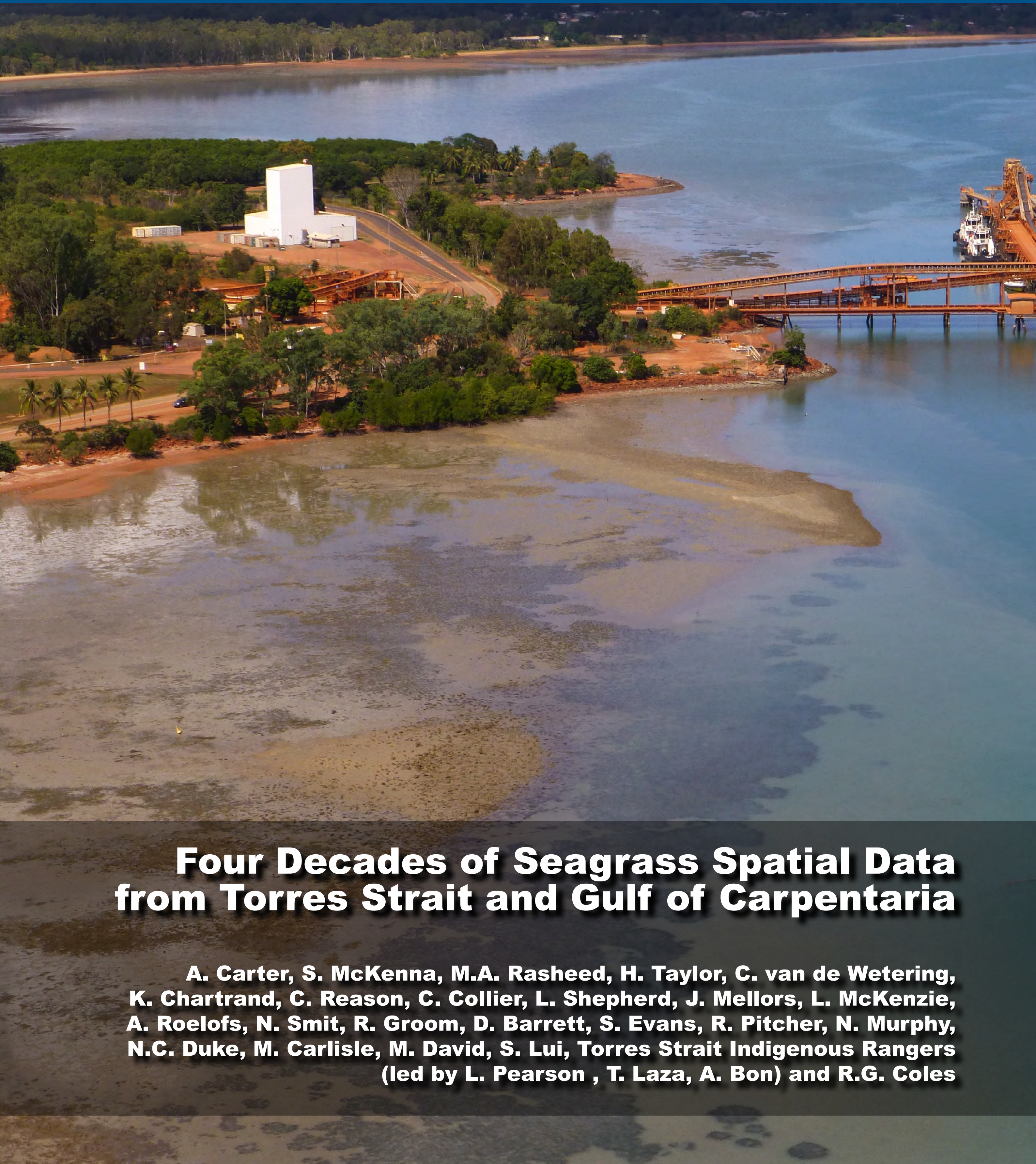
Marine and Coastal

National Environmental Science Program

FINAL REPORT

Project 1.13



Four Decades of Seagrass Spatial Data from Torres Strait and Gulf of Carpentaria

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Supported by the Australian Government's
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ISBN: 978-1-922640-08-6

This report should be cited as:

Carter, A., McKenna, S., Rasheed, M., Taylor, H., van de Wetering, C., Chartrand, K., Reason, C., Collier, C., Shepherd, L., Mellors, J., McKenzie, L., Roelofs, A., Smit, N., Groom, R., Barrett, D., Evans, S., Pitcher, R., Murphy, N., Duke, N.C., Carlisle, M., David, M., Lui, S., Torres Strait Indigenous Rangers (led by Pearson, L., Laza, T., Bon, A.), and Coles, R.G. (2022). *Four Decades of Seagrass Spatial Data from Torres Strait and Gulf of Carpentaria.* Report to the Reef and Rainforest Research Centre, Cairns, Queensland. (44pp)

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Acknowledgment

This project is supported with funding from the Australian Government under the National Environmental Science Program. The Marine and Coastal Hub is funded by the Australian Government under the National Environmental Science Program.

Front Cover image: Seagrass meadows fringing the Port of Weipa (Credit: TropWATER)

Back Cover image: Fish traps in seagrass meadows at Erub Island (Credit: TropWATER)

This report is available for download from the NESP Marine and Coastal Hub website at www.nespmarinecoastal.edu.au

Acknowledgement to Country

The Marine and Coastal Hub acknowledges Aboriginal and Torres Strait Islander people as the first peoples and Traditional Owners and custodians of the land and waterways on which we live and work. We honour and pay our respects to Elders past, present and emerging.

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Acknowledgements

We acknowledge the Traditional Owners of the Sea Country on which this research took place, and pay our respects to Elders past, present and future. We honour their continuing culture, knowledge, beliefs and spiritual relationship and connection to Country. We also recognise Aboriginal and Torres Strait Islander peoples as the Traditional Owners of the land and sea, and as Australia's first scientists.

This project was funded by the National Environmental Science Programme (NESP) Marine and Coastal Hub and Torres Strait Regional Authority (TSRA) in partnership with the Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), James Cook University.

We thank the many individuals who contributed towards data collection and to create the original spatial layers included in this consolidation. We thank Australian Fisheries Management Authority; Cape York Natural Heritage Trust; Carpentaria Land Council Aboriginal Corporation; Commonwealth Scientific and Industrial Research Organisation; CRC Torres Strait; CRC Reef Research Centre; Fisheries Research Development Corporation; Ii-Anthawirriyarra Sea Ranger Unit; Mabunji Aboriginal Resource Indigenous Corporation; National Oceans Office; Natural Heritage Trust, Australian Government Department of Environment and Heritage; National Environmental Science Program (NESP) Tropical Water Quality Hub and Northern Australia Environmental Resources Hub; North Australian Indigenous Land and Sea Management Alliance; Northern Territory Department of Environment, Parks and Water Security (formerly Northern Territory Department of Infrastructure, Planning and Environment, Parks and Wildlife Commission); North Queensland Bulk Ports; Parks Australia North Network; Migratory Species Section, Biodiversity Conservation Division, Department of Agriculture, Water and Environment; Ports North; Queensland Department of Agriculture and Fisheries; and TSRA for providing funding for seagrass surveys and/or data included in this project.

The authors wish to thank Adam Fletcher, Louise Johns, Coco Cullen-Knox, Donna Kwan, Micheli Costa and Simone Strydom for their thoughtful reviews of this work.

Executive Summary

The Gulf of Carpentaria and Torres Strait in northern Australia support globally significant seagrass ecosystems which provide food for migratory species such as dugong and turtle, habitat for commercially important fisheries, and underpin the livelihoods and wellbeing of the region's First Nations saltwater people. Having a source of reliable data on seagrass distribution and species composition is critical to understanding how this ecosystem may be changing while managing for resilience and mitigating risks, and when designing monitoring programs in this remote region. Spatial data on seagrass has been collected across these regions since the early 1980's, but the data was often poorly curated and its location and storage disparate. In many cases the data has not been publicly available, and in some cases has already been lost. To address these issues, we compiled, validated, and synthesized historical seagrass spatial data to create a publicly available database accessible on eAtlas (https://doi.org/10.26274/2CR2-JK51) under a Creative Commons 4.0 Licence.

This spatial database includes compiled and standardised data from 40 years of field surveys. It includes (1) a site layer with 48,612 geolocated data points including features such as seagrass and seagrass species presence/absence, depth, dominant sediment type, collection date, and data custodian; and (2) a meadow layer that includes 641 individual seagrass meadows with features including meadow persistence, meadow depth (intertidal/subtidal), meadow density based on mean biomass and/or mean percent cover, meadow area, meadow area range (based on the composite of seagrass meadows across different survey dates at the same location), dominant seagrass species, seagrass species present, survey date range, and survey method. We include records collected under commercial contracts being made available here for the first time, and previously unpublished data collected during mangrove surveys in 2017 (Duke et al. 2020).

This data has resulted in the identification of thirteen seagrass species in the region. The deepest seagrass was found at -38 m mean sea level (MSL). Our database is a valuable resource that provides management agencies, rangers, Traditional Owners, ports, industry, and researchers with a long-term spatial resource describing seagrass populations from the early-1980s through to early 2022 against which to assess change.

This seagrass data compilation provides an important evidence base for marine spatial planning and management, to underpin or assist with:

- Assessments of benthic habitats and associated species (fish, turtle, dugong) in the Gulf of Carpentaria and Torres Strait.
- Understanding how risk, land use management and spatial protection intersect with the location of seagrass communities, e.g. Queensland, Northern Territory and Commonwealth Marine Parks, Indigenous Protected Areas, Fish Habitat Areas and Port Exclusion Zones.
- A transparent methodology to expand spatial analysis across northern Australia, including the remainder of the Northern Territory coast and tropical Western Australia coast.
- Regional assessments of seagrass resources used in combination with the previous synthesis of seagrass spatial data from the Great Barrier Reef.
- Designing a stratified seagrass monitoring program for northern Australia, and a reference spatial data set against which to identify future seagrass change.

- Identification of significant knowledge gaps that will guide future mapping and monitoring efforts, including consistent data collection and curation methods for seagrass communities in the Gulf of Carpentaria.
- Seagrass species identification and initial DNA assessment for "future proofing" ecological systems in any restoration endeavours.

Our work highlights the important role of historical data in understanding spatial complexity and for making informed management decisions on the current state of seagrass in northern Australia. Our approach can be adapted for monitoring, management, and assessment of pressures at a range of spatial scales and jurisdictions.

Introduction

Tropical seagrasses

Seagrasses grow in a range of locations, including estuaries, coastal bays, lagoons, reef-tops and open seas; deep subtidal through to shallow intertidal; and in tropical and temperate regions (McKenzie et al. 2021; McKenzie et al. 2020; Green and Short 2003; Carruthers et al. 2002). Their presence and species composition are determined by the biophysical landscape, including water temperature, salinity, desiccation, bottom current stress, light and water quality (Carter et al. 2021e; McKenzie et al. 2020; Jayathilake and Costello 2018). Availability of propagules, connectivity amongst meadows, and grazing pressure can also influence resilience, persistence, and biomass through time (Schlaefer et al. 2022; Scott et al. 2021). Seventy-two seagrass species from six families have been recorded worldwide (Short et al. 2011). In the tropics they often co-occur as mixes of species or communities (Jayathilake and Costello 2018; Short et al. 2011; den Hartog and Kuo 2006; Green and Short 2003).

Seagrasses are one of the key marine ecosystems in northern Australia, with extensive areas of seagrass mapped in the Great Barrier Reef lagoon and adjacent estuaries, Torres Strait, Gulf of Carpentaria, Northern Territory and the tropical Kimberley (Carter et al. 2021b; Carter et al. 2021a; Huisman et al. 2021; Carter et al. 2014; Roelofs et al. 2005; Green and Short 2003; Poiner et al. 1989). The ecosystem goods and benefits these seagrass communities provide include substrate stabilization and water quality improvements by filtering organic matter and microbes from the water, baffling wave and tidal energy which reduces suspended particulate matter and improving water clarity (Bainbridge et al. 2018; Lamb et al. 2017; Nordlund et al. 2016; Costanza et al. 2014). Seagrass meadows play a critical role as food and shelter for fish and crustaceans caught by recreational, traditional and commercial fishers (Hayes et al. 2020; Jänes et al. 2020b; Jänes et al. 2020a). They are also important carbon sinks, sequestering and capturing carbon in the sediments, helping to offset the impacts of carbon emissions(Macreadie et al. 2021) . They provide essential food for dugongs (*Dugong dugon*) and green sea turtles (*Chelonia mydas*) (Scott et al. 2020; Scott et al. 2018; Tol et al. 2016; Kelkar et al. 2013; Marsh et al. 2011). These species have significant spiritual, economic and ceremonial importance for the Traditional Owners and Custodians of Sea Country in the Gulf of Carpentaria and Torres Strait (Butler et al. 2012; Bradley 1997).

There is strong evidence that globally there has been a net decline in seagrass meadows in recent decades, particularly those influenced by coastal processes and human impact (Dunic et al. 2021; Turschwell et al. 2021; Waycott et al. 2009). Climate change-induced increases in water temperature, and frequency and severity of tropical storms, have the potential to exacerbate this decline (Carter et al. 2022; Serrano et al. 2021; Strydom et al. 2020). Critical to understanding the challenges marine ecosystems such as seagrass face around the world is access to reliable data at a range of spatial and temporal scales. This data can be used for assessing the present condition of ecosystems and for understanding long-term trends. It can be used to define the desired state of the diversity of habitats (Carter et al. 2022; Collier et al. 2020), establish ecologically relevant targets that can be used to maintain resilience (Lambert et al. 2021; Brodie et al. 2017), and to implement appropriate management frameworks that maintain resilience or promote recovery (O'Brien et al. 2017; York et al. 2017; Hallett et al. 2016; Levin and Möllmann 2015). The importance of incorporating spatial information into such data is increasingly recognised, with Geographic Information Systems (GIS) used to record, synthesize, and analyse spatial data and to inform research, conservation, ecosystem-based management, and marine spatial planning (Carter et al. 2021b; St. Martin and Hall-Arber 2008; St. Martin 2004).

Study location

The Gulf of Carpentaria on Australia's northern tropical coast is an extensive and low energy shallow semi-enclosed sea. It is characterised by complex, mangrove-lined creeks and estuaries and extensive seagrass meadows that grow along the coast (Duke et al. 2020; Wightman 2006; Roelofs et al. 2005; Poiner et al. 1987) (Figure 1). The Gulf includes three major island groups, the Wellesley Islands in the south-east, Sir Edward Pellew Group in the south-west, and the Anindilyakwa archipelago off the west coast. Seagrass grows around all these islands, which are known dugong habitat (Udyawer et al. 2021; Griffiths et al. 2020; Kyne et al. 2018; Marsh et al. 2008). There are several major river systems that flow into the Gulf of Carpentaria with most of the river flow restricted to the seasonal monsoon. The magnitude, intensity and timing of these flows are significant drivers of population dynamics of key fishery species including banana prawns, barramundi and mud crabs, and key habitats such as mangroves and seagrass (Plagányi et al. 2022; Rasheed and Unsworth 2011). There is a large industrial port at Weipa on the eastern coast, and smaller ports at Karumba in the south-east, Bing Bong in the south-west, and Alyangula (Milner Bay) on Groote Eylandt.

The Torres Strait is a shallow water body with a complex hydrodynamic environment between Queensland's Cape York Peninsula and Papua New Guinea (Wolanski et al. 2013; Saint-Cast 2008). The area covers more than 48,000 km^2 and is prone to high velocity tidal currents, with a large number of shoals, reefs and islands. There is little influence from river input to Torres Strait from the Australian coast, but the northern region is exposed to limited outflow from Papua New Guinea river systems (Waterhouse et al. 2021). Seagrass meadows are common throughout Torres Strait, but are most abundant in nearshore waters, on and surrounding reefs, and in subtidal waters in the western region (Carter et al. 2022; Carter and Rasheed 2016; Carter et al. 2014; Haywood et al. 2008). As in the Gulf of Carpentaria, these meadows provide critical habitat and food for fishery species, dugong and green turtle (Cleguer et al. 2016; Hagihara et al. 2016; Marsh and Kwan 2008). A segment of the Torres Strait Protected Zone and adjacent area was designated as a Dugong Sanctuary, in which all hunting of dugong is prohibited (https://www.legislation.gov.au/Details/F2007B00345).

While survey coverage was limited in the early years, Torres Strait and Gulf of Carpentaria seagrass research extends back to the 1970s (Bridges et al. 1982; Moriarty 1977). Data collection in a consistent manner and with a major spatial/mapping focus commenced in the early 1980s in the Gulf of Carpentaria (Poiner et al. 1987; Coles and Lee Long 1985), and early 2000s in Torres Strait (Scott and Rasheed 2021). Mapping and spatially-explicit monitoring projects since that time range from surveys quantifying seabed benthic cover across the entire Torres Strait and Gulf of Carpentaria, to more targeted seagrass assessments such as in Limmen Marine Park, western and eastern Torres Strait, to meadow-scale long term monitoring of reef tops and in the ports of Karumba, Weipa and Thursday Island, to small-scale transect-based monitoring led by rangers in Torres Strait ( ). Few of these spatial data sets are publicly available. Compiling spatial data has not previously occurred for the Gulf of Carpentaria and is not up-to-date for Torres Strait. There is a risk that older data is not secure and, if not compiled and validated, is in danger of being lost if not made available in a contemporary format or readily available to potential data users.

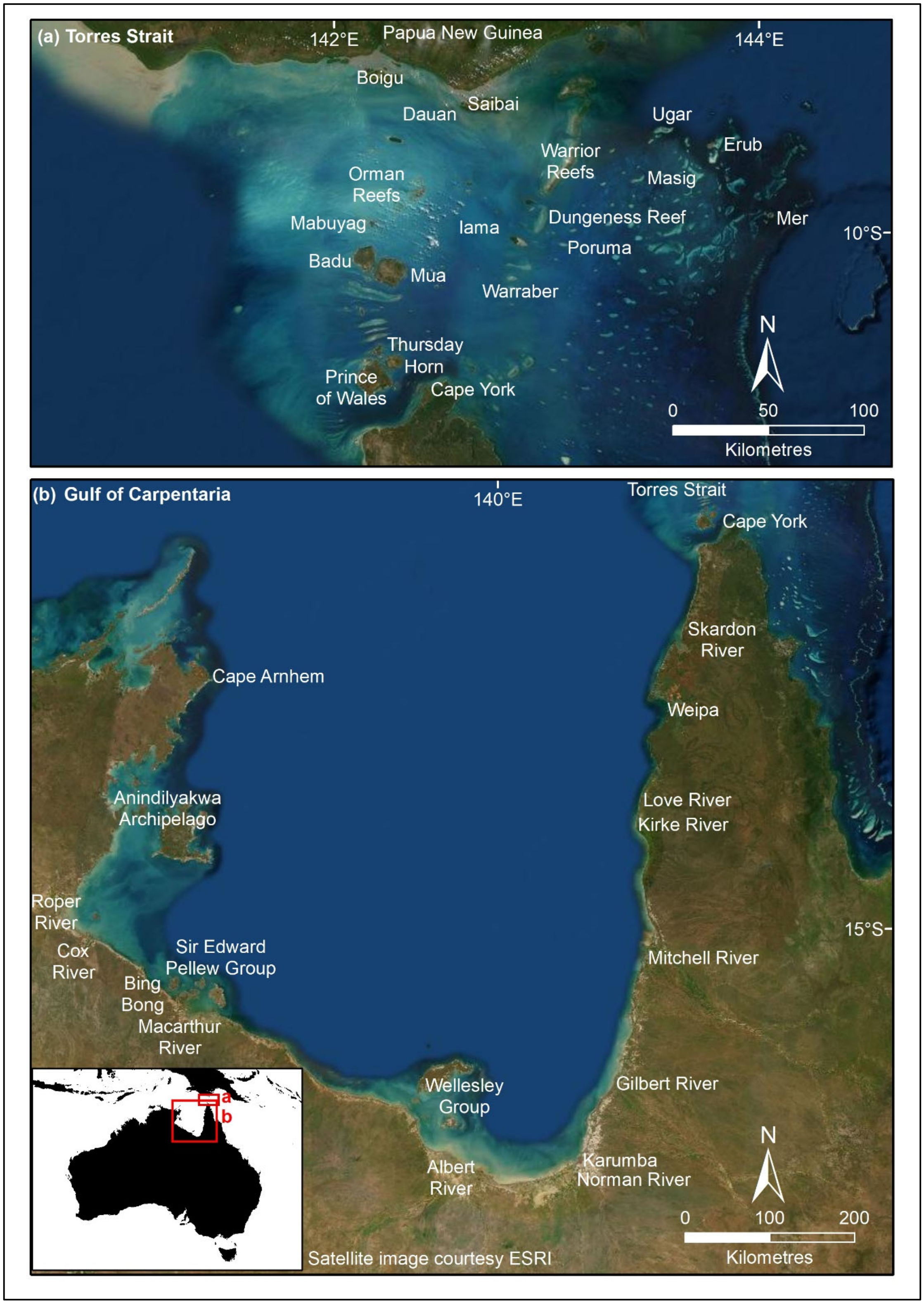

Figure 1 Survey area for (a) Torres Strait and (b) Gulf of Carpentaria.

Study approach

We compiled seagrass spatial data collected during surveys from 1983 to early 2022 in Torres Strait and the Gulf of Carpentaria (Table 1) into a standardised form with point-specific and meadow-specific spatial and temporal information. We revisited, evaluated, simplified, standardised, and corrected individual records, including those collected several decades ago by drawing on the knowledge of one of our authors (RG Coles) who led the early seagrass data collection and mapping programs. We also incorporate new data, such as from photo records of an aerial assessment of mangroves in the Gulf of Carpentaria in 2017 (Duke et al. 2020).

This project follows on from our previous work compiling 35 years of seagrass spatial point data and 30 years of seagrass meadow extent data for the Great Barrier Reef World Heritage Area (GBRWHA) and adjacent estuaries, funded through successive NESP Tropical Water Quality Hub Projects 3.1 (2015-2016) and 5.4 (2018-2020). Both projects are underpinned by the FAIR Data Principles - Findability, Accessibility, Interoperability, and Reusability - for scientific data management and stewardship (Wilkinson et al. 2016). Both data sets are publicly available through the eAtlas data portal; the GBRWHA data set here: https://doi.org/10.25909/y1yk-9w85 (Carter et al. 2021b) and the Torres Strait and the Gulf of Carpentaria data produced for this project here: https://doi.org/10.26274/2CR2-JK51.

Our objective for the present project was to:

(1) Collate seagrass information for Torres Strait and the Gulf of Carpentaria using the standardised approach developed for the Great Barrier Reef data compilation so that the data is compatible and comparable, and

(2) Provide these extensive seagrass data sets, along with an interactive website (eAtlas), as a long-term spatial resource for management agencies, rangers, Traditional Owners, ports, industry, and researchers to interrogate seagrass and seagrass species distributions and to benchmark trends through time.

Methods

Data sets

We compiled spatial data from seagrass surveys conducted between 1983 and 2022. Data custodians include TropWATER JCU, TSRA, CSIRO Oceans and Atmosphere, Mabunji Aboriginal Resource Indigenous Corporation, Northern Territory Department of Environment, Parks and Water Security, North Queensland Bulk Ports, PortsNorth, and the Department of Agriculture, Water and Environment.

Data was limited to that collected in the Gulf of Carpentaria between Cape Arnhem (Northern Territory) and Cape York (Queensland). Torres Strait data was restricted to north of Queensland's Great Barrier Reef World Heritage Area boundary, and includes data collected along the Papua New Guinea coastline (Figure 1). Data were originally collected for five major purposes (Table 1):

(1) Region-scale mapping conducted by CSIRO and the Northern Territory and Queensland governments;
(2) Torres Strait seagrass monitoring including small-scale transect (3 x set transects within a 50 x 50 m area) and block-based monitoring (random camera drops within 3 x ~350 ha survey blocks) by rangers, and meadow-scale monitoring by TropWATER, James Cook University;
(3) Targeted mapping projects such as for Parks Australia, the Torres Strait Regional Authority, and various Port Authorities;
(4) Long-term seagrass monitoring for Queensland ports (Karumba, Weipa, Thursday Island) that were generally conducted annually;
(5) Incidental seagrass data collected during other monitoring activities.

(3) The data were collected using a variety of survey methods to describe and monitor seagrass sites and meadows. For intertidal sites/meadows, these include walking, observations from helicopters in low hover, and observations from hovercraft when intertidal banks were exposed. For subtidal sites/meadows, methods included free diving, scuba diving, video transects from towed cameras attached to a sled with/without a sled net, video drops with filmed fixed-size quadrats, trawl and net samples, and van Veen grab samples. These methods were selected and tailored by the data custodians to the location, habitat surveyed, and technology available. Important site and method descriptions and contextual information is contained in the original trip reports and publications for each data set provided in Table 1. For long-term monitoring data only the most recent report is referenced.

Table 1 Survey purpose and location of spatial data used in seagrass data compilation, 1983 - 2022.

Survey purpose/ Data location	**Year/s**	**Site (S) Meadow (M)**	**Reference**
(1) Region-scale baseline surveys			
Gulf of Carpentaria intertidal seagrass	2004	S, M	Roelofs et al. (2005)
Gulf of Carpentaria seagrass	1986	S, M	Coles et al. (2004)
Torres Strait inter-reefal benthic assemblages	2005	S	Haywood et al. (2008)

(2) Torres Strait seagrass monitoring			
Dungeness Reef intertidal	2016-2021	S, M	Carter et al. (2021f)
Dungeness Reef subtidal	2017-2022	S	Carter et al. (2021f)
Orman Reef intertidal	2017-2021	S, M	Carter et al. (2021f)
Orman Reef subtidal	2017-2022	S	Carter et al. (2021f)
Masig Island intertidal	2020-2021	S, M	Carter et al. (2021f)
Dugong Sanctuary subtidal	2011-2022	S	Carter et al. (2021f)
Poruma Island PM1	2016-2022	S	Carter et al. (2021f)
Poruma Island PM2	2016-2022	S	Carter et al. (2021f)
Iama Island IM1	2010-2022	S	Carter et al. (2021f)
Iama Island IM2	2010-2022	S	Carter et al. (2021f)
Mer Island MR1	2009-2022	S	Carter et al. (2021f)
Mer Island MR2	2009-2022	S	Carter et al. (2021f)
Mua Island MU1	2011-2022	S	Carter et al. (2021f)
Mua Island MU3	2011-2022	S	Carter et al. (2021f)
Mabuyag Island MG1	2009-2021	S	Carter et al. (2021f)
Mabuyag Island MG2	2009-2021	S	Carter et al. (2021f)
Badu Island BD1	2010-2022	S	Carter et al. (2021f)
Badu Island BD2	2010-2022	S	Carter et al. (2021f)
(3) Targeted seagrass mapping surveys			
Torres Strait - Dungeness Reef subtidal	2017	S, M	Carter et al. (2017)
Torres Strait - North-West and PNG	2015-2016	S, M	Carter and Rasheed (2016)
Torres Strait - Eastern Cluster	2020	S, M	Carter et al. (2021d)
Torres Strait - Northern Dugong Sanctuary and Orman Reefs	2020	S, M	Carter et al. (2021c)
Torres Strait - Dugong Sanctuary	2010	S, M	Taylor and Rasheed (2010b)
Limmen Bight Marine Park and Limmen Marine Park	2021	S, M	Collier et al. (in prep)
Torres Strait - Ugar Island and surrounding reefs	2022	S, M	Reason et al. (in prep)
GOC - Love River	1999	S, M	Rasheed (2000)
GOC - Wellesley Islands	1983-1984, 2007	S, M	Taylor et al. (2007); Coles and Lee Long (1985)
GOC - Port Musgrave	2009-2010	S, M	Chartrand and Rasheed (2010)
GOC - Boyd Bay	2007-2008	S, M	Rasheed and Unsworth (2008)
GOC - Skardon River	2002, 2003, 2010	S, M	Thomas and Chartrand (2010); Roelofs et al. (2004); Roelofs et al. (2002)
GOC - Kirke River	1999, 2001	S, M	Sheppard et al. (2001); Rasheed (2000)
Torres Strait - Badu Island	2010	S, M	Taylor and Rasheed (2010a)
Torres Strait – Mua/Moa Island	2011	S, M	Taylor (2011)
Torres Strait - Mabuyag Island	2009	S, M	Chartrand et al. (2009)

Torres Strait - Orman Reefs	2004	S, M	Rasheed et al. (2008); Rasheed et al. (2006a)
Torres Strait - Prince of Wales and Adolphus Shipping Channels	2002-2006	S, M	Rasheed et al. (2006b)
Torres Strait - Poruma to Ugar Islands	2008	S, M	Taylor et al. (2008)
Torres Strait - Kirkcaldie Reef to Bramble Cay	2009	S, M	Taylor et al. (2009)
Torres Strait - Moa Island to Mabuiag Island	2010	S, M	Taylor et al. (2010)
Torres Strait - No. 2 Reef to Mabuiag Reef	2011	S, M	Taylor et al. (2011)
Torres Strait - Woiz Reef to Kaliko Reef	2012	S, M	Taylor and McKenna (2012)
Torres Strait - Seo Reef to Kai-Wareg Reef	2013	S, M	Carter et al. (2013)
(4) Queensland ports seagrass monitoring			
Karumba	1994-2021	S, M	Scott et al. (2022)
Weipa	2000-2021	S, M	McKenna et al. (2021)
Thursday Island	2002-2021	S, M	Scott and Rasheed (2021)
(5) *Other surveys (incidental seagrass data)*			
Torres Strait sea cucumber surveys	2000-2010	S	Murphy et al. (2010); Skewes et al. (2010)
Torres Strait rock lobster surveys	2000-2014	S	Plaganyi-Lloyd et al. (2016)
Gulf of Carpentaria mangrove monitoring	2017	S	Duke et al. (2020)

Taxonomy

Seagrass taxonomic revision over the last couple of decades has resulted in the revision and reclassification of some tropical species. For example, *Zostera capricorni* has been reclassified as *Zostera muelleri* subsp. c*apricorni*, *Halophila minor* a synonym of *Halophila ovalis*, and *Halodule pinifolia* a synonym of *Halodule uninervis*. Field surveys have at times grouped species that are difficult to distinguish in the field. To address these issues, we amalgamated some species into complexes: *Halophila minor* and *Halophila ovalis* are included as *Halophila ovalis* complex. *Zostera muelleri* subsp. *capricorni* has been abbreviated to *Zostera capricorni* throughout for simplicity.

Geographic Information System (GIS)

Mapping data for historic records (1980s) were transcribed from original logged and mapped data based on coastal topography, dead reckoning fixes and RADAR estimations. More recent data (1990's onwards) is GPS located. All spatial data were converted to shapefiles with the same coordinate system (GDA 1994 Geoscience Australia Lambert), then compiled into a single point shapefile and a single polygon shapefile (seagrass meadows) using ArcMap (ArcGIS version 10.8 Redlands, CA: Environmental Systems Research Institute, ESRI). Some early spatial data was offset by several hundred metres and where this occurred data was repositioned to match the current coastline projection. The satellite base map used throughout this report is a courtesy from ESRI 2022.

Seagrass site layer

This layer contains information on data collected at assessment sites, and includes:

1. Temporal survey details – Survey month and year;
2. Spatial position - Latitude/longitude;
3. Survey name;
4. Depth for each subtidal site is m below mean sea level (MSL). Depth for each site was extracted from the Australian Bathymetry and Topography Grid, June 2009 (Whiteway 2009). This approach was taken due to inconsistencies in depth recordings among data sets, e.g. converted to depth below MSL, direct readings from depth sounder with no conversion, or no depth recorded. Depth for intertidal sites was recorded as 0 m MSL, with an intertidal site defined as one surveyed by helicopter, walking, or hovercraft when banks were exposed during low tide;
5. Seagrass information including presence/absence of seagrass, total number of species recorded at a site, and whether individual species were present/absent at a site;
6. Dominant sediment type - Sediment type in the original data sets were based on grain size analysis or deck descriptions. For consistency, in this compilation we include only the most dominant sediment type (mud, sand, shell, rock, rubble), removed descriptors such as “fine”, “very fine”, “coarse”, etc., and replaced redundant terms, e.g. “mud” and “silt” are termed “mud”;
7. Survey methods – In this compilation we have updated and standardised the terms used to describe survey methods from the original reports; and
8. Data custodians.

Seagrass meadow layer

The seagrass meadow layer is a composite of all the spatial polygon data we could access where meadow boundaries were mapped as part of the survey. All spatial layers were compiled into a single spatial layer using the ArcToolbox ‘merge’ function in ArcMap. Where the same meadow was surveyed multiple times as part of a long-term monitoring program (e.g. Figure 2), the overlapping polygons were compiled into a single polygon using the ‘merge’ function in ArcMap. Meadow data includes:

1. Temporal survey details – Survey month and year, or a list of survey dates for meadows repeatedly sampled;
2. Survey methods;
3. Meadow persistence – Classified into three categories (unknown, enduring, transitory).
    a. **Unknown** – Unknown persistence as the meadow was surveyed less than five times;
    b. **Enduring** – Seagrass is present in the meadow ≥90% of the surveys. This threshold was selected because it allows for an average of one significant environmental impact to seagrass meadows to occur every 10 years (e.g. tropical cyclone or significant flood), thereby allowing for decadal-scale cycles of seagrass loss and recovery typical in tropical seagrass systems that occur even in enduring meadows (Carter et al. 2022);
    c. **Transitory** – Seagrass is present in the meadow <90% of the surveys;
4. Meadow depth – Classified into three categories:
    a. **Intertidal** – Meadow was mapped on an exposed bank during low tide, e.g. Karumba monitoring meadow;
    b. **Subtidal** – Meadow remains completely submerged during spring low tides, e.g. Dugong Sanctuary meadow;

   c. **Intertidal-Subtidal** – Meadow includes sections that expose during low tide and sections that remain completely submerged, e.g. meadows adjacent to the Thursday Island shipping channel;
5. Dominant species of the meadow based on the most recent survey;
6. Presence or absence of individual seagrass species in a meadow;
7. Meadow density categories – Seagrass meadows were classified as light, moderate, dense, or variable based on the consistency of mean above-ground biomass of the dominant species among all surveys, or percent cover of all species combined (Table 2). For example, a *Halophila ovalis* dominated meadow would be classed as "light" if the mean meadow biomass was always <1 gram dry weight m^{-2} (g DW m^{-2}) among years, "variable" if mean meadow biomass ranged from <1 - >5 g DW m^{-2}, and "dense" if mean meadow biomass was always >5 g DW m^{-2} among years. For meadows with density assessments based on both percent cover (generally from older surveys) and biomass, we assessed density categories based on the biomass data as this made the assessment comparable to a greater number of meadows, and comparable to the most recent data. Meadows with only one year of data were assigned a density category based on that year but no assessment of variability could be made;
8. Mean meadow biomass range measured in g DW m^{-2} ($\pm$ standard error if available), or the mean meadow biomass if surveyed once;
9. Mean meadow percent cover range, or the mean meadow percent cover if surveyed once;
10. Meadow area (hectares; ha) of each meadow was estimated in the GDA 1994 Geoscience Australia Lambert projection using the 'calculate geometry' function in ArcMap. For meadows that were mapped multiple times, meadow area represents the total extent for all surveys;
11. Meadow area range for meadows surveyed more than once. Where possible, we retained area range data reported in the original shapefiles (and calculated using original projections). Where area data did not exist in original shapefiles (e.g. 1986 Gulf of Carpentaria surveys; Coles et al. (2004)), we calculated area using the 'calculate geometry' function in ArcMap in the GDA 1994 Geoscience Australia Lambert projection;
12. Data custodians.

Table 2: Seagrass meadow density categories based on ranges in mean percent cover, or mean above-ground biomass (grams dry weight m^{-2}) of the dominant species.

Density category	***Percent cover***	***Above-ground g DW m^{-2}***					
	All species	*H. uninervis* (narrow)*	*H. ovalis* *H. decipiens* *H. capricorni*	*H. uninervis* (wide)* *C. serrulata* *C. rotundata* *S. isoetifolium* *T. hemprichii*	*H. spinulosa* *H. tricostata*	*Z. capricorni*	*E. acoroides* *T. ciliatum*
Light	1-10%	<1	<1	<5	<15	<20	<40
Moderate	>10 – 50%	1 - 4	1 - 5	5 - 25	15 - 35	20 - 60	40 - 100
Dense	>50%	>4	>5	>25	>35	>60	>100
Variable		<1 - >4	<1 - >5	<5 - >25	<15 - >35	<20 - >60	<40 - >100

**Halodule uninervis* occurs as narrow and wide leaf morphologies. These are not differentiated in the site or meadow GIS layers, but are when calculating seagrass density

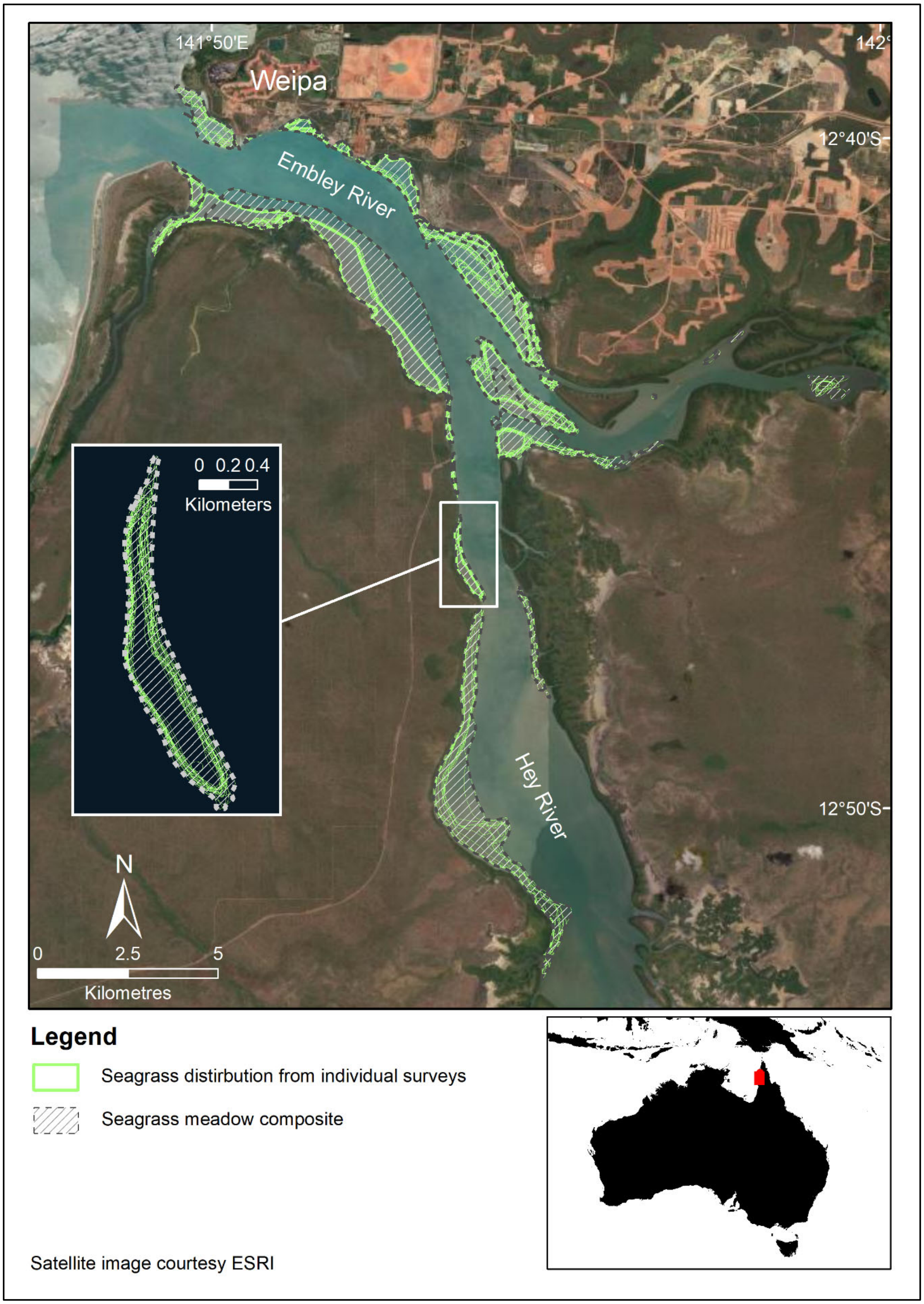

Figure 2 Example of multiple meadows surveyed over consecutive years in Weipa, 1986 – 2021. Green lines indicate the extent of each polygon from each survey year and grey hash and black line (inset) indicates resulting merged (composite) meadow.

Data age, limitations, and variability

The data included extends back to the early 1980s. Large parts of the coast have not been mapped for seagrass presence since that time (Figure 3). Technology and methods for mapping and position fixing have improved dramatically in 40 years. Early data included here has been re-checked and re-entered on several occasions and previously included in other spatial platforms (Carter et al. 2014; McKenzie et al. 2014). For early data (1980's and 1990's), each data point was reviewed and compared with original trip logs and recollections of trip participants, where possible, and we have only included point and polygon (meadow) data in this report where we are confident that they represent the most reliable interpretation of that early data. Since the original surveys in the 1980's there have been changes to the shoreline, the most obvious being movement of mangrove forests and shoreline alterations for port development and access. We have not edited seagrass point or meadow layers to prevent older data from overlapping these features.

Seagrass data came from a variety of surveys conducted for different purposes. Early seagrass data mostly comes from broad-scale vessel-based surveys. This has been built on in recent times by helicopter based intertidal surveys along the coasts, and extensive boat and helicopter surveys in the Torres Strait, eastern Gulf of Carpentaria, and in Limmen Bight. Three ports in our area of our study - Thursday Island, Weipa, Karumba - have been surveyed annually for more than 20 years. Seagrass monitoring data from the port at Alyangula (Groote Eylandt) could not be accessed for this project. Data from Torres Strait Rangers' intertidal monitoring at Badu, Mabuyag, Mua, Iama, Poruma and Mer Islands is comprehensive over time, with surveys occurring up to four times in a year, but the data included here is not spatially resolved beyond a single latitude/longitude to identify the 50 m x 50 m area where three replicate transects are surveyed. This is also the case for the Torres Strait Ranger's subtidal monitoring; in some cases only the starting latitude/longitude are included for the 10 quadrats surveyed.

Data sets with large temporal and spatial coverage all have some survey-specific limitations and nuances beyond what can easily be described in this report. For example, seagrasses may form transitory meadows (Kilminster et al. 2015), where seagrass presence and species composition fluctuate over time. Most seagrass data included here was collected during the seagrass growing season, but annual species like *Halophila decipiens* and *Halophila ovalis* may not be present for considerable parts of the year during the senescent season (Chartrand et al. 2017; York et al. 2015). This is important to understand if this data is used to compare annual changes in seagrass distribution. We recommend checking the survey month in the data sets, and contacting the data custodians (listed in the shapefile attribute tables, and in Table 1) when using this data to ensure those limitations are understood.

Significant differences in seagrass distribution and species presence can occur between high rainfall La Niña years and drier El Niño periods depending on location (Carter et al. 2022; Lambert et al. 2021; Rasheed and Unsworth 2011). Work in Weipa where long-term monitoring is undertaken has highlighted that decadal cycles of daytime tidal exposure can have major impacts on seagrass condition (Unsworth et al. 2012), and nearly 30 years of seagrass monitoring in Karumba has shown seagrass condition is strongly linked to rainfall and flooding of local rivers (Rasheed and Unsworth 2011). It is important to understand the implications these cycles have on seagrass state, including lag times and recovery responses for different seagrass species. These cycles, while the result of natural phenomena, have implications for the animals that rely on seagrass meadows for shelter and food, including turtles (Flint et al. 2017; Flint et al. 2015) and dugong (Wooldridge 2017; Flint and Limpus 2013).

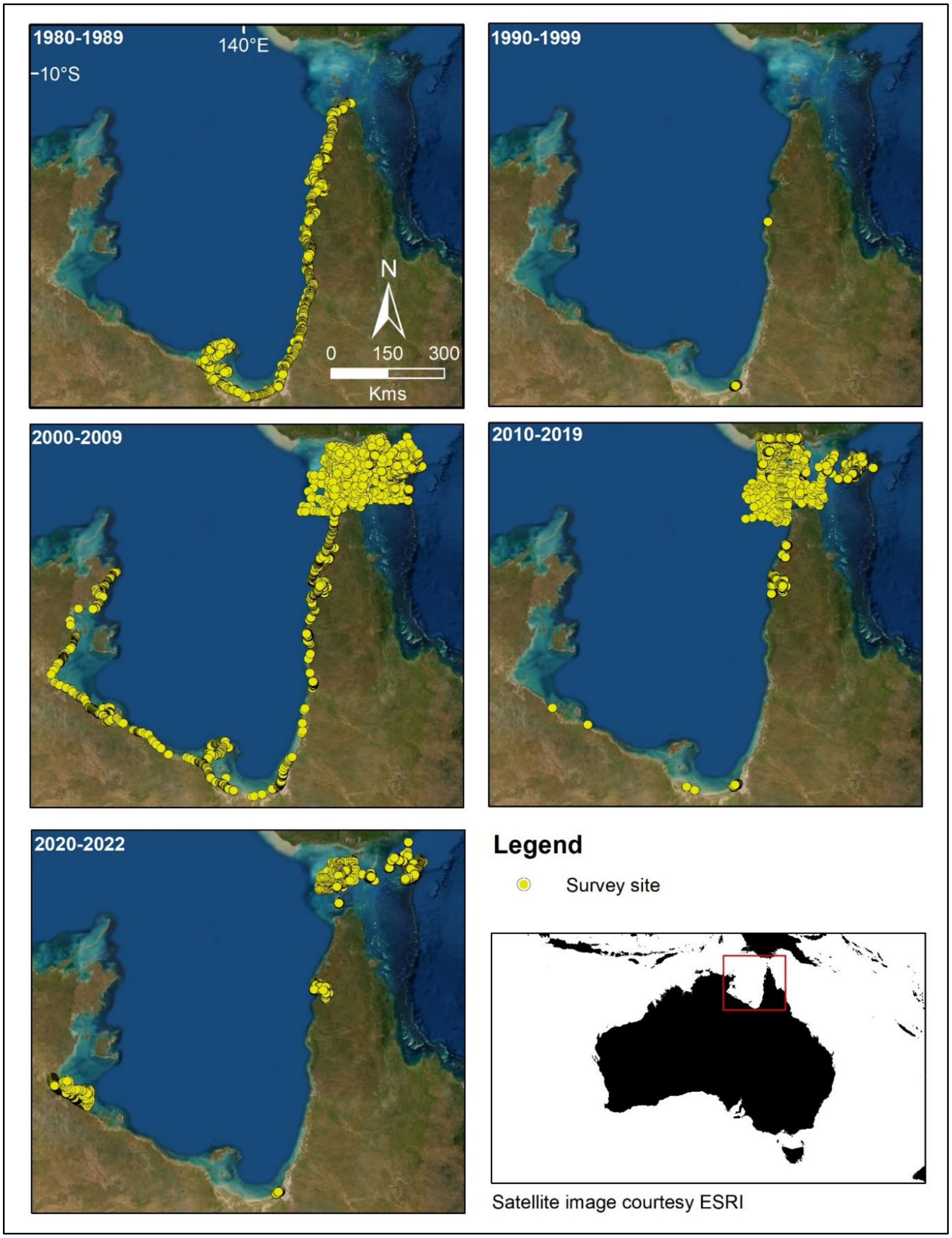

Figure 3 Distribution of survey sites (yellow dots) throughout Torres Strait and the Gulf of Carpentaria in 10-year increments, 1983 – 2022

Data exclusions

Our synthesis excluded several historical data sets to ensure that the information we present is as accurate as possible and all data custodians agreed to publication. Data were excluded for the following reasons:

1. The survey data from published reports was lost over the years. This includes the extensive spatial data collected between Crab Island (western Cape York) and Cape Arnhem in 1982 – 1984 and is only available as a published figure (Poiner et al. 1989; Poiner et al. 1987).
2. We were unable to establish that the information was verified at the time of collection. For example, data were excluded from recent field observations taken during mangrove surveys in the Gulf of Carpentaria (Duke et al. 2020) where aerial photographs with spatial information were taken of likely seagrass meadows but no sample was taken to verify this, or spatial information was not available for photographs (Figure 4).
3. Permission for public distribution from all data custodians was not provided.
4. Published seagrass meadow information and online data sets with insufficient metadata for us to include. Examples include data compiled by the United Nations Environment World Conservation Monitoring Centre (https://data.unep-wcmc.org/datasets/7) and CSIRO's Coastal and Marine Resources Information System (https://data.csiro.au/collections/collection/CIcsiro:12640v1).

Figure 4 Likely seagrass meadows photographed during mangrove surveys (Duke et al. 2020) in the Gulf of Carpentaria

Results

Seagrasses of Torres Strait and the Gulf of Carpentaria

In total, the site data set has 48,612 data points (Figure 5), and the meadow data set has 641 individual polygons (Figure 6) surveyed in Torres Strait and the Gulf of Carpentaria between 1983 and 2022. The data is heavily skewed to intertidal seagrass, with 75% of sites surveyed by helicopter, hovercraft or walking. Subtidal waters were surveyed to a depth of -97 m MSL but seagrass was not recorded deeper than -38 m MSL (*H. spinulosa* and *H. decipiens*).

Information on 13 seagrass species from three families are included in the data (Figure 7). These are:

- *Cymodocea rotundata* (Ascherson & Schweinfurth, 1870),
- *Cymodocea serrulata* ((R.Brown) Ascherson & Magnus 1870),
- *Enhalus acoroides* ((Linnaeus f.) Royle, 1839),
- *Halophila capricorni* (Larkum, 1995),
- *Halophila decipiens* (Ostenfeld, 1902),
- *Halophila ovalis* ((R.Brown) J. D. Hooker, 1858),
- *Halophila spinulosa* ((R.Brown) Ascherson, 1875),
- *Halophila tricostata* (Greenway),
- *Halodule uninervis* ((Forsskål) Ascherson, 1882),
- *Syringodium isoetifolium* ((Ascherson) Dandy, 1939),
- *Thalassodendron ciliatum* ((Forssk.) Hartog, 1976),
- *Thalassia hemprichii* ((Ehrenberg) Ascherson, 1871),
- *Zostera muelleri* subsp. *capricorni* ((Ascherson) S. W. L. Jacobs, 2006).

Seagrass distribution varied among species (Figure 8 and Figure 9). *Cymodocea serrulata* and *Cymodocea rotundata* were common throughout Torres Strait but with limited distribution in the Gulf of Carpentaria to the Wellesley and Sir Edward Pellew Islands (*C. rotundata*) and Limmen Bight Marine Park (*C. serrulata*). *Enhalus acoroides* was patchily distributed throughout the area, with high densities around Weipa and the continental islands between Cape York and Papua New Guinea. *Halophila decipiens* was common in subtidal seagrass meadows in western Torres Strait, along the west Cape York coast, and limited points in the southern and western Gulf of Carpentaria, while *Halophila ovalis and Halodule uninervis* were common throughout Torres Strait and the Gulf. *Syringodium isoetifolium* and *Halophila spinulosa* were common throughout Torres Strait, and patchier in the southern Gulf of Carpentaria around Limmen Bight Marine Park and the Wellesley Islands. *Thalassia hemprichii* distribution was largely restricted to Torres Strait, Cape York and Weipa, while *Thalassodendron ciliatum* and *Zostera capricorni* were found only in Torres Strait. *Halophila capricorni* and *Halophila tricostata* were limited to only a few occurrences in the data set.

This analysis includes 1,464,981 hectares of seagrass as a composite of all years (the maximum extent of all years (1984 – 2022) merged) (Figure 6). The seagrass distribution recorded in this composite was predominately located in intertidal-shallow subtidal areas of the coastline. The most comprehensive seagrass surveys that extend into deeper subtidal waters were conducted in the Torres Strait Dugong Sanctuary (to -30 m MSL), the Limmen Marine Park (to -25m MSL), and CSIRO seabed biodiversity and sea cucumber surveys in eastern Torres Strait (to -97 m MSL). Outside of these surveys, the extent of subtidal deep seagrass remains unknown. This bias in seagrass data collected from relatively accessible coastal areas reflects the logistical difficulties and costs in surveying offshore deeper waters, and is a common problem in seagrass data sets (Carter et al. 2022; Carter et al. 2021b).

The Torres Strait region had the largest distribution of seagrass, the most diverse seagrass meadows, and the largest single continuous composite meadow: 954,075 ha (Figure 10). The 2010 survey of the Torres Strait Dugong Sanctuary mapped the largest single continuous meadow of 875,244 ha (Taylor and Rasheed 2010b). More recent surveys (2020) of the north-eastern section of the Dugong Sanctuary found that this large meadow had been reduced to relatively small patches of seagrass of low-biomass species (Carter et al. 2021c).

For the rest of the study area, seagrass meadows were almost entirely restricted to inshore islands, small bays, and estuaries, with large gaps of open bare substrate between seagrass meadows. In the Gulf of Carpentaria, *Halodule uninervis* and *Halophila* species dominated most individual seagrass meadows. Significant areas of seagrass have been mapped around the Mornington and Wellesley Islands, and the Sir Edward Pellew Islands (Yanyuwa Indigenous Protected Area). These areas were also dominated by *Halodule uninervis* and *Halophila* species. Of note is a large meadow (24,341 ha) dominated by *Syringodium isoetifolium* in the Limmen Bight Marine Park, mapped in 2021. This meadow had up to six species of seagrass in it.

Where dedicated long-term monitoring programs exist in Torres Strait, Weipa and Karumba, extensive information is available on the distribution, density, and persistence of seagrass meadows. Figure 2 demonstrates at least 30 surveys that have occurred in the port of Weipa between 1986 and 2021, most of these surveys completed as part of a long-term monitoring program. Outside of these extensively monitored areas, temporally resolved information on seagrass, particularly in the Gulf of Carpentaria.

Data availability

Data, metadata, and the interactive website are available under a Creative Commons 4.0 License at on eAtlas (https://doi.org/10.26274/2CR2-JK51). We intend this data to be used as a stand-alone product or integrated with other publicly available seagrass data (Carter et al. 2021b) and biophysical data sets and models to explain distributions and change.

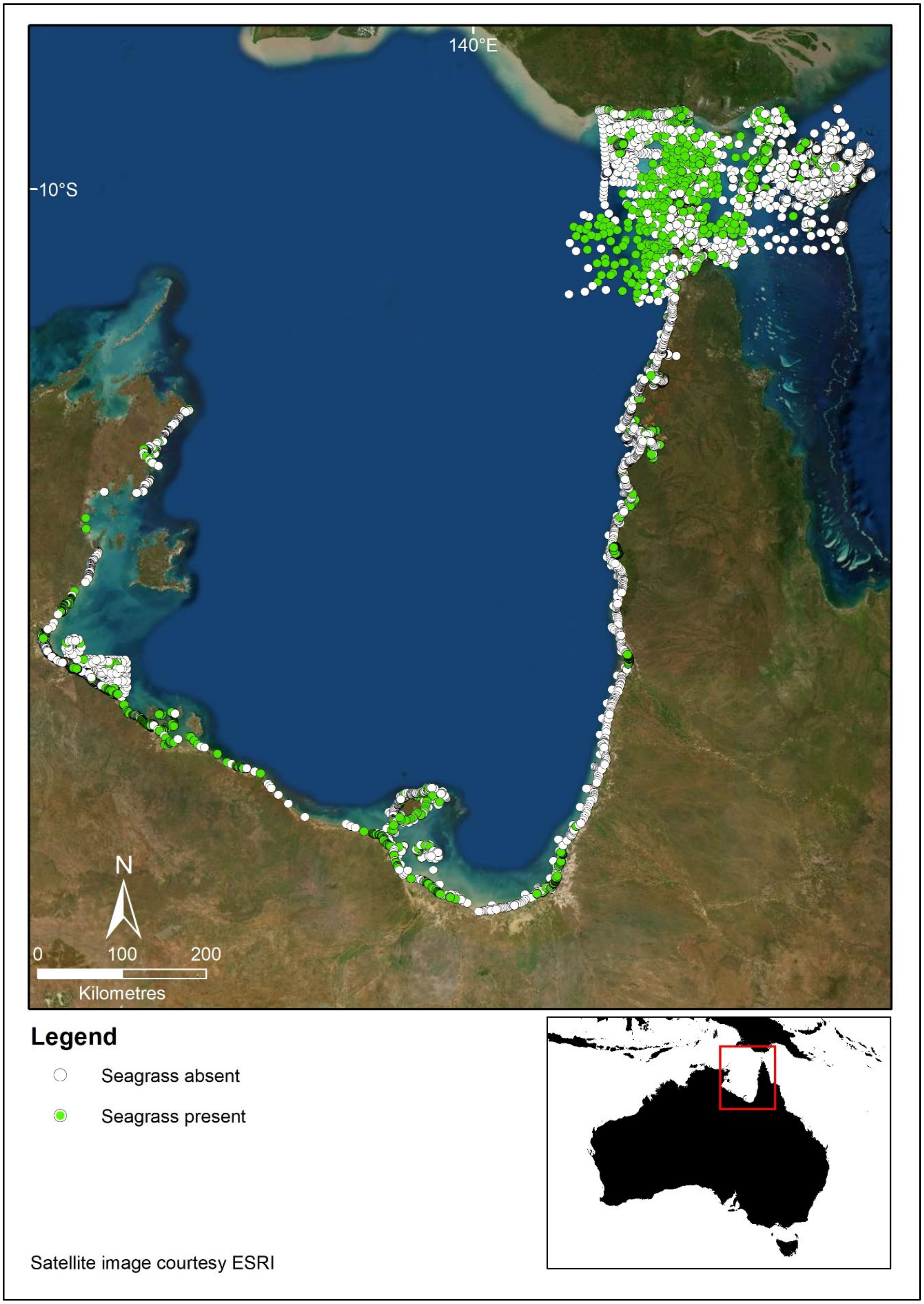

Figure 5 Seagrass presence and absence at individual survey sites across Torres Strait and the Gulf of Carpentaria, 1983 – 2022

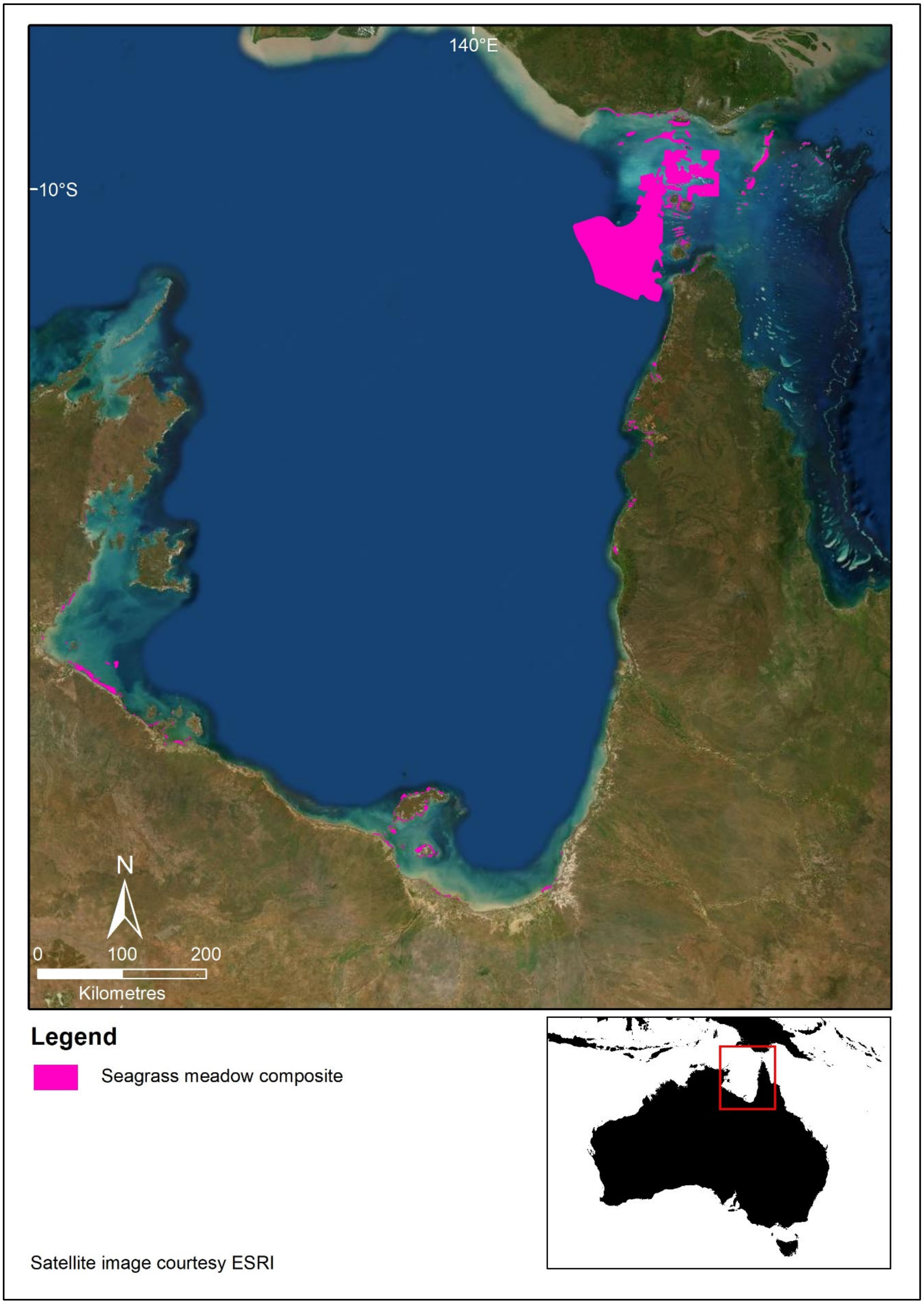

Figure 6 Seagrass meadows across Torres Strait and the Gulf of Carpentaria, 1984 – 2022

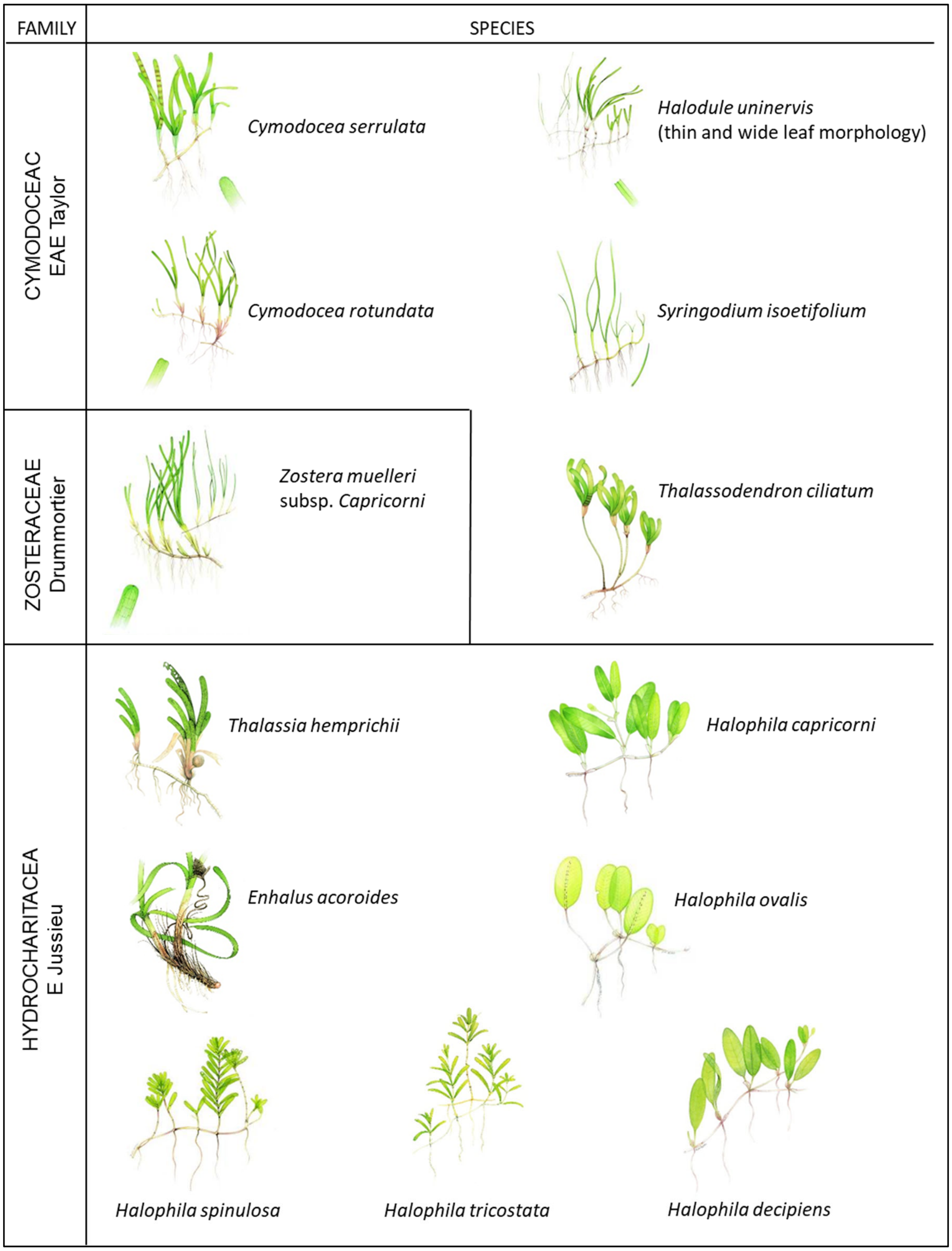

Figure 7 Seagrass species recorded within Torres Strait and the Gulf of Carpentaria, 1983 – 2022

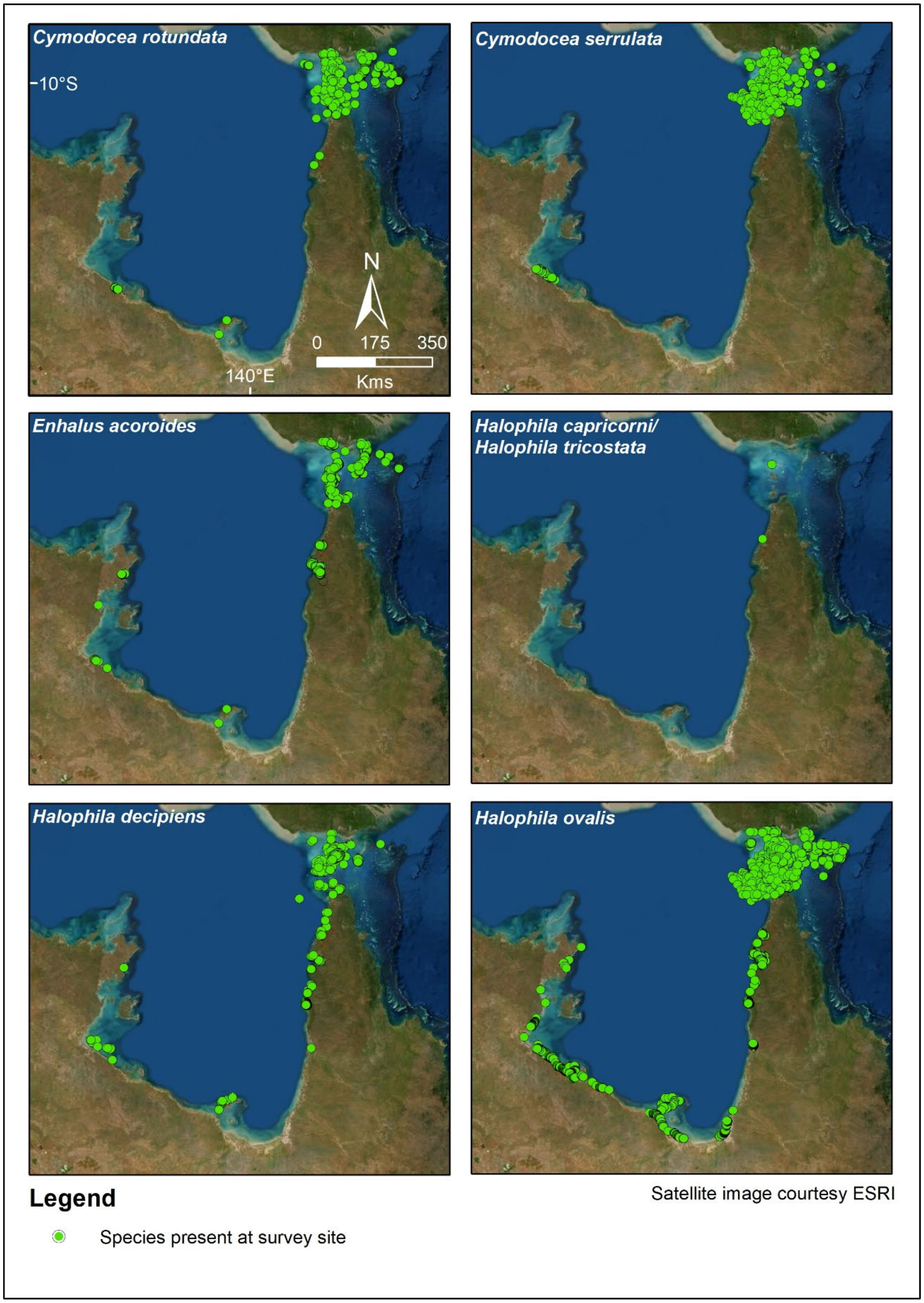

Figure 8 Distribution of *Cymodocea serrulata*, *Cymodocea rotundata*, *Enhalus acoroides*, *Halophila capricorni*, *Halophila tricostata*, *Halophila decipiens* and *Halophila ovalis* (green dots) throughout Torres Strait and the Gulf of Carpentaria in the site data synthesis, 1983 – 2022

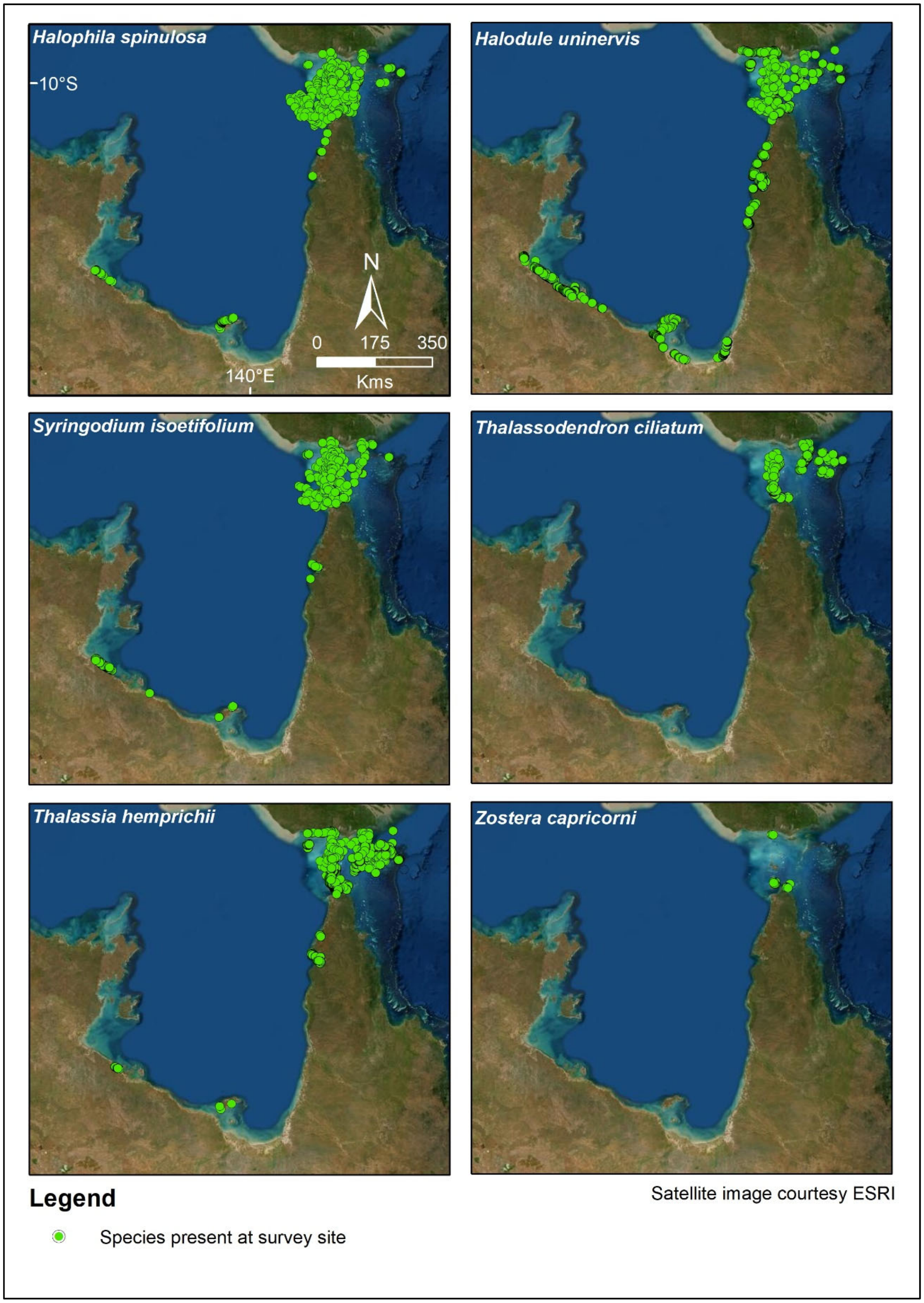

Figure 9 Distribution of *Halophila spinulosa*, *Halodule uninervis*, *Syringodium isoetifolium*, *Thalassodendron ciliatum*, *Thalassia hemprichii* and *Zostera capricorni* in our data set (green dots) throughout Torres Strait and the Gulf of Carpentaria observed in the site data synthesis, 1983 – 2022

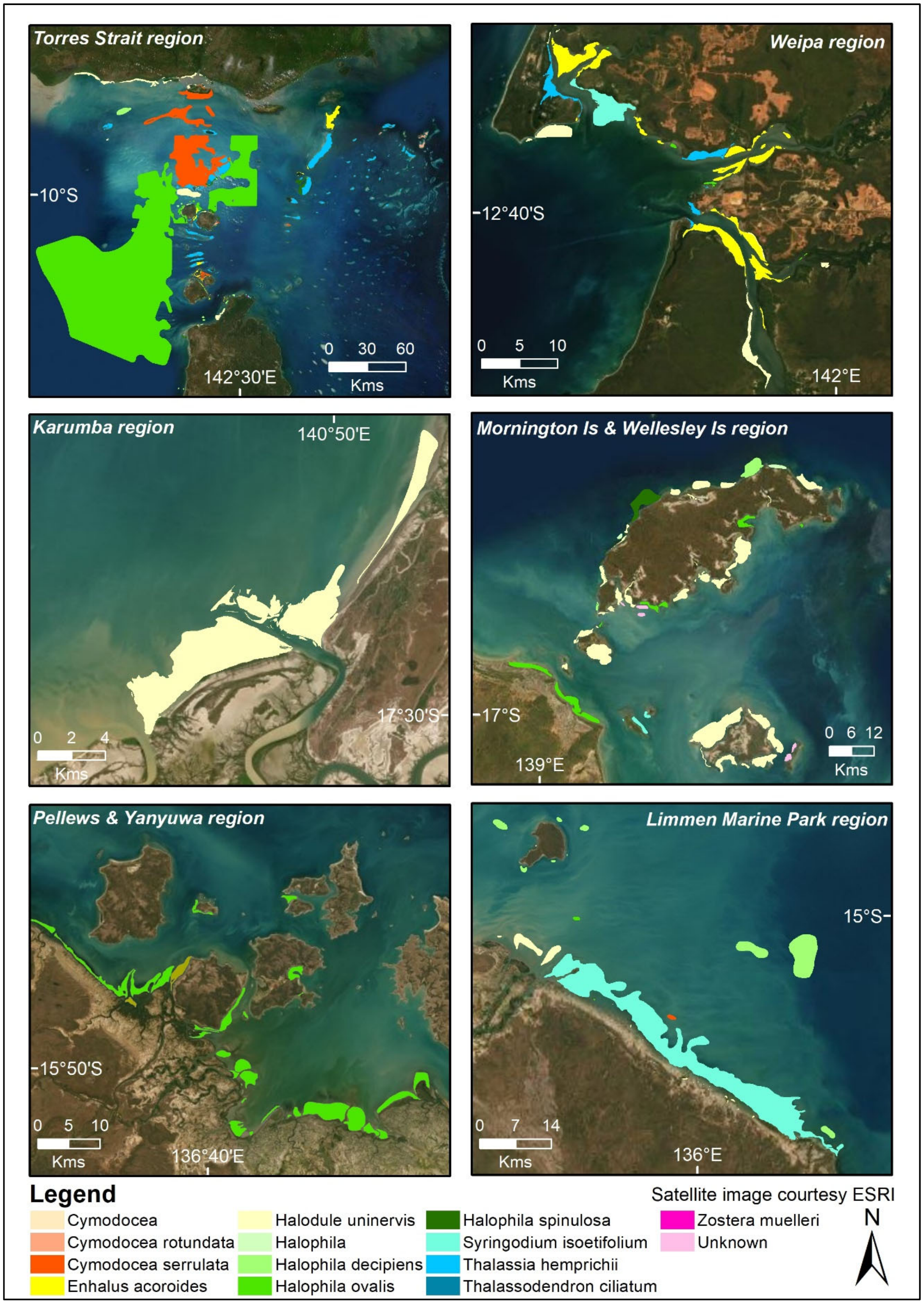

Figure 10 Dominant species in seagrass meadows at a selection of locations in Torres Strait and Gulf of Carpentaria.

Applications and Recommendations

This project adds to, and makes publicly available, a comprehensive tropical seagrass data set for northern Australia. We include location information not just for sites that were surveyed, and seagrass recorded, but also location information where surveys did not find seagrass. The management and conservation of marine ecosystems requires accurate spatial data at scales that match human activities and impacts (Lagabrielle et al. 2018; Visconti et al. 2013; Halpern et al. 2008; Hughes et al. 2005). A key strategy to assist this at a global scale is to ensure data is validated and reliable despite being collected over the years or decades (Rajabifard et al. 2005). By building on our previous work compiling 35 years of seagrass spatial site data and 30 years of seagrass meadow data for the GBRWHA and adjacent estuaries (Carter et al. 2021b), we provide a synthesis that can be used to inform marine spatial planning, ecosystem based management, research, and education for a large part of northern Australia (Figure 11). By ensuring consistency in the structure of both point and polygon (meadow) data sets for the Great Barrier Reef and this project, and making these publicly available on eAtlas, we provide a mechanism for additional data to be added, archived, and easily compared.

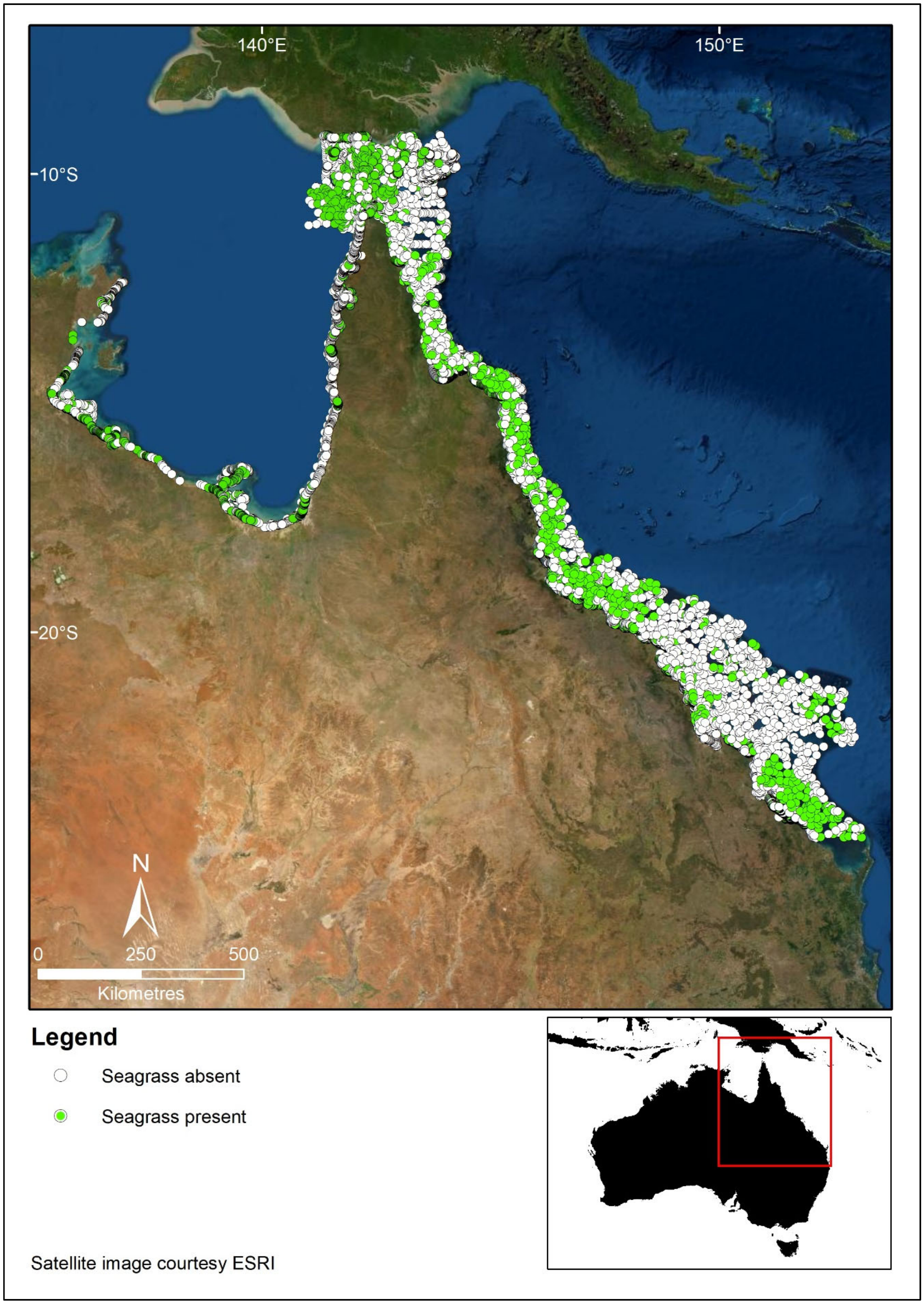

Figure 11 Seagrass presence and absence at individual survey sites across Torres Strait, the Gulf of Carpentaria, and the Great Barrier Reef World Heritage Area and adjacent estuaries

Spatial planning

By harvesting and verifying all available information and spatially describing seagrass points and meadows in a quantitative way, we identified areas with data scarcities. As a priority, these gaps need to be remedied. The data in the Gulf of Carpentaria is limited to the inshore coastline, leaving the vast majority of the seabed within the Gulf of Carpentaria unsurveyed. Depth and light penetration in this turbid water body make large areas of seagrass in deeper waters unlikely, but this needs confirmation. Aerial surveys have confirmed dugong presence tens of kilometres from shore in the Gulf of Carpentaria, indicating seagrass habitat extends further offshore than the current seagrass data extent (Griffiths et al. 2020; Marsh et al. 2008).

Jurisdictional complexities are inherent in areas as large as Torres Strait and the Gulf of Carpentaria. The majority of the region is managed under Australian Commonwealth legislation. The inshore strip is managed by the Queensland and Northern Territory governments, with jurisdictions such as Indigenous Protected Areas, port authority management and local government authorities also influencing activities and environmental pressures. As many as 65 legislative instruments can influence Queensland's management approaches in addition to Australia's common law and customary traditional rights (McGrath 2011). The Northern Territory has similar management policies and plans (Northern Territory Government 2019) and foreshore protection planning, however Aboriginal people own and manage 78% of the Northern Territory coastline through inalienable Aboriginal freehold granted under the *Aboriginal Land Rights (Northern Territory) Act 1976 (Cth).* A further 12% of the coast is subject to outstanding land claims, conferring a high degree of control over access and use. Importantly, the High Court of Australia handed down a decision (known as the Blue Mud Bay decision) that confirms that waters overlaying Aboriginal land are no different from the land itself, and permission of the Traditional Owners is required to access the waters overlying granted Aboriginal land, including the intertidal zone (Northern Territory Government 2019).

Queensland and Northern Territory governments have a legal responsibility for estuaries, coastlines, and adjacent land environmental management (where not owned by Aboriginal and Torres Strait Islander people or the Commonwealth). Traditional Owner's rights and interests also extend beyond Indigenous Protected Areas over their land and sea country which also needs to be considered in spatial planning. Indigenous ranger groups conduct year-round management activities, however the remoteness and restricted access through much of the year due to the monsoonal wet season is a challenge for active monitoring and management. The Torres Strait by comparison is a much smaller area and is managed by either the Queensland Government in Queensland waters or by the Australian Government and guided by the requirements of the Torres Strait Treaty between Australia and Papua New Guinea. There is an active and well-resourced ranger program that includes monitoring of intertidal and subtidal seagrass supported by TropWATER, JCU that provides a reliable and curated data stream and is included in this work.

Various instruments are used to manage environmental protection in both regions (Figure 12). Protections include Queensland Government Fish Habitat Areas which protect direct disturbance to habitats, to Commonwealth Marine Parks that include National Park and Habitat Protection Zones which protect seagrass from activities that may cause harm to seafloor habitats (Director of National Parks 2018). There are four Commonwealth Marine Parks in the region – the Wessel Marine Park north of Cape Arnhem, Limmen Marine Park in the south-west Gulf of Carpentaria, Gulf of Carpentaria Marine Park north of the Wellesley Islands, and West Cape York Marine Park which overlaps with the southern section of the Torres Strait Dugong Sanctuary, and numerous Indigenous Protected Areas (Figure 12). Port Exclusion Zones have no intentional aim to protect habitat but may do so inadvertently by excluding activities such a bottom trawling. How seagrass meadows intersect with layers of spatial protection, and the effectiveness of that protection for seagrass, has not been quantified though is a priority for management. The evaluation of indirect risks from environmental threats including those caused by extreme weather events, development and activities in adjacent catchments, and climate change and how these overlay with protected zones and reduce their value, and interact with the complex responses embedded in prescriptive and non-prescriptive protection approaches identified by Coles and Fortes (2001) is also necessary.

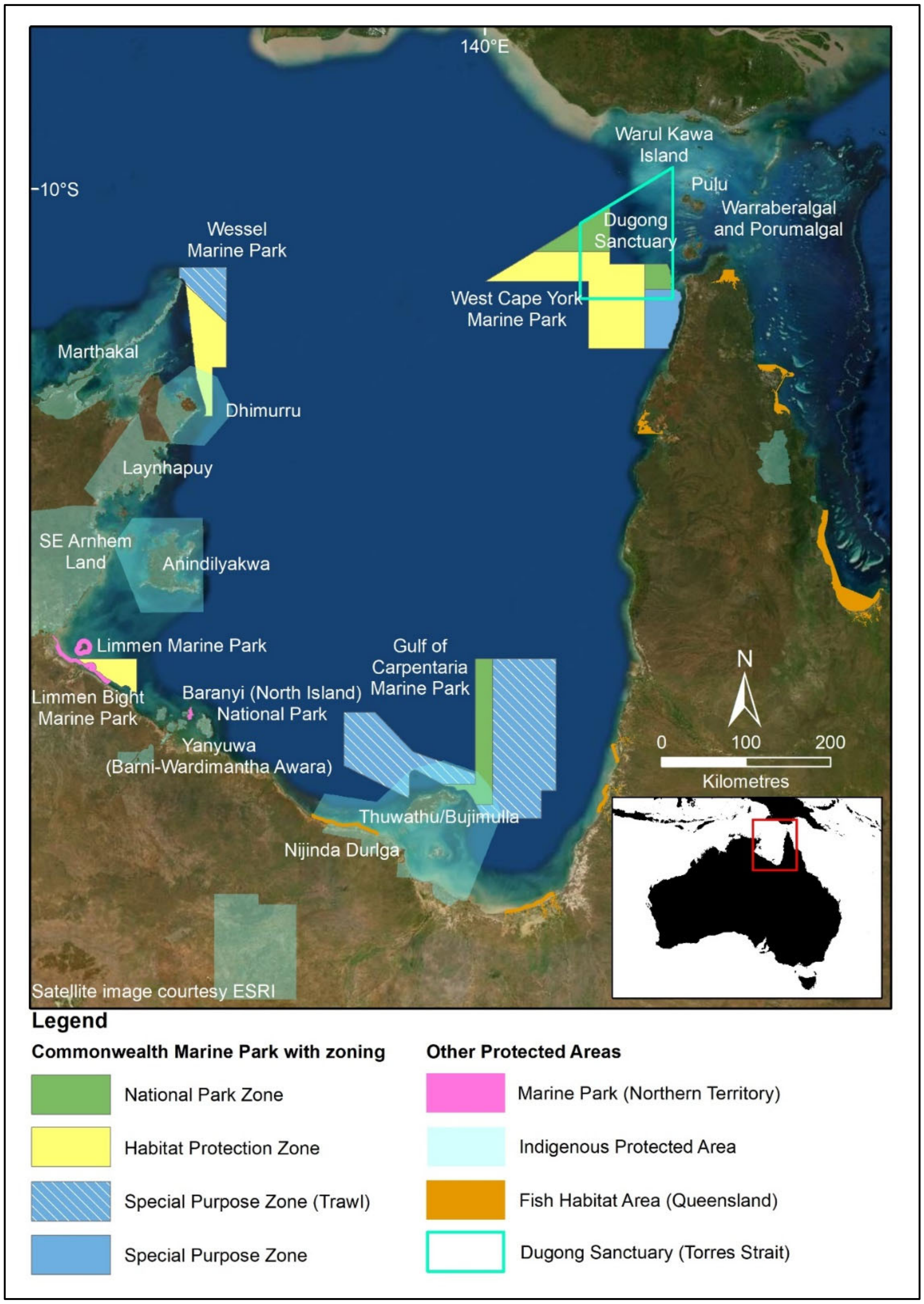

Figure 12 Protected areas in Torres Strait and the Gulf of Carpentaria

Understanding seagrass condition and trends

The National Environment Science Program Marine and Coastal Hub's objective is to improve our understanding of Australia's environment through practical and applied research that informs decision making and on-ground action that will yield measurable improvements to the environment (https://www.rrrc.org.au/nesp-mac/).

The seagrass datasets compiled through this project provide a huge step forward in our understanding of the spatial extent of northern Australian seagrass, the distribution of 13 seagrass species, and in identifying significant knowledge gaps. These data sets are intended to facilitate management planning and decision making, guide and inform current and future mapping and monitoring activities and allow a better assessment of the vulnerability of seagrasses to the risks inherent in climate variability and coastal processes.

The immediate scientific value of projects like this have been demonstrated on Queensland's east coast, where the GBRWHA data synthesis has been used to answer a number of key ecological questions, including the probability of seagrass distribution and communities in the GBRWHA and adjacent estuaries (Carter et al. 2021b; Carter et al. 2021a), defining the desired state of seagrass communities in the Townsville region (Collier et al. 2020) and GBRWHA (Carter et al. 2022), examining management targets for rivers influencing seagrass habitat (Collier et al. 2021; Lambert et al. 2021), and in designing a GBR-scale monitoring program (Udy et al. 2019). Seagrass data such as this has also been used on the GBR to model risk exposure (Waterhouse et al. 2017; Grech et al. 2012; Grech et al. 2011); propagule distribution (Schlaefer et al. 2022; Grech et al. 2016); and connectivity among meadows (Grech et al. 2018; Tol et al. 2017). We now make available similar data for the Gulf of Carpentaria and Torres Strait to answer similarly important questions for this region. This data is already being used to initiate hydrodynamic modelling approaches to better understand seagrass connectivity and resilience in the Torres Strait (Schlaefer et al. 2022).

Outcomes for Traditional Owners

With recent growth across northern Australia in Indigenous Protected Areas, Commonwealth Marine Parks, Queensland and Northern Territory protected areas, and Indigenous ranger programs, there is an increasing focus and demand for relevant and up-to-date information to improve coastal management. This seagrass data synthesis provides a valuable regional overview of available scientific data, and highlights areas where extensive seagrass meadows occur and where scientific information is lacking but Indigenous Ecological Knowledge is high.

Torres Strait Indigenous rangers have been conducting seagrass monitoring to track the health of Sea Country for over a decade, and combine scientific data with Indigenous Ecological Knowledge to interpret changes in seagrass condition. There is increasing interest by ranger groups and Traditional Owners in understanding seagrass resources and establishing their own research and monitoring programs in the Gulf of Carpentaria. The remoteness of this region lends itself to trialling new technologies to assist rangers, Traditional Owners, and scientists to monitor habitat condition, including remote sensing, drones, and artificial intelligence/ machine learning (McKenzie et al. 2022).

Research opportunities

Data gaps and age

The region has some areas which have long-term and ongoing seagrass monitoring including in key ports (Karumba, Weipa, Thursday Island) and at a network of locations across Torres Strait. These programs have provided valuable insights into temporal and spatial change in seagrasses of the region and some of their key drivers (Unsworth et al. 2012; Rasheed and Unsworth 2011) and some of the longest continuing annual seagrass monitoring programs around the world spanning almost three decades (Scott et al. 2022). However, there are significant spatial gaps in recent seagrass data, and in long-term temporal data, for much of the Gulf of Carpentaria. Recent large-scale seagrass surveys in the Limmen Marine Park (Commonwealth) and Limmen Bight Marine Park (NT) (Collier et al, in prep), West Cape York Marine Park and surrounding waters (Carter et al., in prep), and Yanyuwa Indigenous Protected Area (Groom et al., in prep), and planned surveys of South-East Arnhem Land, will provide long-overdue and detailed assessments of seagrass in areas of the Gulf of Carpentaria that are critical foraging areas for green turtle and dugong (Griffiths et al. 2020). The Wellesley Islands should be prioritised for large-scale seagrass surveys considering that location's previously mapped seagrass habitat (Taylor et al. 2007; Coles and Lee Long 1985) and importance for dugong foraging (Marsh et al. 2008).

Understanding risk for northern Australian seagrass

How risk intersects with the vulnerability of different seagrass species can be used to prioritise management activities. The highest risk to seagrass occurs where anthropogenic risks accumulate, particularly where industrial ports are located and rivers discharge (York et al. 2017; Grech et al. 2011). Australian estuaries and rivers that flow into the Gulf of Carpentaria and Torres Strait are small by international standards, but their flow and sediment load variability in a monsoon-influenced coastline makes them significant sources of environmental forcing (Plagányi et al. 2022).

Climate change also means that risk profile for seagrass may be changing (Rasheed and Unsworth 2011). Recent large-scale loss of seagrass caused by marine heat waves in Western Australia (Strydom et al. 2020; Arias-Ortiz et al. 2018), and high temperature intolerance in some seagrass species (Adams et al. 2020; Collier et al. 2018; Collier et al. 2017; Collier et al. 2011) raises concerns for seagrass resilience to warming sea temperatures in northern Australia. More intense tropical storms and sea–level rise will also increase the level of environmental risk for some seagrass communities. This seagrass spatial data has the potential to improve our assessment of risk for seagrass by overlaying the spatial coverage of seagrass species, which have unique levels of vulnerability because of their varying distribution (Figure 8, Figure 9).

Quantifying the complexity of seagrass communities and the environmental conditions that define seagrass presence and seagrass species boundaries will improve our understanding of when and where it may be appropriate to intervene with restoration after a seagrass meadow has been lost or impacted following an anthropogenic or climate-related event. Recent modelling on the connectivity among meadows suggests high connectivity and propagule exchange in Torres Strait that should lead to natural recovery without assistance (Schlaefer et al. 2022), but this exercise has not been conducted for Gulf of Carpentaria seagrass.

Conclusion

Spatial data is an important tool for assessing and managing marine and coastal environments (St. Martin and Hall-Arber 2008; Hughes et al. 2005; Rajabifard et al. 2005). We provide a region-scale assessment for communicating and assessing spatial and temporal variability, with potential for implementation in multiple management areas.

Included in our data is verified seagrass information; we have excluded some aerial surveys where photographs show areas that are very likely seagrass but do not meet our criteria for inclusion. This is also the case where positioning information is uncertain or where there are widely published maps that are no longer supported by data, or data was not recorded in an earlier time.

The composite meadow layer identifies an enormous area of tropical seagrass habitat. This is important as it is located in an area identified by Halpern et al. (2008) as one of the few in the world where the marine environment is relatively pristine, largely due to its remoteness from human populations. However, climate change threatens this region with a recent loss of mangroves and subsequent sediment remobilization observed (Duke et al. 2021). Our synthesis is valuable as a baseline, but a comprehensive network of dedicated monitoring sites is required to detect and understand climate-related changes, particularly in the Gulf of Carpentaria.

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