, and floodplains that sustain a diverse assemblage of waterbirds and various aquatic and marine species. The region holds the highest freshwater fish species richness in Australia, with over 246 recorded fish species inhabiting its tidal and freshwater systems (Kakadu National Park, 2016; Pusey et al., 2015). The regions also support five species of marine turtles, along with dugongs and shorebirds. Kakadu also provides critical habitats for several threatened species, including the critically endangered river shark, two vulnerable

sawfish species, two inshore dolphin species, and the Freshwater Whipray (Kakadu National Park, 2016). The marine ecosystems of northern Australia, particularly those within Kakadu, are believed to sustain some of the world's last remaining viable sawfish populations (Larson, 2002).

Threatened and Endangered Species can rely on different ecosystems to complete important life cycles. Birds, fish, and reptiles utilise distinct habitats for feeding, breeding, and roosting. Therefore, a change in habitat extent and condition can influence many life stages and ecosystem functions, which vary among species (Chatto, 2005). Kakadu is the only large, protected area in the world with significant critical nursery and breeding areas for four shark species: the Northern River shark (*Glyphis garricki*), the Spear tooth shark (*Glyphis glyphis*), and the freshwater and dwarf sawfish (*Pristis clavata*). The Northern River shark total population size of this species is estimated to be 250 mature individuals. The Speartooth shark's population is estimated to consist of less than 250 mature individuals per subpopulation (Lyon, 2020). Survey findings suggest that adult sharks inhabit distinct environments, likely residing entirely in marine habitats rather than the estuarine areas where juveniles are typically observed (Field et al., 2013).

Kakadu is also recognised for supporting thirty-nine shorebird species, including 29 non-breeding migratory species of international and national importance. The site is considered internationally important for migratory shorebirds in the East Asian-Australasian Flyway (Bamford et al., 2008). Mangrove habitats adjacent to and east of the South Alligator River support a critical roosting colony. This extensive multi-species colony can exceed 13,000 birds annually in some years, with eight confirmed breeding waterbird species (Chatto, 2005). Another significant colony is located within mangroves along the southern banks of the East Alligator River, extending into a tributary from the river mouth. This site supports ten breeding waterbird species, with an estimated annual occupancy exceeding 11,500 birds (Ramsar). Furthermore, Chatto (2005) documented substantial shorebird aggregations in Finke Bay, recording 9,000 individuals in 1993 and in coastal areas between the South Alligator River and MiniMini Creek.

Other threatened marine species with critical habitats within Kakadu include Pig-nosed turtle, Flatback turtle, Green turtle and dugong (Groom et al., 2017; Marsh et al., 2005; Schäuble et al., 2006). Surveys estimate the Australian Pig-nosed turtle population at approximately 3,000 individuals, with a one per cent threshold of 30 individuals. Georges and Kennett (1989) reported the widespread distribution of Pig-nosed turtles between the tidal reaches and headwaters of the South Alligator River, where they are present in high densities. Flatback turtles nest on Field Island, and conservation efforts within Kakadu primarily focus on managing nesting habitats and ensuring long-term protection. Additionally, ongoing annual monitoring programs assess nesting turtle populations to support conservation initiatives (WBM, 2010).

Table 1. List of threatened species and their conservation status. EPBC Act: *Environment Protection and Biodiversity Conservation Act 1999*, TPWC: *Territory Parks and Wildlife Conservation Act 1976*, IUCN: International Union for Conservation of Nature. (CR: Critically Endangered, EN: Endangered, VU: Vulnerable, NT: Near Threatened).

Common name	Scientific name	Status		
		EPBC Act	TPWC	IUCN
Northern river shark	*Glyphis garricki*	EN	EN	VU
Speartooth shark	*Glyphis glyphis*	CR	VU	VU
Dwarf sawfish	*Pristis clavata*	VU	VU	CR
Largetooth sawfish	*Pristis pristis*	VU	VU	CR
Narrow sawfish	*Anoxypristis cuspidata*			CR
Green sawfish	*Pristis zijsron*	VU	VU	CR
Flatback turtle	*Natator depressus*	VU		
Green turtle	*Chelonia mydas*	VU		EN
Olive Ridley turtle	*Lepidochelys olivacea*	EN	VU	VU
Hawksbill turtle	*Eretmochelys imbricata*	VU	VU	CR
Loggerhead turtle	*Caretta caretta*	EN	VU	EN
Lesser sand plover	*Charadrius mongolus*	EN	VU	EN
Australian painted snipe	*Rostratula australis*	EN	VU	EN
Bar-tailed godwit	*Limosa lapponica bauri*	EN	VU	NT
Eastern curlew	*Numenius madagascariensis*	CR	VU	EN
Asian dowitcher	*Limnodromus semipalmatus*	VU	VU	NT
Red knot	*Calidris canutus*	VU	VU	NT
Great knot	*Calidris tenuirostris*	VU	VU	EN
Curlew sandpiper	*Calidris ferruginea*	CR	VU	VU
Dugong	*Dugong dugon*	Migratory/ Marine		VU
Australian snubfin dolphin	*Orcaella heinsohni*	Vulnerable, Migratory and Cetacean		VU
Australian humpback dolphin	*Sousa sahulensis*	Vulnerable, Migratory and Cetacean		VU
Indo-Pacific bottlenose dolphin	*Tursiops aduncus*	Cetacean / Migratory		NT

There is a lack of research on threatened species in Kakadu, including a lack of empirical data on population abundance and life cycle characteristics for species such as river sharks. Currently, there are no formal monitoring programs to evaluate population trends or assess the effectiveness of conservation management strategies for threatened species in Kakadu (WBM, 2010). Further research is needed to understand how species interact with the available habitats and to identify their specific ecological requirements (Aplin, 2004). Habitat connectivity is particularly critical for river sharks, as any disruption may significantly impact their movement patterns and upstream migration. Moreover, a thorough understanding of the impacts of climate change on these species is necessary, particularly regarding the effects of sea level rise on nesting habitats. This is especially pertinent for flatback turtles, which are classified as Data Deficient in the Northern Territory and the IUCN Red List (2010).

3.2 Mangrove forests, estuaries and reefs

The wetlands of Kakadu remain relatively undisturbed compared to other wetland ecosystems in Australia (Boustead, 2009) and have been designated as internationally significant under the Ramsar Convention on Wetlands (Finlayson et al., 2006). Australia hosts one of the most floristically diverse mangrove systems globally, comprising 47 species, representing 59% of the world's total mangrove diversity, of which 39 species are recorded within the Kakadu region (Rogers et al., 2022).

The mangrove ecosystems within the Kakadu National Park are among the most species-rich in northern Australia (NPA, 2007). The majority of mangrove species present in Kakadu are widely distributed across Australia and the broader Indo-Melanesian biogeographic region (Duke, 1992). These mangrove communities play a crucial ecological role, serving as breeding habitats for waterbird colonies and contributing to Kakadu's ecological character, a factor that supported its Ramsar designation. Furthermore, mangroves function as vital nursery habitats for various aquatic species, including catfish, threadfin salmon, barramundi, mud crabs, and prawns (Boustead, 2009). These ecosystems are of significant ecological and economic importance, supporting fisheries resources while also providing opportunities for recreation and tourism.

The presence of large river systems flowing into the relatively enclosed waters of the Gulf, combined with extensive sheltered shallow water habitats and mangrove forests, establishes the estuaries as critical nursery areas for both commercially and non-commercially valuable fish species (NPA, 2007). Additionally, these estuarine environments support two of northern Australia's most iconic species, the Barramundi and the Estuarine Crocodile. Notably, saltwater crocodile populations within these estuarine systems have increased significantly since the prohibition of hunting in 1971 (Finlayson et al., 2006).

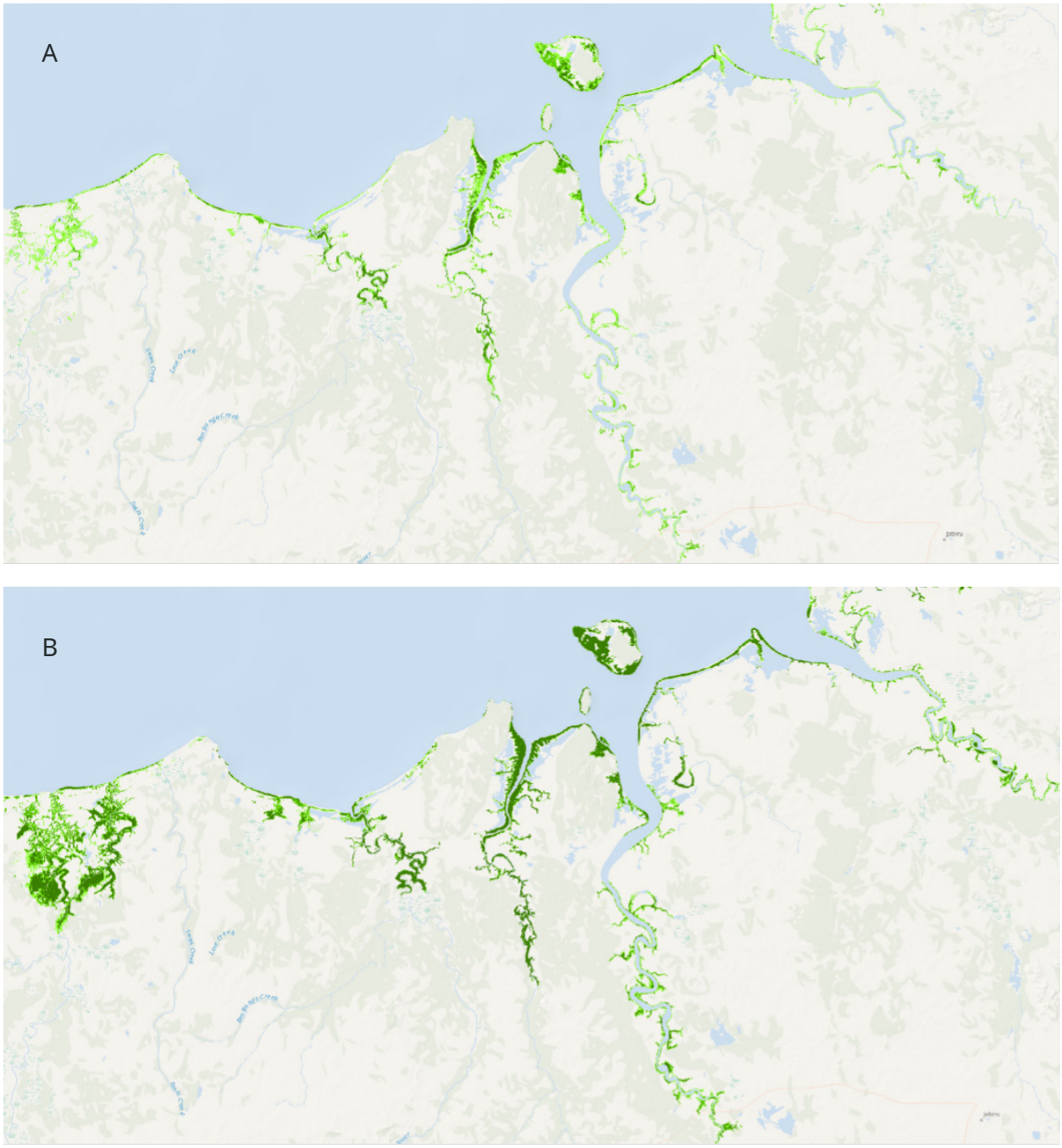

Figure 2. Mangrove extent and cover Kakadu coast in a) 1987, and b) 2022.
Source: Geoscience Australia Portal.

Mangrove degradation and deforestation areas remain relatively small in the Northern Territory and are influenced by various natural and anthropogenic factors. These include cyclones, coastal erosion, extreme El Niño–Southern Oscillation (ENSO) events and disturbances caused by invasive fauna such as ungulates (Pike et al., 2024; Phebe I Rowland & Catherine E Lovelock, 2024). More recently, fluctuations in mangrove cover, including both declines and increases, have been associated with rising sea levels and periods of above-average rainfall (Asbridge & Lucas, 2016). Cobb et al. (2007) identified a long-term pattern of mangrove expansion occurring between at least 1950 and 1991.

Additionally, Landsat imagery data from Geoscience Australia indicate a continued increase in mangrove extent and canopy density from 1987 to 2022.

3.3 Seagrass meadows, mudflats and saltmarsh and their importance

Seagrasses often form meadows that can trap sediments, stabilise substrates, reduce suspended particulate matter, and improve water quality (do Amaral Camara Lima et al., 2023). A seagrass survey was conducted by Roelofs et al., 2005, which found intertidal habitats around Gardangal (Field Island) and at the entrance to the South Alligator River and west of Gularri (Point Farewell) near the mouth of the East Alligator River. Nearly all observed seagrass meadows exhibited signs of turtle activity and dugong foraging. Certain small patches showed significant grazing pressure and may serve as essential feeding sites for dugongs migrating along the coastline.

During low tide, extensive intertidal mudflats serve as critical feeding grounds for large aggregations of shorebirds. Unvegetated low-lying hypersaline mudflats are also found adjacent to the tidal reaches of rivers and creeks. These tidal flats are located on the landward side of mangrove communities, often forming complex habitat mosaics alongside intertidal saltmarshes and mangroves (Roelofs et al., 2005). Saltmarshes play a crucial ecological role, functioning as natural buffers and filters for nutrients and pollutants entering the estuary. Saltmarshes also reduce erosion, maintain water quality, and support diverse faunal species. As integral components of estuarine and coastal ecosystems, saltmarshes facilitate ecological connectivity across freshwater, brackish, tidal, and subtidal habitats.

Although seagrass meadows in Kakadu are not extensive, they serve as critical habitats and provide essential ecosystem functions, including supporting fisheries, maintaining water quality, and mitigating the impacts of flooding. Seagrass and algal ecosystems are globally recognised as the third most valuable in ecosystem services per hectare, ranking behind estuaries and swamp floodplains. The most significant threats to seagrass in Kakadu are likely associated with climate variability and long-term climate change. Rising water temperatures and increased turbidity caused by freshwater runoff from intense rainfall events pose substantial risks to the viability of these ecosystems (Zimmerman, 2021). Given that the effects of climate change have already been observed in Kakadu, it is imperative to enhance understanding of seagrass meadows, mudflats, and saltmarsh habitats, particularly their ecological functions and interactions with both natural and cultural values.

3.4 Connectivity with terrestrial ecosystems

Kakadu National Park's coast comprises several interlinked estuarine and freshwater habitats that cannot be effectively managed in isolation. The high seasonal rainfall and massive tidal movements influence the marine and terrestrial ecosystem connectivity. Together, they help form vast alluvial plains, including saltmarsh, resulting from saline tidal movements and freshwater floodplains. During the wet season, these areas become inundated and are predominantly covered by herbaceous aquatic vegetation, while in the

dry season, they desiccate and develop surface cracks. The alluvial plain is hydrologically connected to the lower floodplains through a network of channels, swamps, and gullies while also connecting to the upper floodplains in elevated regions. These processes contribute to the formation of Melaleuca forests, dense vegetation, and billabongs, which emerge when sections of river channels become isolated due to the accumulation of sand plugs or the development of natural levees (Boustead, 2009).

During the wet season, the monsoonal flows flush the tidal channel, reducing salinity levels to freshwater conditions throughout the estuary's entire length. As water levels recede, tidal dynamics become the dominant hydrological force, with tidal influence extending approximately 105 kilometres inland from the estuary's mouth in Van Diemen Gulf. Significant monsoonal rainfall, coupled with seasonal variations in tidal and fluvial processes, exerts a profound influence on the geomorphology, water quality, and ecological functions of the coastal lowlands (WBM, 2010). River channels and riparian vegetation provide essential habitats for a diverse array of flora and fauna, including threatened and endemic species, waterbirds, fish, and species of cultural significance. During the late wet season, large-scale upstream migrations primarily involve small-bodied fish, moving from floodplain nursery habitats to dry-season refuges. These migrations are particularly notable for their magnitude, often involving several hundred thousand fish per hour passing a single observation point (Finlayson et al., 2006).

Extensive, deep floodplains retain water longer into the dry season than smaller, shallower, and more densely vegetated wetlands. Consequently, this hydrological variation has resulted in predictable patterns of habitat utilisation among different species. These patterns not only influence the temporal distribution of species throughout the year but have also driven the evolution of adaptive persistence strategies that enable species to endure seasonal fluctuations in water availability (Chatto, 2006).

With sea level rise, freshwater ecosystems are projected to transform into marine-dominated ecosystems (Bowman et al., 2010; Sloane et al., 2018) . This is due to the low-lying topography, which, in many cases, is below high tide and protected only by fragile cheniers and natural levees. The increasing penetration of saline water into previously buffered environments heightens the likelihood of further Melaleuca dieback and compromises soil integrity, facilitating the formation of fissures that may exacerbate the lateral spread of saltwater intrusion (Chariton et al., 2018). Cases where such ridges have been breached in Kakadu have resulted in the rapid intrusion of saline water into freshwater wetlands, associated mangrove encroachment and Melaleuca dieback (Asbridge & Lucas, 2016). Melaleuca dieback has also been caused by feral buffalo damage, such as trampling, de-vegetation, swim channels, and wallows, accelerating saltwater intrusion. Given the strong interconnectivity between marine and terrestrial ecosystems in Kakadu, as well as the potential for significant environmental and cultural degradation from anthropogenic influences, there is a need to implement comprehensive land-sea management strategies that extend beyond the Park's current coastal boundaries (Kiessling et al., 2008).

4 Cultural significance of the marine environment in Kakadu National Park

4.1 Indigenous connections and Traditional Ownership

Kakadu National Park is Aboriginal land, and the custodians of this land, known as Bininj in the north and Mungguy in the south, have maintained a long-standing stewardship over their country. To ensure the protection and management of its invaluable natural and cultural heritage, the Bininj/Mungguy have entered into a lease agreement with the Australian Government, facilitating the joint management of the area as a national park (Kakadu National Park, 2016).

Bininj people, from the north and the coastal region of Kakadu, have a close relationship with the island, estuarine, coastal, and marine environments. Bininj people continue to hunt and gather coastal and marine animal and plant species, such as shellfish, stingrays, mud crabs, marine turtles, fish, and barramundi in and adjacent to Kakadu. They depend on these natural systems for sustenance; Indigenous peoples have strong cultural beliefs that tie ancestral beings to specific coastal attributes (KNP Plan of Management, 2006).

Many clans are culturally responsible for cultural and natural values (Russell B & Smit 2007). Indigenous peoples continue to affirm their rights to Sea Country, including access to and management of marine resources, as recognised under the United Nations Declaration on the Rights of Indigenous Peoples and the Convention on Biological Diversity (UN et al., 2008; Secretariat of the Convention on Biological Diversity, 2010). Coastal Indigenous groups are particularly susceptible to ecological and cultural disruptions if migratory marine species are not effectively managed within their Sea Country and in critical habitats, some of which extend beyond their traditional territories.

4.2 Traditional ecological knowledge

Kakadu has at least 40,000 years of archaeological material and cultural resources, and internationally significant rock art depicting different evolved landscapes (Claudino-Sales & Claudino-Sales, 2019). The Kakadu landscape is deeply embedded within a complex spiritual and social system maintained by the Bininj people. Indigenous cultural-ecological connections intricately link individuals, clans, and Country, reinforcing a profound relationship between people and their ancestral lands. For people to survive in one location for over 40,000 years through periods of climate change, there was an understanding of local conditions and a joint resilience to the changing environment. It is essential to prioritise Indigenous-led and holistic approaches in conservation efforts to uphold and integrate Indigenous values, rights, and traditional knowledge systems within the management of the landscapes that sustain them (Bangalang et al., 2022).

4.3 Rock art and archaeological sites

Kakadu's Sea Country is shaped by an enduring cultural landscape that reflects tens of thousands of years of Aboriginal occupation, stewardship and connection to Country. The Park contains nationally and internationally significant cultural heritage, including archaeological sites, rock art, places of spiritual significance, cultural landscapes and living knowledge systems that continue to guide how Bininj/Mungguy care for Country today (Kowlessar et al., 2023; Marshall et al., 2022).

Rock art, archaeological sites, oral traditions, language, seasonal knowledge and cultural practices together document the long relationship between Bininj/Mungguy and Sea Country. These places and knowledge systems embody cultural authority, law and responsibilities that continue to shape decision-making, resource management and the transmission of knowledge between generations.

Many cultural places are highly significant and are governed by cultural protocols that determine who may access, interpret or speak for them. Research undertaken in Sea Country must recognise and respect these protocols, ensuring that culturally sensitive information is managed appropriately and that Traditional Owners determine how cultural knowledge is documented, shared and protected.

Protecting Kakadu's cultural heritage requires more than conserving physical sites. It also involves supporting the continuation of living cultural knowledge, recognising the importance of Indigenous governance, and ensuring research contributes to the long-term maintenance of cultural values alongside ecological conservation. This approach acknowledges the continuing impacts of colonisation on Aboriginal peoples while supporting Indigenous-led research that strengthens cultural continuity, self-determination and the custodianship of Sea Country.

5 Economic values of the marine environment in Kakadu National Park

5.1 Fisheries and commercial activities

Kakadu supports important fisheries' resources in the form of fisheries' habitats. This is a critical service due to the importance of restocking for commercial viability, supporting recreational fishing tourism, and enhancing contemporary living culture and well-being (WBM, 2010). Many fish, such as salmon, threadfin salmon, barramundi, mullet, and crustaceans such as mud crabs and prawns, spend their juvenile stages in shallow nearshore waters, particularly around mangroves, saltmarsh, and seagrass habitats. Barramundi also inhabit freshwater floodplains and billabongs, spawning in inshore waters (Kyne, 2014; Pusey et al., 2015).

Commercial fishing does not occur within Kakadu, but beyond the low tide mark, it can occur immediately adjacent to its boundaries. While no commercial fishery exists, subsistence and recreational fisheries play a significant role in Indigenous livelihoods. Recreational fishing primarily functions as a sport fishery, predominantly targeting

a single species, the Barramundi. This fishery is subject to management regulations, including minimum size restrictions, limited catch allowances, and seasonal closures adjusted based on monitored fishing pressures (Finlayson et al., 2006).

5.2 Tourism and recreational opportunities

Kakadu is a globally recognised destination, attracting both international and domestic visitors. Tourists are drawn to Kakadu National Park for its rich biodiversity, landscapes, and ancient cultural heritage, including extensive galleries of Aboriginal rock art (Commonwealth of Australia, 1988; Director of National Parks, 2007). The Park's World Heritage designation further enhances its appeal as a premier tourist attraction. Kakadu provides exceptional opportunities to observe some of Australia's most iconic wildlife species alongside an extraordinary diversity and abundance of birdlife (Claudino-Sales & Claudino-Sales, 2019; WBM, 2010).

Kakadu's popularity has also established it as one of the most sought-after boating destinations in the Top End. During its peak in the mid-1990s, Kakadu supported a tourism industry comprising approximately 185 tour operators, attracting an estimated 230,000 visitors annually (Boustead, 2009). The region's wetlands, including the East Alligator River, Sandy Billabong, South Alligator River, and Mamukala, serve as key sites for recreational activities such as birdwatching, fishing, bushwalking, wildlife cruises, and cultural experiences. Additionally, fishing tours and wetland cruises operate within the Park. Although recreational fishing contributes minimally to the regional economy, as most associated expenditure occurs in Darwin before travel, it remains a significant component of the Northern Territory lifestyle.

5.3 Economic benefits for local communities

The tourism industry is the primary source of employment in the Kakadu National Park region, followed by sectors related to recreation and conservation. Tourism and recreation play a critical role in both the regional economy and the broader Northern Territory economy, attracting both national and international visitors (WBM, 2010). The economic impact of tourism in the region is estimated at $691 million per year, with an economic value of $156 million per year, supporting approximately 5,530 jobs (Sangha et al., 2019). As a globally recognised tourism destination, Kakadu National Park contributes substantially to the economic development of the Northern Territory. Additionally, its economic importance is reflected in the substantial procurement of goods and services from regional suppliers (WBM, 2010).

Through direct employment and service outsourcing, Kakadu provides direct and indirect employment opportunities within the regional economy, particularly for Bininj people and organisations. The marine environment also delivers a range of ecosystem goods and services, including climate and water regulation, natural pest and disease control, recreational fishing opportunities, and breeding habitats for marine species.

While these ecosystem services are not typically traded in formal markets, they hold substantial economic value due to their contributions to human well-being at local, regional, and global scales (Sangha et al., 2019).

5.4 Sustainable resource management

There is exceptional natural wealth in Kakadu National Park, characterised by rich biodiversity, wild rivers, pristine coastal and marine ecosystems, and Indigenous cultural and heritage sites of international significance, offering unique opportunities for sustainable development in northern Australia. However, the economic value of these natural assets, including ecosystem services and ecological functions, is often undervalued in economic assessments (Sangha et al., 2019). Enhancing research and communication on ecosystem services is essential for improving awareness and appreciation of the intrinsic value of Kakadu and other protected and well-managed ecological areas.

The Northern Territory's unspoiled coastal and marine environments present significant potential for eco-tourism and other enterprises, such as artisanal crafts and Indigenous cultural camps. These enterprises provide opportunities to showcase traditional knowledge systems while promoting ecologically sustainable livelihoods, reinforcing ongoing conservation initiatives. However, for such initiatives to achieve long-term success and community acceptance, meaningful consultation and collaboration with local Indigenous communities is essential to develop effective management and governance strategies (Sangha et al., 2019). Future conservation efforts could integrate biocultural knowledge systems within existing or restructured conservation science programs, fostering a joint management framework supporting ecological sustainability and cultural heritage preservation (Ligtermoet et al., 2023).

6 Threats to the marine environment of Kakadu National Park

6.1 Climate change

The low elevation of northern Australia renders the region highly susceptible to even minor increases in sea level rise. Projections indicate that global warming could result in sea level increases of up to 50 cm within the next 50–70 years in Kakadu, which will inevitably accelerate saltwater intrusion into freshwater floodplain habitats, leading to adverse ecological consequences (Boustead, 2009; Bowman et al., 2010). This process, compounded by geomorphic disturbances associated with feral buffalo activity, including swim channels, wallowing, and trampling, has already contributed to saltwater encroachment into freshwater margins, providing clear visual evidence of the transition from freshwater to saltwater ecosystems, such as the dieback of Melaleuca forests (Bowman et al., 2010; Bayliss et al., 2017).

Additionally, climate change is predicted to intensify cyclone activity, with storm surges exacerbated in Kakadu due to the region's shallow bathymetry (Sloane et al., 2018). For over two decades, addressing the uncertainties associated with climate change and rising sea levels has been a critical concern for managing Kakadu National Park. Chariton et al. (2018) anticipate an expansion in the lateral movement of seawater into the floodplains, facilitated by the existing network of channels and fissures. The continued intrusion of saline water into previously buffered ecosystems increases the likelihood of vegetation dieback and the degradation of soil integrity, which may, in turn, contribute to the formation of additional fissures, further intensifying saltwater intrusion. The incursion of saline water alters soil chemistry, leading to reduced soil integrity, vegetation dieback, and increased erosion and fissuring – processes that, in turn, create further pathways for seawater to penetrate inland (Bayliss et al., 2017).

The impacts of these processes are already evident in coastal wetlands, with extensive mangrove dieback reported in the Gulf of Carpentaria and potentially in Kakadu (Lucas et al., 2018). Aerial surveys conducted using remotely piloted and fixed-wing aircraft in September 2016 confirmed significant mangrove dieback, with observations suggesting that this decline occurred between late 2015 and 2016, coinciding with widespread mangrove losses in the Gulf of Carpentaria. These ecosystem changes are driven by incremental increases in salinity, which induce osmotic stress, ultimately leading to mortality and profound alterations in ecosystem structure and function (Stephenson et al., 2018).

Kakadu's iconic natural features and ecosystem function are threatened by climate change. Projections indicate that Kakadu National Park could experience an 80% reduction in freshwater wetlands by 2050 under a scenario where average global temperatures increase by 2–3°C (Fyfe, 2005; Bayliss et al., 2017). This degradation would result in significant declines in biodiversity and disrupt essential ecosystem services such as carbon sequestration, nutrient cycling, and freshwater provisioning (IPCC, 2007; Garnaut, 2008). The Park has been recognised as one of several critical wetland hotspots that are particularly susceptible to the adverse impacts of climate change, as highlighted in both the 2007 Intergovernmental Panel on Climate Change (IPCC) Report and the 2008 Garnaut Climate Change Review. Climate change will cause more saltwater intrusion into the freshwater wetlands, decrease biodiversity and conflate other ecosystem service values such as nutrient and carbon cycling.

Kakadu is increasingly recognised as a climate-vulnerable wetland hotspot requiring urgent and adaptive management strategies to mitigate the cumulative impacts of saltwater intrusion, vegetation change, and habitat loss (Bayliss et al., 2017).

6.2 Development and pollution

The Ranger uranium mine has been rigorously monitored to avoid contaminating the downstream wetlands and the animals and plants that contribute to the diet of indigenous communities. This monitoring framework has encompassed comprehensive biological and chemical testing, integrating early warning and long-term components (Finlayson et al., 2006). Following its closure, planning efforts are underway to facilitate the rehabilitation of the mining site, with stakeholder consultation guiding the process. Further assessments

and monitoring programs are also being conducted to evaluate and mitigate potential environmental impacts. The intersection of high natural and cultural heritage values, uranium mining operations, and Indigenous co-management arrangements has sparked ongoing debates regarding the effectiveness of management strategies, particularly concerning the adequacy of information sources in ensuring sustainable conservation outcomes (Finlayson et al., 2006).

Approximately 13 former uranium mines and numerous mineral deposits are within the upper South Alligator River Valley (BMT WBM, 2010). Past mining activities in the region have resulted in abandoned mine shafts, tailings, old access tracks, and localised radiological contamination. While the individual footprint of these abandoned uranium mines in the South Alligator Valley is relatively limited, their collective presence within the boundaries of Kakadu National Park underscores the importance of ensuring that they are appropriately rehabilitated in accordance with environmental and cultural heritage expectations (Kowlessar et al., 2023).

6.3 Overharvesting and unsustainable practices

The saltwater crocodile was historically subjected to unregulated commercial hunting, leading to severe population declines from the 1940s to the 1970s. However, timely recognition of the species' risk of extinction led to the implementation of protective measures, effectively banning commercial hunting. This was followed by regulated, sustainable-use programs and systematic population monitoring, resulting in one of the most notable conservation success stories. As a result, saltwater crocodile populations have demonstrated significant recovery in recent decades (Ligtermoet et al., 2023).

The potential pressures from recreational fishing on species and ecosystems within Kakadu National Park have been acknowledged. Although limited data has been systematically collected, anecdotal evidence and observations from Park staff indicate increased recreational fishing activities, fishing boats and coastal sightseeing tours in recent years. Currently, recreational fishers in the Northern Territory (NT) are not subject to licensing or direct regulation besides catch limits. The Northern Territory Recreational Fishing Survey (Make Your Catch Count) did not include Kakadu. However, its findings demonstrated that recreational fishers capture a significantly greater proportion of the total landed catch, approximately six times more than commercial fisheries (Kiessling et al., 2021).

Currently, publicly available data on the impact of commercial fishing on target and non-target species within Kakadu National Park, including saltwater crocodiles, sawfish, dugongs, and sharks, remain limited (Kiessling et al., 2005). The Bininj community has consistently expressed concerns regarding the effects of commercial and recreational fishing in adjacent marine areas, particularly concerning the Park's ecological integrity and cultural values.

The Northern Territory Offshore Net and Line Fishery (ONLF), operating in waters adjacent to Kakadu, has been documented to interact with various non-target species. The 2020 Ecological Risk Assessment (ERA) for the ONLF reports interactions with several protected species. For instance, during the 2014–15 fishing season, there were recorded interactions with green sawfish (25 individuals), narrow sawfish (16), and flatback turtles (2), among

others. While many of these individuals were released alive, the mortality rates and long-term impacts on these species are not fully understood (NTG, 2020).

The use of pelagic gillnets in the Northern Territory has been associated with interactions involving flatback turtles. The ERA assigns a moderate risk rating to flatback turtles, indicating that while current management measures may mitigate some risks, the potential for significant impacts remains (NTG, 2020). However, the true extent of these interactions is likely underestimated, given the limited observer coverage and the challenges in accurately reporting and monitoring bycatch in these fisheries.

7 Conservation and management of the marine environment in Kakadu National Park

7.1 Legal framework and Protected Areas

The management of Kakadu National Park (KNP) operates under a co-management framework, jointly administered by the Aboriginal Traditional Owners (Bininj/Mungguy) and the Australian Government (Director of National Parks) through a Board of Management. The Traditional Owners of Kakadu, whose rights and responsibilities over specific estates are determined by legally recognised Aboriginal customs, were granted land ownership on the condition that the Park would be leased back to the Australian Government for establishing and jointly managing Kakadu National Park.

The lease agreement governing Kakadu National Park is formalised between the Northern Land Council (NLC) – the statutory body representing the majority of Traditional Owners in the northern half of the Northern Territory (NT) – and the Director of National Parks, a federal government official based in Canberra. Kakadu National Park was inscribed on the World Heritage List in 1981 under the Convention's cultural and natural criteria. The *National Parks and Wildlife Conservation Act 1975* initially provided the legal basis for the progressive declaration of Kakadu National Park, which occurred in stages between 1979 and 1991 and established the Board of Management. This Act was repealed and replaced by the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), which governs the Park's management planning, regulation, and conservation strategies.

Kakadu National Park is also designated as a Ramsar-listed wetland of international significance. Australia's obligations to protect and maintain its ecological character are formally recognised under Commonwealth legislation through the EPBC Act. The Act establishes management standards for Ramsar wetlands through the Australian Ramsar Management Principles. Furthermore, several Northern Territory legislative frameworks are relevant to Kakadu's governance, including the *Territory Parks and Wildlife Conservation Act 1976*, *Fisheries Act 1994*, *Waste Management and Pollution Control Act 1998*, *Water Act 2000*, *Weeds Management Act 2001*, *Mining Management Act 2001* and *Local Government Act 2009*, each of which plays a role in regulating aspects of the Park's environmental management and conservation policies.

7.2 Collaborative approaches and Indigenous Ranger Programs

As Kakadu National Park was established, considerable attention was directed toward its designation as a World Heritage site. While numerous studies have documented its environmental characteristics and biodiversity, relatively less focus has been placed on understanding fundamental ecological processes (Finlayson et al., 2006) or the cultural and livelihood values that the Park holds for Indigenous communities. Indigenous knowledge is not only essential for maintaining cultural continuity, encompassing belief systems, language, social networks, and community well-being, but is also increasingly recognised for its role in redefining human-environment interactions (Ligtermoet et al., 2023).

Bininj Traditional Owners and Kakadu National Park Rangers have collaborated with scientists to monitor and manage Country adaptively, focusing on restoring magpie goose populations to wetlands previously dominated by para grass, an invasive weed. This initiative integrates ethical Artificial Intelligence (AI), including machine learning, with Indigenous Knowledge to enhance environmental stewardship. Drones are employed to identify priority areas for on-ground management. For many Bininj, the magpie goose is a key indicator of ecosystem health and holds significant cultural importance. The project was developed as an Indigenous-led initiative, ensuring that Traditional Owners played a central role in decision-making and management of their lands (McLean et al., 2023).

Incorporating Indigenous-led evaluations into sustainability science allows for continuous assessment, monitoring, and adaptation of methodologies, facilitating effective collaboration and ensuring meaningful conservation outcomes. For example, Traditional Owners, Kakadu Rangers, and Njanjma Rangers implemented targeted para grass control strategies, including aerial spraying via helicopter and follow-up ground treatments in designated priority areas. Post-management evaluations conducted by Bininj Traditional Owners and Rangers revealed a significant reduction in para grass cover, decreasing from 67% in 2018 to 17% in 2019 (NESP Resilient Landscapes Hub, 2020).

This intervention also led to a substantial increase in magpie goose populations, rising from fewer than 50 individuals in 2018 to over 1,800 by 2020. Additionally, ongoing evaluations allowed Bininj Traditional Owners to provide detailed, seasonally based observations on ecosystem health, reporting improvements in long-necked turtle populations, enhanced hunting access to key cultural sites, and strengthened intergenerational knowledge transmission (Robinson et al., 2022).

Further efforts in invasive species management are being undertaken by the Gundjeihmi Aboriginal Corporation's Djurrubu Rangers, who collaborate with Kakadu Rangers to control the highly invasive Salvinia weed. With technical guidance from Northern Territory government experts, the Djurrubu Rangers have established a breeding facility for the Salvinia weevil, a biological control agent. This facility has produced a higher volume of weevils than previously observed in Northern Territory weed management programs, enabling the release of more weevils into Kakadu's wetlands. Weed management specialists anticipate this approach will significantly reduce Salvinia infestations within the park. Biological control has proven effective in managing Salvinia in regions such as the Daly River, Papua New Guinea, and New South Wales (Djurrubu Rangers Media Release).

The North Australia Marine Biodiversity Survey highlighted the potential for conducting significant research through collaborative partnerships between Traditional Owners and ranger groups. Drawing from the experience gained through this survey, it is recommended that Bininj Traditional Owners actively engage in research initiatives, with guidance and support from Park managers and scientists as needed. Future research efforts should focus on conservation and management strategies that extend beyond the coastal boundaries of Kakadu National Park, recognising the strong ecological connectivity between Kakadu's catchments and the adjacent coastal and marine ecosystems (Kiessling et al., 2008).

7.3 Monitoring and research initiatives

Despite the ecological significance of the marine environments of Van Diemen Gulf and the Kakadu coast as critical nursery and breeding habitats for species of commercial, cultural, and conservation importance, these areas remain relatively understudied (Kiessling et al., 2008). This knowledge gap could be addressed through detailed habitat mapping of reefs and seagrass beds in the southern Van Diemen Gulf and seasonal monitoring of green turtle and dugong feeding behaviours. Additionally, comprehensive bathymetric and substrate mapping of Van Diemen Gulf would enhance the understanding of coastal processes and benthic habitats, thereby improving insights into marine ecosystem functioning (Kiessling et al., 2008).

Saltwater intrusion, driven by natural processes, boating activities, and feral buffalo, has already been documented in some regions of Kakadu and the nearby Mary River wetlands (Boustead, 2009). To address this issue, it has been recommended that dedicated, systematic monitoring programs be established in the Kakadu Region to assess floodplain threats and assets, replacing the previously opportunistic and ad hoc survey approaches. Moreover, incorporating cultural health indicators into future monitoring frameworks is necessary to ensure a holistic, socio-ecological approach that reflects the perspectives of Traditional Owners and supports joint management efforts in Kakadu (Bayliss & Ligtermoet, 2017).

Employing a scenario futures approach – which involves comprehensive stakeholder engagement at all stages, scenario planning, and software-supported scenario analyses – establishes a robust framework for the participatory assessment of potential management pathways for Kakadu National Park. The adaptability inherent in scenario planning enables stakeholders to prioritise their interests and expertise, articulate their long-term vision, and collaboratively refine their ideas. This process fosters dynamic interactions, allowing diverse perspectives to integrate and evolve into cohesive, co-designed planning strategies. Furthermore, Indigenous-led sustainability science must remain flexible and responsive to unforeseen challenges, stagnation, and evolving community perspectives (Austin et al., 2019). Researchers working within Indigenous sustainability contexts must remain cognizant of scientific, economic, social, and ecological outcomes to ensure holistic and equitable approaches (Robinson et al., 2022).

In cross-cultural management contexts like Kakadu, human-centred design must be broadened to incorporate Indigenous ethics, governance frameworks, and cultural protocols to ensure the equitable and responsible integration of Indigenous knowledge. Despite the deep cultural and ecological significance of coastal and marine environments, Bininj Traditional Owners have had limited opportunities to directly influence the management of marine activities that may impact their cultural heritage and environmental values (Kiessling et al., 2007). Tools and processes such as cultural mapping and participatory planning could assist in research and management strategies to better align critical intersecting approaches that reflect Kakadu's World Heritage values.

7.4 Education and awareness

There is a lack of studies on marine habitats and species in areas adjacent to Kakadu National Park, specifically at Gardangal (Field Island) and Djidbordu (Barron Island), both of which are located at the mouth of the South Alligator River and fall within the Park's jurisdiction. The absence of permanent water level gauges in Van Diemen Gulf, coupled with insufficient tidal and stream monitoring stations, has resulted in limited hydrological data availability (NPA, 2007). Furthermore, inconsistent scientific datasets and the lack of genuine engagement with Bininj knowledge systems in understanding Sea Country have contributed to the underrepresentation of marine and coastal values within Kakadu's management boundaries, thereby limiting their prominence in formal conservation priorities (Kiessling et al., 2008).

In response, Parks Australia and the Kakadu Research and Management Advisory Committee have developed research guidelines that reflect Bininj expectations regarding collaborative research practices. These guidelines emphasise strategic research priorities, aiming to address knowledge gaps while aligning with Bininj management perspectives. By integrating Indigenous knowledge and viewpoints, the guidelines foster opportunities for meaningful collaboration and employment (Kakadu National Park, 2016). Expanding collaborative and adaptive planning approaches could enhance these opportunities, promoting a more inclusive and co-designed management framework. This can put Indigenous and human-centred perspectives at the forefront and save future researchers time as they can adapt to agreed priorities, lessening the need for a circular consultation process, which fatigues Bininj and park staff alike.

8 Conclusion

8.1 Summary of findings

Kakadu National Park is listed as a World Heritage site for its cultural and natural values. Analysis has shown that cultural value research has taken a back seat to biological interests, and within that context, marine values have been second to terrestrial and freshwater approaches. This is most likely due to the species' endemicity of the sandstone plateau, the vastness and iconic appeal of the freshwater wetlands, and the coastal

fringe's inaccessibility. With the immediate threat of climate change to the marine environment by altering the coastline and increasing the amount and impact of big storms and tidal surges, there needs to be a greater interest in coastal management to best adapt to these changing circumstances.

As Kakadu is a flagship joint-managed arrangement, there needs to be more proactive and participatory planning between the governance agencies that manage the various legislation that impacts Kakadu. Bininj live and operate on Country and have done so for thousands of years. They have dealt with changing environments before and continue to serve as knowledge holders who are best placed to adapt to new and challenging scenarios.

Saltwater intrusion is expected to profoundly impact Kakadu's floodplains, making their current ecological state unlikely to persist into the next century. As these wetland ecosystems transform, there is a high probability of biome loss alongside the emergence of novel ecological assemblages. For Bininj Traditional Owners, these environmental changes will likely result in the loss of critical hunting and fishing grounds and the deterioration of culturally significant sites. Additionally, a decline in tourism is anticipated, carrying economic consequences for tourism operators and reducing revenue streams that are essential for sustaining the management and conservation activities of Kakadu National Park (Chariton et al., 2018).

8.2 Importance of managing the marine environment

The vulnerability of seagrass meadows and saltmarsh ecosystems to climate change has been widely acknowledged, leading to their formal recognition as vulnerable or threatened ecological communities under both state and Commonwealth legislation (Rogers et al., 2016). There may well be important sites along the coast for Bininj that might be affected by submersion and tidal activity. Culturally important plants and animals may utilise vulnerable marine habitats, and impacts on marine resources are poorly understood.

It is well established that sea level rise will lead to saltwater intrusion in low-lying coastal regions, including extensive freshwater wetland areas. However, the scale and rate at which this process will occur remain uncertain (Boustead, 2009). Consequently, developing adaptive management strategies for high-emission climate scenarios is advisable to ensure effective long-term planning and mitigation efforts. This includes understanding the impacts of rapid mangrove expansion into salt marsh and freshwater systems. It will also be valuable to revisit current management plans and renew a focus on seagrass meadow adaptation and prioritising management activities such as weeding on wetland areas unlikely to be affected by saltwater intrusion, such as upstream billabongs and wetlands (Boustead, 1999).

8.3 Recommendations for future research and conservation efforts

Detailed habitat mapping of reefs and seagrass beds occured in 2025. It is important that ongoing monitoring is undertaken to continue to monitor the health of Sea Country. Additionally, further research is required to enhance understanding of the adaptive

responses of key fisheries species, which hold significant cultural and economic value for both Bininj communities and the Northern Territory economy in the context of climate change (Kyne, 2014; Pusey et al., 2015).

While terrestrial and riverine processes driving environmental change have been reasonably well studied, there remains a notable lack of research on the hydrodynamic processes occurring within Van Diemen Gulf and their direct influence on the shorelines of the Alligator Rivers Region. Key disturbance factors include sea level rise, shoreline erosion, and saltwater intrusion, which are further exacerbated by the impacts of feral ungulates (Pike et al., 2024). The combined effects of these pressures could lead to the degradation and loss of saltwater and freshwater wetland ecosystems. The consequences of these changes may include the decline or disappearance of certain sections of the mangrove fringe along the coastline, the widespread loss of Melaleuca forests at wetland margins, and the expansion of mangrove species into creek systems because of saltwater encroachment. Additionally, freshwater wetlands may undergo ecosystem transitions, being gradually replaced by saline mudflats, further altering the ecological composition of the region (Eliot et al., 1999).

The literature consistently highlights threats from sea level rise, saltwater intrusion, feral ungulates, invasive grasses, and climate-driven ecosystem transitions, yet empirical data to support targeted management responses remains limited. Importantly, the reviewed studies underscore the need for research approaches that integrate Indigenous ecological knowledge, cultural heritage values, and participatory frameworks to address complex and dynamic environmental pressures. These recommendations are therefore grounded in evidence and informed by both scientific and cultural understandings of landscape change, with the aim of supporting long-term ecological resilience and culturally responsive governance in Kakadu National Park. Identified needs are outlined in the following tables.

Research Gaps – Environmental themes

Theme	High-priority research needs	Sources
Invasive species (general)	*Quantify damage by introduced species; develop cost-benefit and risk tools.*	Bradshaw et al. (2007)
Invasive species (plants)	*Remote sensing of para grass; fire control trials; invasion dynamics.*	Foxcroft et al. (2013); Boyden et al. (2019)
Invasive species (ungulates)	*Carbon emissions quantification; GHG lifecycle data; wetland impact synthesis. Investigate market opportunities and trade-offs for Traditional Owners.*	Rowland & Lovelock (2024); Groom et al. (2022)

Mining	*Assess mining impacts and remediation opportunities on employment, tourism and visitation in Kakadu.*	Claudino-Sales (2019)
Climate change	*SLR vs buffalo impact data; cultural heritage risk assessments; species' response models.*	Carmichael et al. (2018); Claudino-Sales (2019); Asbridge et al. (2019)
Coastal wetlands	*Map seagrass; model mangrove distribution under climate change.*	Roelofs et al. (2005); Asbridge et al. (2016, 2019)
Blue carbon	*Baseline VCE data; NT-specific sequestration rates; tidal reintroduction viability.*	Groom et al. (2022)
Biodiversity	*Ecology of shorebirds; microbenthic invertebrate knowledge gaps.*	Russell & Smith (2007)
Floodplain	*DEM and LiDAR coverage; seasonal mapping and time series analysis of floodplain vegetation.*	Bayliss et al. (2015); Ward et al. (2014)

Governance and engagement recommendations

Theme	Key recommendations	Sources
Indigenous inclusion in decision-making	*Embed Indigenous-led research; align outputs with Indigenous priorities.*	Robinson et al. (2021); Reardon-Smith (2024)
Communication and knowledge translation	*Translate scientific data for communities; improve stakeholder feedback loops.*	Bradshaw et al. (2007); Carmichael et al. (2017)
Cross-cultural collaboration	*Promote respectful partnerships; facilitate two-way knowledge exchange.*	Bangalang et al. (2022)
Participatory planning tools	*Develop bottom-up risk assessments; apply participatory mapping.*	Robinson et al. (2022); Duncan et al. (2018)
Cultural heritage valuation	*Create methodologies that recognise cultural, aesthetic, and scientific significance.*	Carmichael et al. (2017)
Conservation governance	*Evaluate collaborative frameworks; recognise differing land management goals.*	Robinson et al. (2021); Bradshaw et al. (2007)

The potential for blue carbon initiatives offers an additional incentive for ecosystem restoration under national emissions reduction programs. The ecosystem services provided by tidal marshes and mangrove forests have been estimated at approximately US$ $194,000 per hectare annually (Rogers et al., 2022), highlighting their role in climate change mitigation. Mangroves and coastal saltmarshes can play a critical role in sequestering greenhouse gases, while mangrove ecosystems in northern Australia are estimated to generate $14,000 per hectare annually for commercial fisheries (Rogers et al., 2022). Furthermore, removing feral ungulates from wetland environments offers a range of biodiversity and carbon sequestration benefits, which could be quantified and financially supported through carbon offset programs and biodiversity markets. These emerging markets present opportunities to incentivise restoration initiatives, such as reducing the impact of introduced ungulate species on wetland ecosystems (Rowland & Lovelock, 2024).

Developing strategic plans to safeguard Kakadu's cultural and biodiversity values will require multifaceted approaches, particularly as existing and emerging pressures intensify. A fundamental aspect of effective environmental governance is a comprehensive understanding of drivers of change, supported by robust monitoring programs that provide data-driven insights to inform planning and management decisions (Duncan et al., 2018). Effective land-use planning should be based on participatory frameworks that empower Traditional Owners and Indigenous communities in decision-making processes. Furthermore, any policy or action potentially impacting Indigenous land rights must adhere to rigorous Free, Prior, and Informed Consent (FPIC) standards, ensuring the protection of land ownership and usage rights. A participatory planning approach fosters scientifically informed, community-led discussions, reinforcing a transparent and equitable consent process that upholds Indigenous self-determination and governance (Robinson et al., 2022).

Collaborative approaches prioritising respectful partnerships and empowering local decision-making are increasingly recognised as effective mechanisms for integrating diverse values and knowledge systems into environmental management strategies. Knowledge co-production models that respect Indigenous rights and governance structures can enhance trust-building, facilitate mutually beneficial solutions, and improve biocultural landscape management while promoting community well-being (Bangalang et al., 2022). Analytical tools are available to interpret complex datasets, enabling a clearer understanding of how values, threats, and ecological changes intersect. Participatory planning and mapping are instrumental in identifying areas where ecosystem degradation occurs, the historical drivers of environmental change, and the long-term consequences for ecosystem integrity.

Collaborative research, including Bininj, scientists and rangers, will bring greater experience and understanding to a research perspective, increasing shared experience and ownership. Some of Kakadu's most significant features are highly dynamic coastal systems such as mangrove, wetlands and floodplain environments. They include human values such as sacred sites, traditional resources, commercial species and recreation opportunities. The land-sea connection is essential for Kakadu's coastal ecosystems, and human activities on land often directly influence the health and productivity of these ecosystems. A collaborative approach will create a tangible impact on targeted shared values and improve management outcomes.

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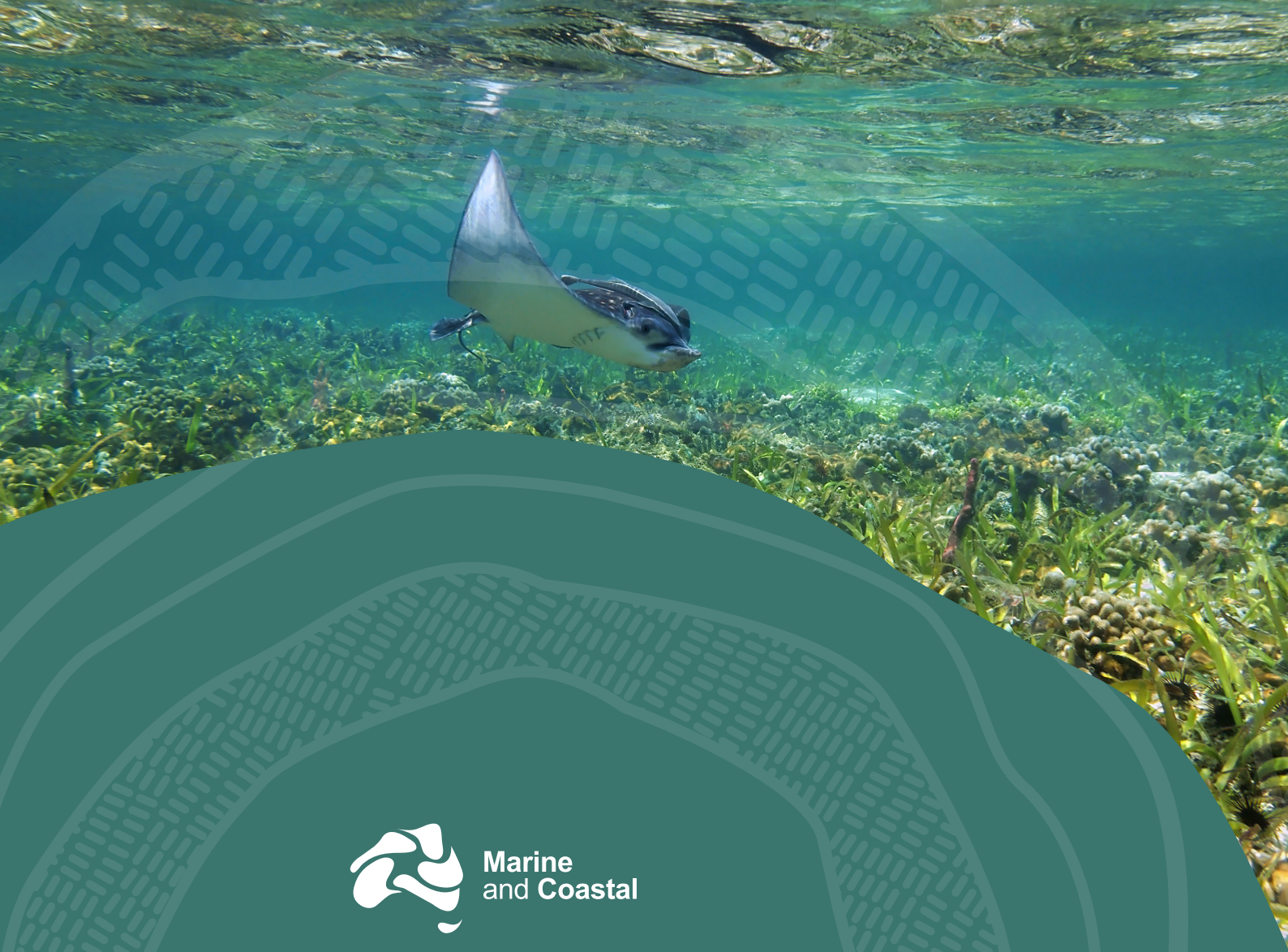

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