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Technical Report

A framework for defining seagrass habitat for the Great Barrier Reef, Australia

Alex B. Carter, Catherine Collier, Michael A. Rasheed, Len McKenzie and James Udy

James Cook University Australia

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A case study for seagrass meadows in the Burdekin region

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ACRONYMS AND ABBREVIATIONS

DPSIR.........................Drivers, Pressures, State, Impact, Response
ERT.............................Ecologically Relevant Target
GBR............................Great Barrier Reef
GBRMP.......................Great Barrier Reef Marine Park
GBRWHA....................Great Barrier Reef World Heritage Area
GIS..............................Geographic Information System
ITEM ....Intertidal extents model
JCU.............................James Cook University
NESP ....National Environmental Science Programme
NRM............................Natural Resource Management
MMP............................Marine Monitoring Program
MWB...........................Marine Water Bodies
QLUMP.......................Queensland Land Use Mapping Program
QPSMP.......................Queensland Ports Seagrass Monitoring Program
Reef 2050 Plan...........Reef 2050 Long Term Sustainability Plan
RIMReP ....Reef 2050 Integrated Monitoring and Reporting Program
TropWATER...............Centre for Tropical Water & Aquatic Ecosystem Research
TWQ............................Tropical Water Quality

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EXECUTIVE SUMMARY

This report describes a framework to define seagrass habitat and seagrass desired state for the Great Barrier Reef (GBR). We developed this by defining assessment zones using key physical attributes for the GBR. The assessment zones were developed with two main objectives: (1) to assess the representativeness of existing seagrass data throughout the GBR; and (2) to provide a framework in which to develop seagrass desired state (i.e. condition targets).

We defined assessment zones using spatial data that reflect environmental and benthic condition likely to affect seagrass distribution, diversity and density. These include: (1) latitude, defined as regions using 6 Natural Resource Management (NRM) boundaries, (2) influence from and proximity to land (estuarine, coastal, reef, and offshore water bodies), and (3) water depth (intertidal, shallow subtidal <10m, and deep subtidal >10m) resulting in 68 zones for the GBR. The largest assessment zone was the offshore water body in every region. Deep subtidal was the largest depth zone in coastal, reef, and offshore waters in each region. The estuarine deep subtidal zone was limited. Zones are seagrass-centric and not analogous to the Great Barrier Reef Marine Park zoning.

Data from extensive seagrass surveys and long-term monitoring across the GBR since the early 1980s provides information on seagrass presence/absence, species composition, abundance, and spatial extent. Data rich areas include coastal and estuarine intertidal and shallow subtidal zones. Data from reef and offshore zones, and in deep subtidal zones, are more limited as it comes from sporadic one-off surveys and few meadows have been mapped. Available seagrass data ranges from sporadic large-scale survey data with low to medium spatial and low temporal resolution, to high spatial and high temporal resolution data collected seasonally at discrete sites.

Defining these assessment zones is a critical first step in defining habitat types and quantifying desired state for GBR seagrasses. Habitat attributes not included in the zones, such as sediment type and exposure to wind and waves, as well as new seagrass biomass data will be used to update the framework, turning it into a full habitat assessment for defining desired state. A case study based in Cleveland Bay, as well as previous research, will be used to identify how this framework will be updated. Seagrass desired state is an ecological target that can be used to assess the effectiveness of management strategies to protect seagrass of the GBR. Desired state analysis requires data with medium to high spatial and temporal resolution that allows assessment in the context of disturbance events, recovery trajectories, and seasonal fluctuations. Robust analysis will be restricted to locations within zones where continuous data collection has occurred, e.g. the Marine Monitoring Program (MMP) and Queensland Ports Seagrass Monitoring Program (QPSMP), and for an adequate time span (generally >10 years).

1.0 INTRODUCTION

The Great Barrier Reef (GBR) contains one of the world's largest seagrass ecosystems. Extensive seagrass meadows stretch along intertidal banks and reef-tops, extend from coastal estuaries to offshore inter-reef waters in the subtidal zone, and range from tropical (10°S) to subtropical (~25°S) (Coles et al., 2015). Seagrass is identified as a key ecosystem and a measure of ecosystem health, actions, targets and objectives in The Reef 2050 Long Term Sustainability Plan (Reef 2050 Plan), which provides the strategy for management of the Great Barrier Reef (GBR; Commonwealth of Australia, 2015). Seagrasses provide critical ecosystem services, including coastal protection, support of fisheries production, nutrient cycling, particle trapping, removal of bacterial pathogens, and acting as a carbon sink (Coles et al., 1993; Fourqurean et al., 2012; Hemminga et al., 2000; Lamb et al., 2017; Watson et al., 1993). In addition, seagrass meadows provide food for large herbivores like dugong (*Dugong dugon*) and green turtle (*Chelonia mydas*) (Heck et al., 2008; Marsh et al., 2011; Unsworth et al., 2010).

Seagrass is highly sensitive to water quality. Declines in water quality and available light can have catastrophic consequences for seagrass, with catchment-derived pollutants, particularly sediment loads, linked to GBR-wide seagrass loss from 2008 to 2011 (Coles et al., 2015; McKenna et al., 2015; McKenzie et al., 2012; Petus et al., 2014; Schaffelke et al., 2017; Waterhouse et al., 2017). Seagrass is particularly sensitive to benthic light because the quality and quantity of light, the primary driver of photosynthesis, affects the growth, survival and depth penetration of seagrass (Dennison, 1987; Dennison et al., 1985). The available light for seagrass growth and persistence in Queensland is influenced by environmental conditions (e.g. rainfall, river flow, daytime tidal exposure, wind-driven resuspension, water temperature); impacts (e.g. tropical cyclones, floods, and dredging); and habitat (e.g. depth, sediment) (Carter et al., 2014; McKenna et al., 2015; Rasheed et al., 2014; Rasheed et al., 2011; Unsworth et al., 2012; York et al., 2015). Minimum light requirements for seagrass growth also vary among species (Chartrand et al., 2016; Collier et al., 2016; Collier et al., 2012).

The Reef 2050 Plan has an overarching objective that "the quality of water entering the reef has no detrimental impact on health and resilience of the GBR". The Reef 2050 Plan therefore requires ecologically relevant and measurable targets against which to assess progress towards meeting tangible outcomes and objectives (Commonwealth of Australia, 2015). The effectiveness of the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP), an important component of the Reef 2050 Plan, requires biologically relevant targets that provide a basis for monitoring and reporting.

Water quality and pollution load targets that protect ecosystem condition in the GBR are termed Ecologically Relevant Targets (ERTs) (Brodie et al., 2017). Ecologically Relevant Targets that protect seagrass from long-term decline on the GBR have not been established. Establishing ERTs requires: (1) defining seagrass desired state; (2) determining the water quality required to meet seagrass desired state; and (3) calculating ERTs for terrestrially sourced sediment loads. The broad objective of NESP TWQ Hub Project 3.2.1 *Deriving ecologically relevant load targets to meet desired ecosystem condition for the Great Barrier Reef: A case study for seagrass meadows in the Burdekin region* (http://nesptropical.edu.au/index.php/round-3-projects/project-3-2-1/), is to establish ERTs that achieve seagrass desired state for Cleveland Bay. This report describes a major component of (1), where our objective was to develop a framework for defining seagrass desired state for the entire GBR. The seagrass assessment zone developed here is also being used in the RIMReP (Udy et al., 2018).

Defining seagrass desired state for the GBR is a considerable undertaking considering the diversity of seagrass species and the habitats in which they grow. Twenty percent of the world's 72 seagrass species grow in the GBR (Short et al., 2011), with a gradual decline in species diversity from north to south (Mukai, 1993). These seagrasses display the full range of life history traits (whether a species is colonising, opportunistic or persistent), meadow form (whether a meadow is enduring or transitory), and physical habitat (proximity to land, water depth, and wave exposure) (Kilminster et al., 2015). Habitat type and life history traits largely influence meadow form; all factors affect seagrass resilience and the monitoring approach required to inform effective management (Kilminster et al., 2015). Four general habitat types have been previously used to define GBR seagrasses: estuarine, coastal, deep-water (subtidal), and reef, where the dominant controlling factors are terrigenous runoff, physical disturbance, low light, and low nutrients, respectively (Carruthers et al., 2002; Coles et al., 2015; Waycott et al., 2005). Regional differences in land habitat type, climate, and land use, e.g. tropical and subtropical, wet and dry tropics, pristine and cattle-dominated catchments (Hopley, 1986; Waycott et al., 2005), adds further complexity to defining seagrass desired state at the GBR-scale.

No map of potential seagrass habitat currently exists for the GBR, which has limited the ability of scientists and managers to conduct detailed but broad-scale evaluations of the available seagrass data within the context of the range of habitats. Habitat maps provide a powerful tool to evaluate the association of species and assemblages of interest with key environmental drivers likely to affect those assemblages (Greene et al., 2007). The combination of habitat maps with biological data allows for characterization of distinct habitat classes (Young et al., 2015), and allows for large-scale spatial assessment of habitats (Greene et al., 2007). Our objectives in developing a framework for defining seagrass desired state were to (1) create a classification map of assessment zones within which seagrass may occur for the GBR using Geographic Information Systems (GIS); and (2) use this map in combination with historical seagrass data to assess spatial coverage of seagrass knowledge and define seagrass communities within the range of habitats found in the GBR.

2.0 METHODS

2.1 Defining seagrass assessment zones in the GBR

We defined assessment zones where seagrass may have the potential to inhabit using existing spatial data of boundaries that reflect environmental and benthic conditions likely to affect seagrass distribution, diversity and density (Table 1). These include: (1) region/ latitude using Natural Resource Management (NRM) boundaries, (2) water bodies defined by the GBRMPA based influence from and proximity to land (estuarine, coastal, reef, offshore), and (3) water depth (intertidal, shallow subtidal, deep subtidal) (Figure 1). Within-zone environmental conditions such as benthic substrate, bay orientation, and resuspension, will further affect seagrass communities and their extent. The addition of these conditions to future iterations will enable further refinement of the zones, but was beyond the scope of this preliminary analysis; these data will be added in NESP extension project 5.4. Spatial data were combined to create a shapefile for each of the three zones, and a union performed to create a single shapefile that defines assessment zones for the GBR. Spatial analysis was conducted using a Geographic Information System (GIS) with ArcMap® software (version 10.4.1). The area of each zone was calculated in square kilometres in the Lambert projection.

Table 1: Spatial data sets and sources used to define seagrass assessment zones.

Spatial data set	**Author/ Agency**
Natural Resource Management region boundaries (NRM Marine and NRM2014)	State of Queensland, Department of Natural Resources, Mines and Energy
Great Barrier Reef World Heritage Area	Commonwealth of Australia, Department of the Environment and Energy
5% Flood Plume exceedence boundary	(Waterhouse et al., 2017)
Gbr100 depth model (version 4)	(Beaman, 2010)
Marine Water Bodies (version 2_4)	Commonwealth of Australia, Great Barrier Reef Marine Park Authority
Queensland Land Use Mapping Program (QLUMP)	State of Queensland, Department of Science, Information Technology and Innovation
Dry reefs within the GBR	Commonwealth of Australia, Great Barrier Reef Marine Park Authority
Intertidal Extent Model (version 1)	(Geoscience Australia, 2017)
Mapped distribution of intertidal habitat	(Dhanjal-Adams et al., 2015)
Seagrass sites	(Carter et al., 2016)
Seagrass meadows	(Carter et al., 2016)
Satellite image source layers	Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

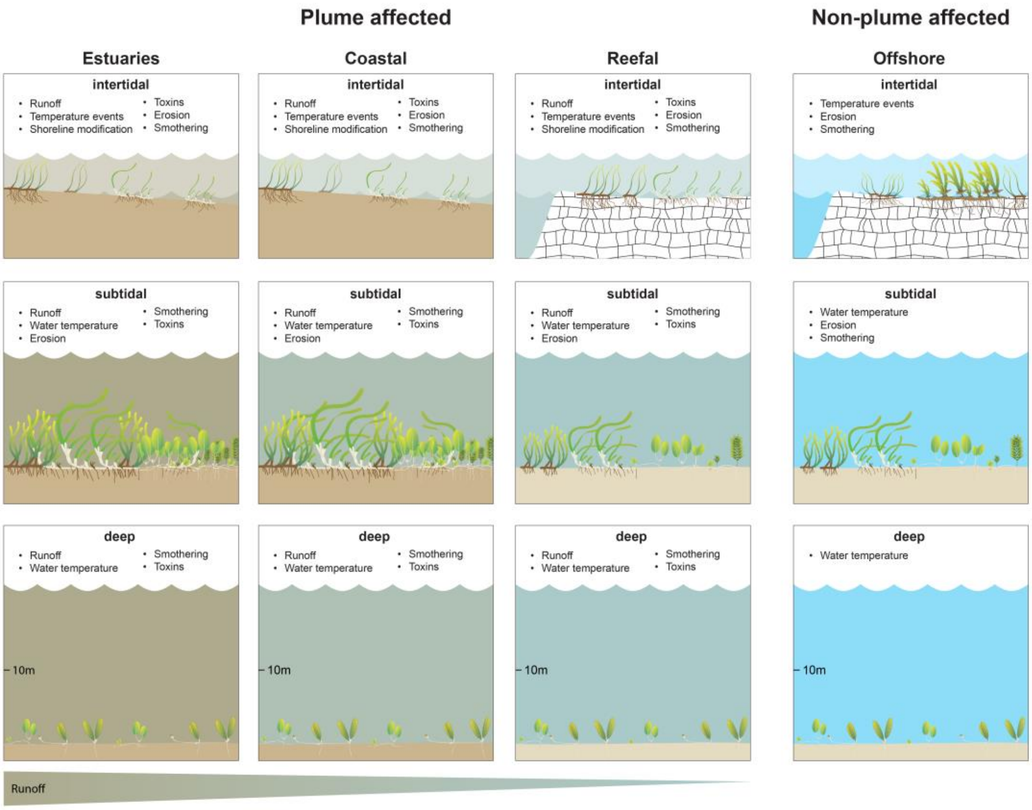


Figure 1: Major influences on seagrass habitat within depth (intertidal, shallow and deep subtidal) and water body (estuarine, coastal, reef, offshore) assessment zones on the Great Barrier Reef

2.1.1 Defining regional zones

Natural Resource Management (NRM) boundaries were incorporated into the assessment zones to allow seagrass assessment on a regional scale. The GBR incorporates six NRM regions that allow for broad latitudinal groupings along Queensland's east coast that vary in terms of land habitat type, climate, and land use. Cape York is the most northern region to incorporate the GBR; it is tropical and remote, with low human population, limited anthropogenic influence, and relatively unmodified river systems. Cattle grazing is the major primary industry (http://www.capeyorknrm.com.au/about/our-region). The Wet Tropics is characterized by wet tropical rainforest, high rainfall, and primary industries including cane and banana farming, dairy and grazing, and fishing (https://terrain.org.au/about-terrain/the-wet-tropics-region/). The Burdekin is a dry tropical region largely influenced by the Burdekin River, which has the second largest catchment in Queensland. Beef cattle grazing covers 96% of the region's land area (http://www.nqdrytropics.com.au/about-the-region/). Land use in the Mackay-Whitsunday region is predominantly cropping (mostly sugar), horticulture and beef grazing, and tourism in the Whitsunday area (http://reefcatchments.com.au/files/2015/02/Socio-Economic-Report.pdf). The subtropical Fitzroy region in central Queensland contains the Fitzroy River, the largest catchment that drains to the GBR lagoon, and significant agricultural and coal mining industries (https://www.fba.org.au/fitzroy-basin/). The Burnett Mary is the most southern region to include the GBR. It incorporates five major river basins and extensive primary production including sugar cane, horticulture, tree and grain crops, and beef grazing (http://www.bmrg.org.au/about/our-region/). This NRM region extends south of the GBRWHA boundary to Hervey Bay; mapping of assessment zones in this region was limited to the area within the GBRWHA.

Two NRM shapefiles were used to define zones by region, the NRM2014 Land shapefile (Figure 2a) and the NRM Marine shapefile (Figure 2b) (Data © State of Queensland (Department of Natural Resources, Mines and Energy) 2018. Updated data available at http://qldspatial.information.qld.gov.au/catalogue//). This enabled regional zones to extend to the north, east and south boundaries (offshore boundaries) of the GBRWHA (© Commonwealth of Australia, Department of the Environment and Energy 2018) (Figure 2b, c).

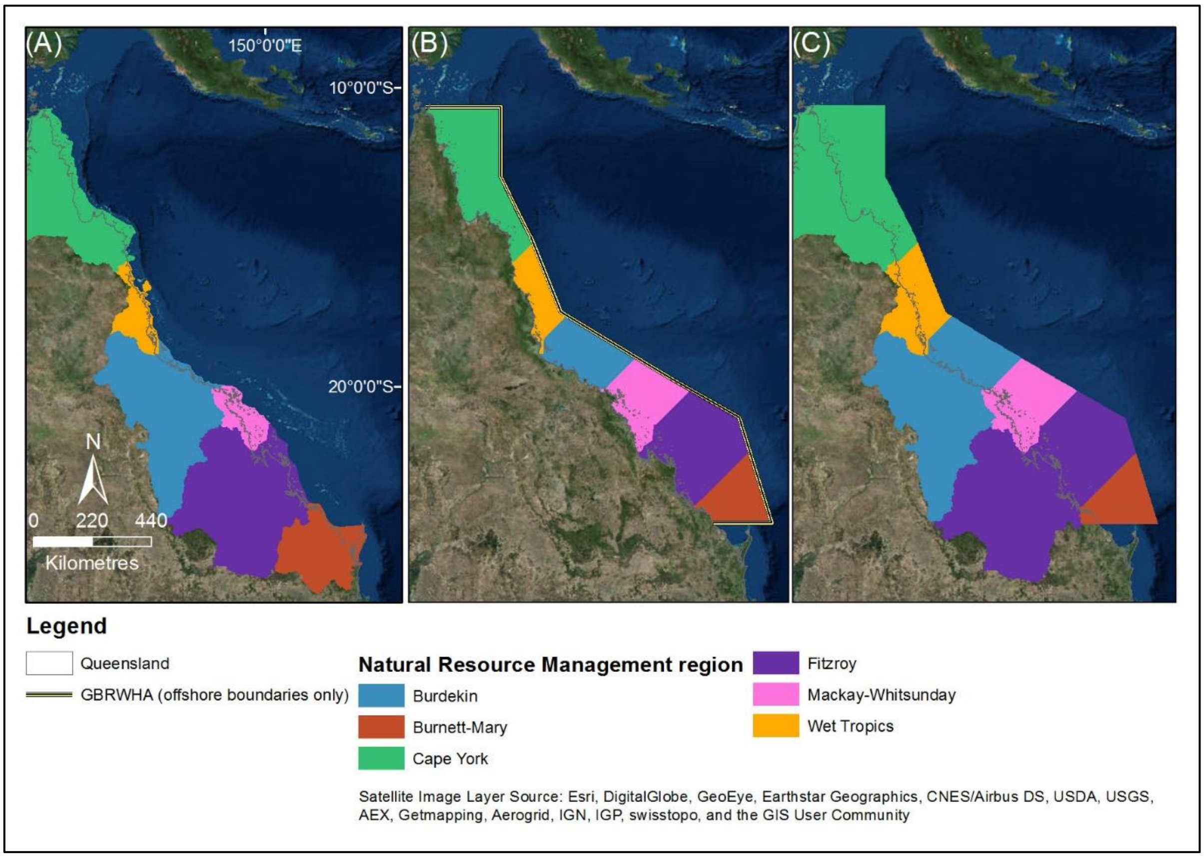


Figure 2: Shapefiles used to define seagrass assessment zones by region: (A) Natural Resource Management (NRM) Land shapefile (regions adjacent to the GBRWHA only), and (B) NRM Marine shapefile and GBRWHA offshore boundaries. (C) Final regional zones

2.1.2 Defining water body zones

Water body zones were defined according to influence from, and proximity to, the mainland. Four water bodies were included: non-plume affected (offshore), and plume affected (reef, coastal, estuarine).

The offshore zone rarely directly receives the inputs that characterise plume-affected zones, and is principally influenced by oceanic waters (Kilminster et al., 2015; Waterhouse et al., 2017). The offshore zone was defined as the non-plume affected area beyond (east of) the flood plume 5% exceedance boundary, i.e. beyond areas where plume water was found for >5% of wet season weeks from 2003-2016 (Waterhouse et al., 2017), and extending to the offshore GBRWHA boundary (Figure 3).

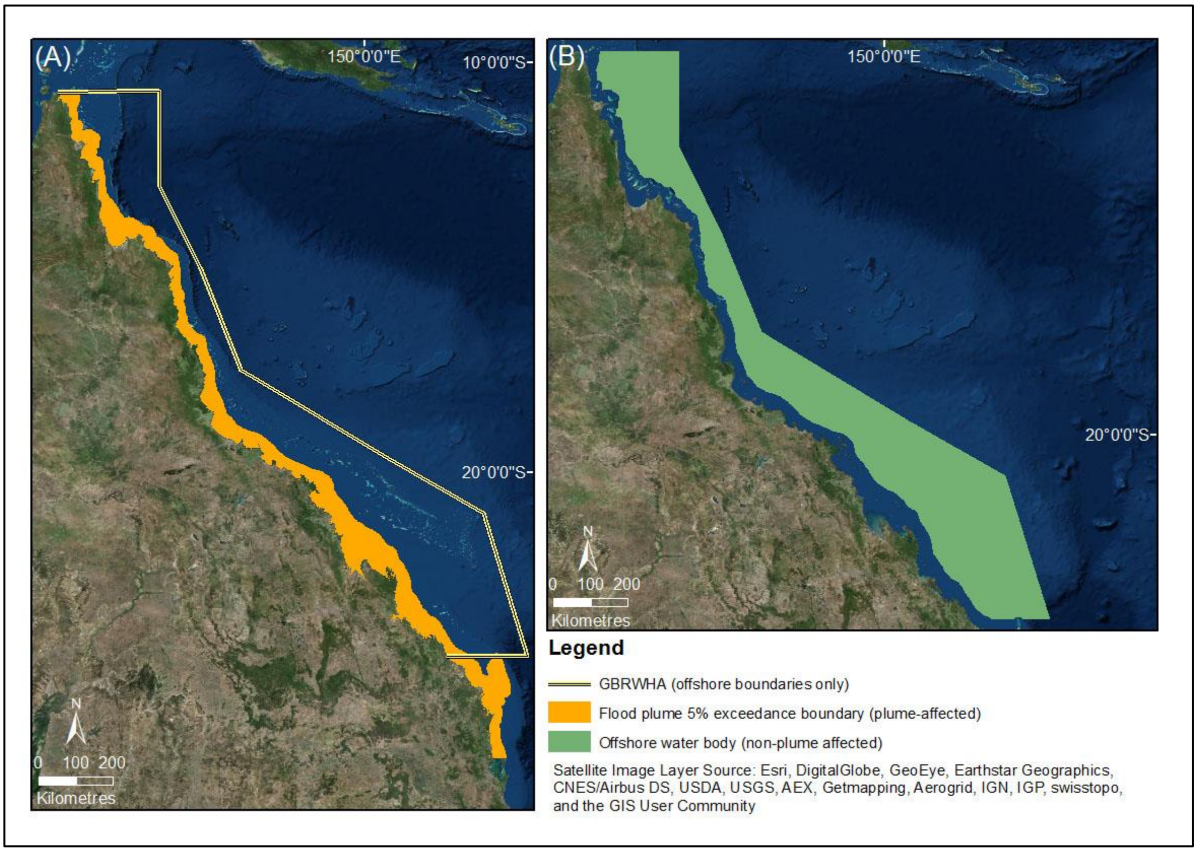


Figure 3: Spatial data used to define seagrass assessment zones by water body: (A) The flood plume 5% exceedance area and Great Barrier Reef World Heritage Area (GBRWHA) offshore boundaries. (B) Final offshore (non-plume affected) zone defined as east of the flood plume 5% exceedance boundary and extending to the GBRWHA offshore boundaries

Coastal zones are highly productive and dynamic and regularly exposed to terrigenous and anthropogenic inputs, with physical disturbance the limiting factor (Carruthers et al., 2002; Kilminster et al., 2015). Reef zones are exposed to terrigenous and anthropogenic inputs much less frequently than estuarine and coastal zones due to a greater distance from land, with the limiting factor being low nutrients (Carruthers et al., 2002); however, this zone remains affected to some degree by flood plumes (Waterhouse et al., 2017).

Reef and coastal water body zones were defined as the plume-affected region (within the flood plume 5% exceedance boundary; Figure 3a) between the offshore and estuarine zones. Reef and coastal zones were defined using the Marine Water Bodies (MWB) dataset (version 2_4; Data courtesy of the Great Barrier Reef Marine Park Authority; Figure 4a). The reef zone was defined as mid-shelf and offshore waters from the MWB shapefile (Figure 4a, b). The coastal zone was defined as macro tidal enclosed coastal, macro tidal open coastal, enclosed coastal, and open coastal waters from the MWB shapefile (Figure 4a, b). Any reef or coastal areas beyond the flood plume 5% exceedance boundary or the GBRWHA offshore boundary were erased (Figure 4c, d). These distinctions were included to differentiate between levels of exposure to plume water, but could be merged or modified in future refinements of the classification, particularly as other relevant spatial information becomes available.

Estuarine waters are highly dynamic, where variable river flow results in salinity, temperature, light, nutrient, and sediment deposition fluctuations, and terrigenous runoff is the limiting factor (Carruthers et al., 2002; Kilminster et al., 2015). The estuarine water body was defined using the Queensland Land Use Mapping Program (QLUMP) data (available at http://qldspatial.information.qld.gov.au Copyright State of Queensland (Department of Science, Information Technology and Innovation) 2017). This dataset classifies five primary classes of land use plus water as a sixth class (Figure 5a). Water is divided according to secondary classes: lakes, reservoirs/dams, rivers, channels/aqueducts, marshes/wetlands, and estuaries/coastal waters. Historical seagrass data (Carter et al., 2016) was overlaid to determine which secondary water classes seagrass has been recorded in, and therefore which classes should be retained and reclassified as estuarine. These were estuary/coastal waters, marsh/wetlands, and rivers (Figure 5b). Any estuarine polygons that were not adjacent to coastal zone polygons, e.g. inland rivers, were reclassified as “inland waters” and removed from the dataset (Figure 5b).

The MWB and QLUMP spatial data used to define coastal and estuarine zones often overlapped, criss-crossed, and ran parallel upstream (Figure 5c). Where overlaps occurred, the overlapping portions of the coastal zone polygons were erased (Figure 5c, d). Where coastal and estuarine zones ran parallel upstream, the coastal polygon was cut at the downstream mouth of the estuary in line with the estuarine polygon, and all polygons upstream of this boundary were classed as estuarine (Figure 5c, d). Where criss-crossing occurred (generally upstream from the coastal/estuarine boundary), all coastal and estuarine polygons were merged to create one estuary (Figure 5c, d).

Approximately 800 seagrass sites (Carter et al., 2016) fell immediately outside of the water body zone shapefile. This was because sites were classed as being on land, or there were gaps between the coastal and estuarine zone boundaries. Where this occurred, the boundaries of adjacent polygons were manually adjusted to incorporate these sites.

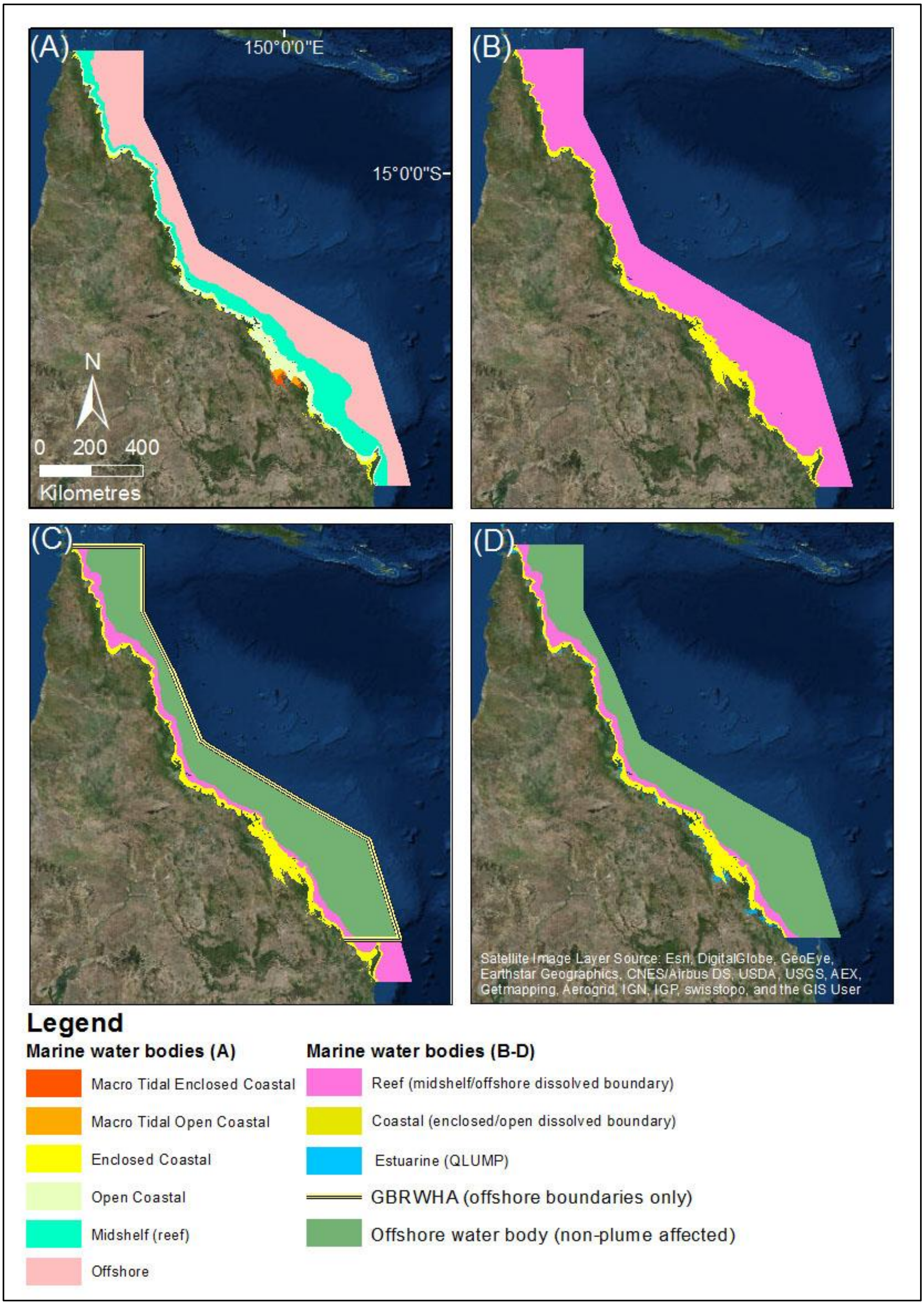


Figure 4: Spatial data used to define assessment zones by water body. (A, B) The Marine Water Bodies shapefile was used to define the reef zone (mid-shelf and offshore waters) and coastal zone (all enclosed and open coastal waters). (C, D) Any reef or coastal areas that overlapped with the flood plume 5% exceedance boundary or extended beyond the GBRWHA offshore boundary were erased. (D) Estuarine waters were added to create the final water body zones

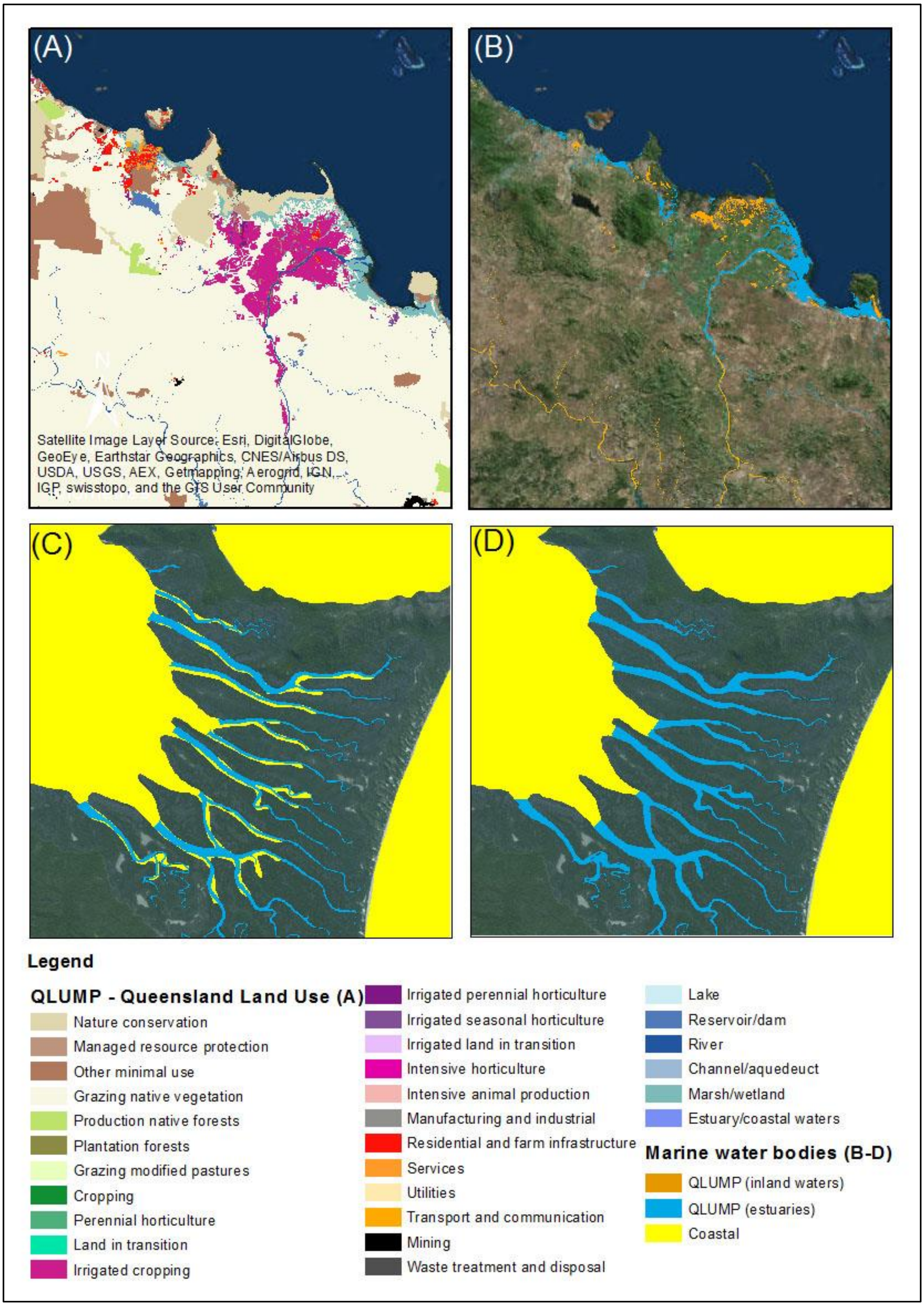


Figure 5: Spatial data used to define estuarine and coastal zones. (A) The Queensland Land Use Mapping Program (QLUMP) shapefile was used to define the estuarine zone (estuary/coastal waters, marsh/wetland, and river). (B) Inland waters (estuary/coastal waters, marsh/wetland, and river polygons that did not join adjacent coastal zones) were removed from the dataset. (C) Coastal and estuarine zones often overlapped, crisscrossed, and ran parallel upstream. (D) These zones were defined as estuarine

2.1.3 Defining depth zones

Three depth zones were defined following Kilminster et al.'s (2015) description of seagrass habitat: intertidal, where seagrasses are exposed at some time during the tidal cycle, and shallow (shallower than 10m) and deep (deeper than 10m) subtidal habitats that are never exposed to air.

Five spatial datasets were used to define the intertidal zone: (1) the Intertidal Extents Model (ITEM version 1; Geoscience Australia, 2017) (Figure 6a), (2) the distribution of intertidal habitats in Australia based on Landsat imagery from 1999-2014 (Dhanjal-Adams et al., 2015) (Figure 6a), (3) the distribution of dry reefs (reef tops that expose during low tide) within the GBR (Data courtesy of the Spatial Data Centre, Great Barrier Reef Marine Park Authority © Commonwealth of Australia (GBRMPA) 2018) (Figure 6b), (4) the GBR seagrass site composite (Figure 6b) (Carter et al., 2016), and (5) the GBR seagrass meadow composite (Figure 6b) (Carter et al., 2016). Seagrass data used in the site and meadow composites was collected between 1984 and 2014 and collated for NESP TWQ Project 3.1 *Seagrass mapping synthesis: A resource for coastal management in the Great Barrier Reef World Heritage Area* (Carter et al., 2016).

ITEM is a national-scale gridded dataset that characterizes spatial extent of the exposed intertidal zone at intervals of the observed tidal range, using Landsat imagery from 1987-2015 (Geoscience Australia, 2017). ITEM includes the Relative Extents Model, a raster dataset that uses tidal information to indicate the spatial extent of intertidal substratum exposed at percentile intervals of the observed tidal range for that cell, where 0 = always water, 1 = exposed at lowest 0-10% of observed tidal range, increasing to a maximum value of 9 (exposed at highest 80-100% of observed tidal range). We reclassified this raster into two categories: (1) subtidal (raster value of 0) and (2) intertidal (raster value of 1-9), converted the raster to a shapefile using the conversion tool, then deleted all subtidal polygons. Areas of the shapefile that overlapped Queensland's islands and the mainland were erased (Figure 6a). Offshore areas of the ITEM layer had lots of noise, e.g. small intertidal polygons in deep offshore waters; therefore, any intertidal polygons that were within or intersected reef or offshore zones were removed (see Section 2.2 for zone boundaries). For estuarine and coastal zones, intertidal polygons that fell within the deep subtidal zone were removed manually using satellite imagery as a guide.

The ITEM (Geoscience Australia, 2017) and Dhanjal-Adams et al. (2015) datasets underestimated intertidal extent, relative to our understanding of intertidal extent based on seagrass surveys conducted by helicopter and walking on exposed banks. This is likely because intertidal seagrass surveys are conducted only on extreme low spring tides that occur for relatively short periods annually, and therefore did not feature in the Landsat images used to create these datasets. We therefore added the Carter et al. (2016) seagrass site and meadow composite data to help define the intertidal zone. We classed sites/meadows as intertidal if they were surveyed only by helicopter or walking, and/or field notes indicated the site/meadow was exposed during sampling. Some intertidal sites were outside the intertidal meadow boundaries because (1) seagrass was absent or (2) seagrass was recorded but no meadow was mapped. Where this occurred, a 250m (polygon) buffer was created around all intertidal sites, then a 230m internal buffer around these polygons was erased. This created intertidal polygons that followed the edge of intertidal sites, but where a 20m buffer around sites was included so lone intertidal sites were not erased completely from the layer (Figure 6b). A composite of the five intertidal shapefiles was created using the union function. This resulted in a shapefile with overlapping boundaries (Figure 6c) which were dissolved (Figure 6d).

The subtidal zone was defined using the gbr100 dataset (version 4; Beaman, 2010). This raster data set is a high-resolution bathymetry and Digital Elevation Model covering the Great Barrier Reef, Coral Sea and neighbouring Queensland coastline (Figure 7a). It has a grid pixel size of 0.001-arc degrees (~100m) with a horizontal datum of WGS84 and a vertical datum of MSL. The raster was reclassified and converted to a shapefile with three categories: (1) shallow subtidal - shallower than -10m MSL, (2) deep subtidal - between -10m and -125m MSL, and (3) very deep subtidal - deeper than -125m MSL (Figure 7b). The very deep subtidal polygons were erased. This resulted in a shapefile with a spatial extent that incorporated all seagrass composite data (Carter et al., 2016) but excluded waters east of the continental shelf too deep for seagrass (Figure 7b, c). Areas that overlapped Queensland's mainland and islands were erased, and the shapefile was clipped to the northern and southern limits of the offshore GBRWHA boundary (Figure 7c).

Intertidal and subtidal zone shapefiles were joined using the union function. In areas where subtidal and intertidal polygons overlapped, the subtidal polygon was erased. Finally, ~500 sites (Carter et al., 2016) fell outside of the depth shapefile because they were classed as being on land, i.e. Queensland's mainland or islands. The boundaries of adjacent depth polygons were moved manually to incorporate these sites to create the final depth zone shapefile (Figure 7d).

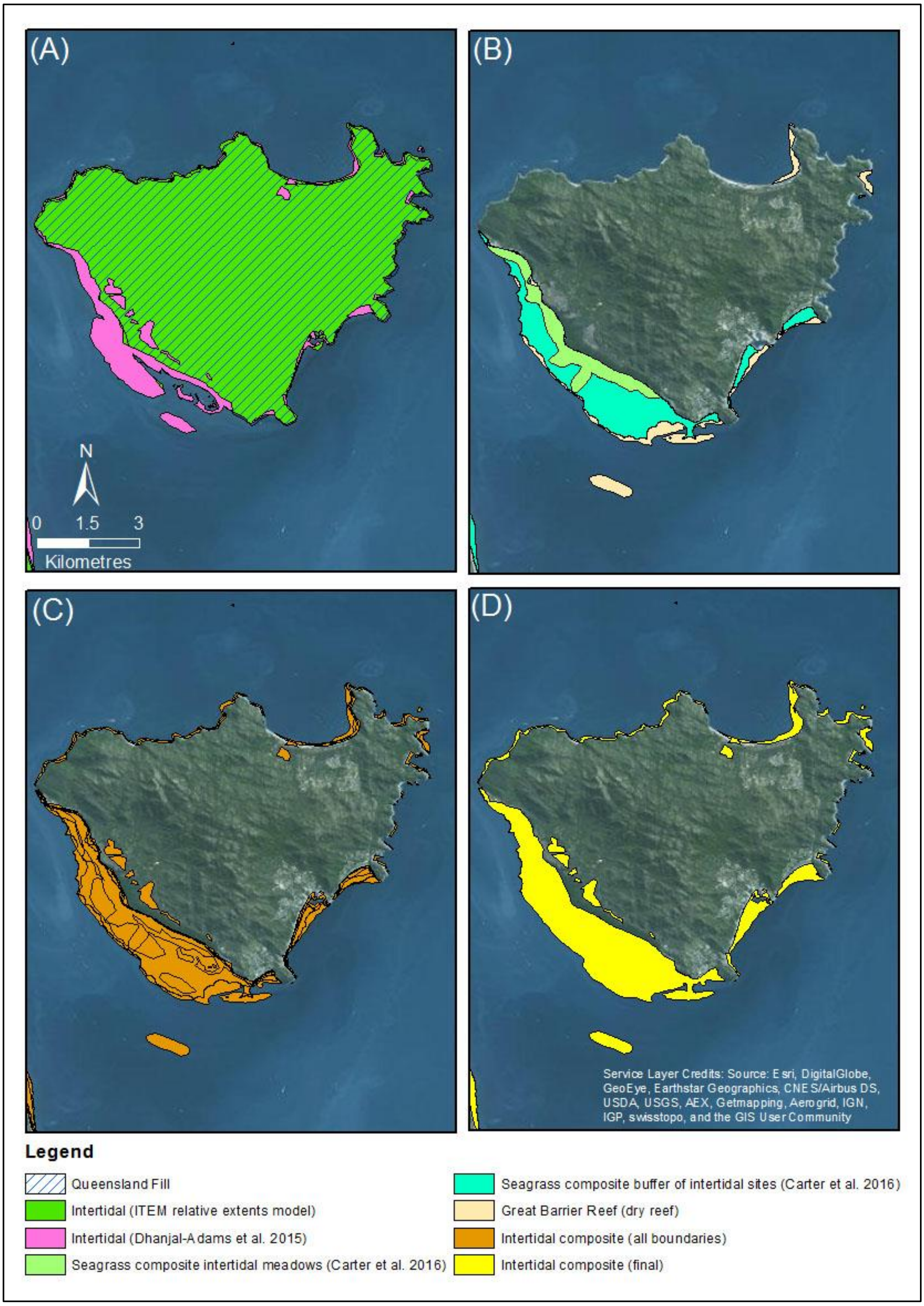


Figure 6: Spatial data used to define the intertidal zone included (A) the Intertidal Extent Model (ITEM) (Geoscience Australia, 2017) with Queensland's mainland and islands and distribution of intertidal habitats in Australia (Dhanjal-Adams et al., 2015); and (B) the distribution of dry reefs within the GBRWHA (© Commonwealth of Australia (GBRMPA) 2018) and the seagrass site and meadow composite shapefiles (Carter et al., 2016). (C) Five intertidal shapefiles were combined into a single shapefile with overlapping polygons. (D) Final intertidal zone shapefile with overlapping polygon boundaries dissolved

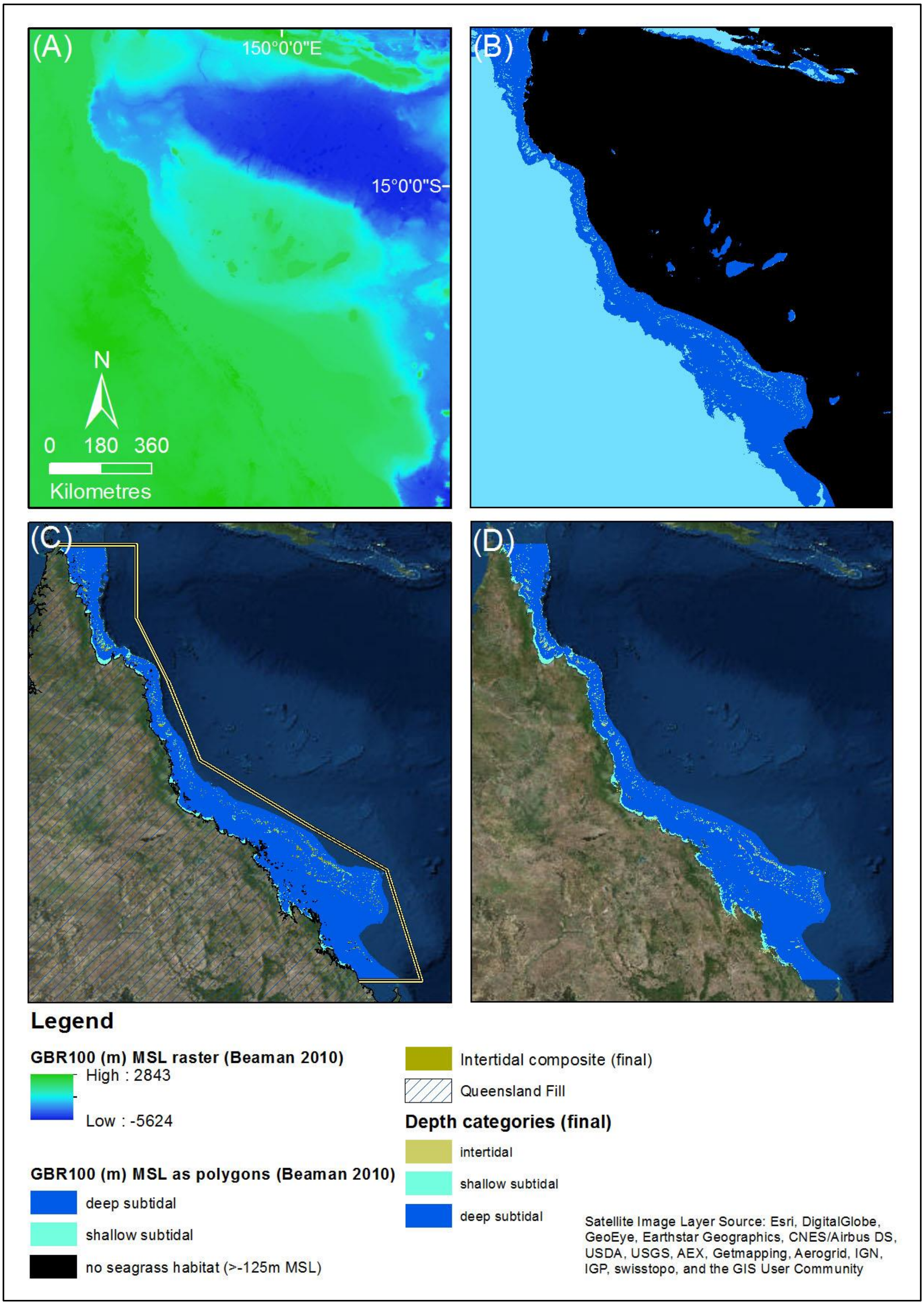


Figure 7: Spatial data used to define subtidal and intertidal depth zones. (A, B) The gbr100 raster (version 4; Beaman, 2010) was reclassified and converted to a shapefile that defined subtidal depth zones as shallow subtidal (shallower than -10m MSL), deep subtidal (between -10m and -125m MSL), and no seagrass (deeper than -125m MSL). (C, D) Subtidal and intertidal shapefiles were joined, and the following areas removed: subtidal waters deeper than -125m MSL, areas extending beyond the GBRWHA offshore boundary, and Queensland's mainland and islands

2.2 Application of historical seagrass data to assessment zones

Seagrass sites (~66,200 sites) in the composite data set (Carter et al., 2016) were defined according to the seagrass assessment zone they are located in. The meadow composite (polygon) layer (Carter et al., 2016) contains information on the maximum extent of ~1,200 individual meadows, which frequently overlap in the data set. To eliminate overlap and accurately estimate mapped meadow area for each asessment zone, all meadows were merged, then split by zone using the intersect function. Individual meadow polygons were assigned a unique identification number. The area of mapped seagrass for each zone was calculated in hectares in the Lambert projection.

Different seagrass assemblages occur within the range of assessment zones. These species have different life history traits and so respond differently to pressures (Kilminster et al., 2015). Seagrass communities for intertidal and shallow subtidal meadows were defined according to the species that occurred most frequently for all sites within each meadow. The same method could not be applied for deep subtidal meadows because few have been mapped, and most sites fell outside meadow boundaries. Instead, seagrass communities were defined according to the species that occurred most frequently across all sites in each deep subtidal zone.

3.0 RESULTS

3.1 Seagrass assessment zones of the Great Barrier Reef

Sixty-eight assessment zones were created covering 228,342 km^2 of the GBR during the delineation process (6 regions, 3 depths, 4 water bodies). Four zones were absent: the Mackay-Whitsunday reef intertidal and shallow subtidal zones, the Burnett Mary reef intertidal zone where the majority of reefs are located in the offshore zone, and the Burdekin estuarine deep subtidal zone (Figure 8; Table 2). Offshore was the largest water body zone in every region. Deep subtidal was the largest depth zone in coastal, reef, and offshore waters but in estuarine waters the deep subtidal zone was very small (Figure 8; Table 2).

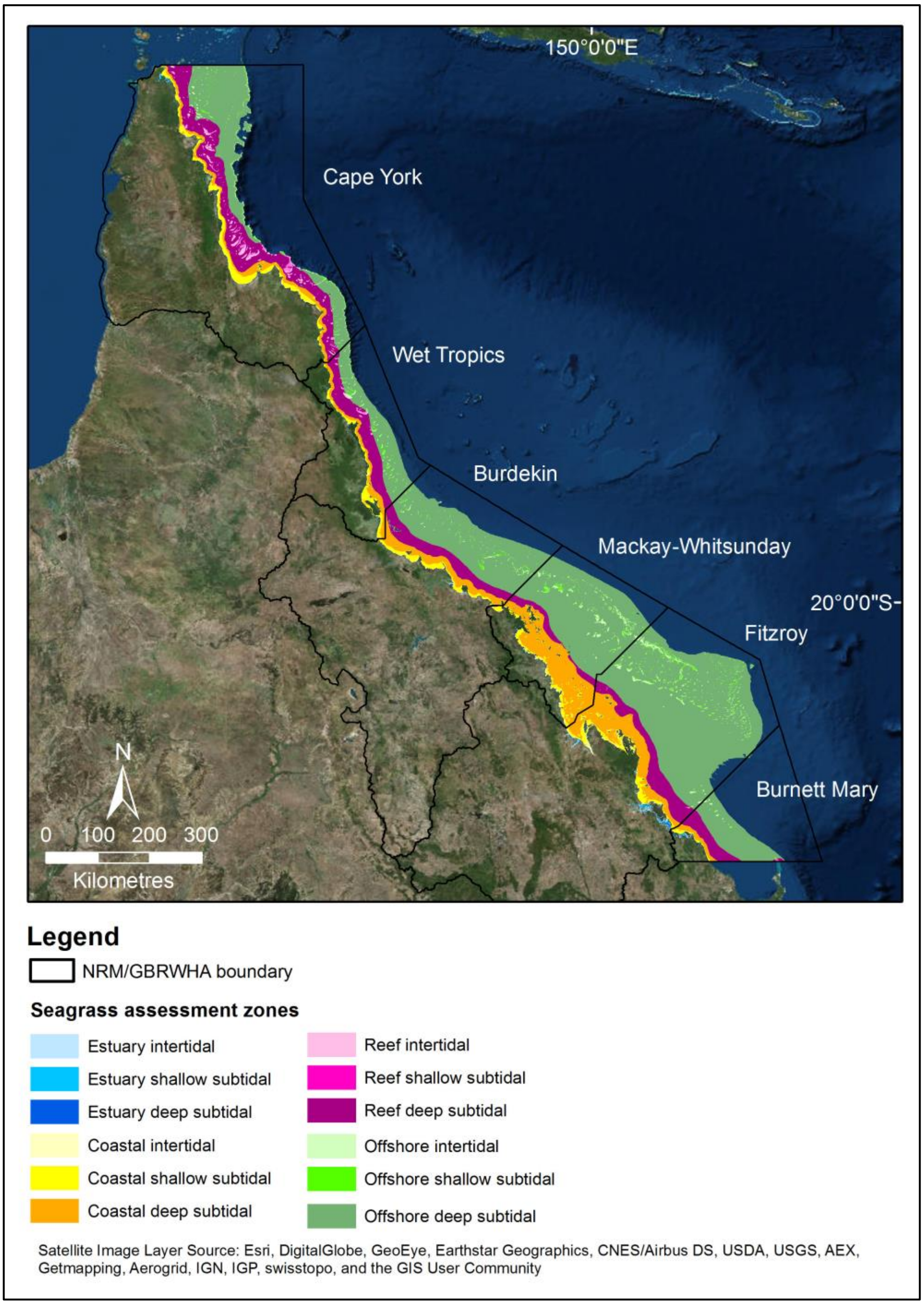


Figure 8: Distribution of assessment zones in the Great Barrier Reef World Heritage Area (GBRWHA). Zones defined by water body (estuarine, coastal, reef, offshore), depth (intertidal, shallow subtidal, deep subtidal), and Natural Resource Management (NRM) region

Table 2: Total area (km²) of seagrass assessment zones: Water type and depth zones for each Natural Resource Management (NRM) region

Burdekin NRM			
Estuary intertidal	87.8	Reef intertidal	34.1
Estuary shallow subtidal	9.0	Reef shallow subtidal	11.0
Estuary deep subtidal	0	Reef deep subtidal	5 510.7
Coastal intertidal	159.4	Offshore intertidal	351.5
Coastal shallow subtidal	1 439.8	Offshore shallow subtidal	346.5
Coastal deep subtidal	3 630.4	Offshore deep subtidal	22 183.3
Burnett Mary NRM			
Estuary intertidal	75.1	Reef intertidal	0
Estuary shallow subtidal	55.4	Reef shallow subtidal	30.0
Estuary deep subtidal	0.2	Reef deep subtidal	2 667.5
Coastal intertidal	14.0	Offshore intertidal	79.8
Coastal shallow subtidal	263.0	Offshore shallow subtidal	39.3
Coastal deep subtidal	742.8	Offshore deep subtidal	7 556.4
Cape York NRM			
Estuary intertidal	57.6	Reef intertidal	1 339.4
Estuary shallow subtidal	71.4	Reef shallow subtidal	1 094.6
Estuary deep subtidal	0.2	Reef deep subtidal	16 374.8
Coastal intertidal	374.1	Offshore intertidal	899.6
Coastal shallow subtidal	3 921.0	Offshore shallow subtidal	528.5
Coastal deep subtidal	3 967.1	Offshore deep subtidal	20 903.9
Fitzroy NRM			
Estuary intertidal	405.7	Reef intertidal	9.5
Estuary shallow subtidal	275.0	Reef shallow subtidal	12.4
Estuary deep subtidal	45.7	Reef deep subtidal	6 139.1
Coastal intertidal	514.4	Offshore intertidal	1 535.1
Coastal shallow subtidal	1 960.7	Offshore shallow subtidal	993.2
Coastal deep subtidal	7 993.3	Offshore deep subtidal	51 155.4
Mackay-Whitsunday NRM			
Estuary intertidal	62.5	Reef intertidal	0
Estuary shallow subtidal	19.8	Reef shallow subtidal	0
Estuary deep subtidal	0.3	Reef deep subtidal	2 038.3
Coastal intertidal	351.2	Offshore intertidal	997.1
Coastal shallow subtidal	1 547.9	Offshore shallow subtidal	490.1
Coastal deep subtidal	10 088.8	Offshore deep subtidal	26 781.6
Wet Tropics NRM			
Estuary intertidal	53.1	Reef intertidal	127.0
Estuary shallow subtidal	25.3	Reef shallow subtidal	144.4
Estuary deep subtidal	1.3	Reef deep subtidal	6 243.9
Coastal intertidal	113.2	Offshore intertidal	371.6
Coastal shallow subtidal	1 384.4	Offshore shallow subtidal	440.1
Coastal deep subtidal	2 269.9	Offshore deep subtidal	8 931.4

3.2 Spatial extent of seagrass data by assessment zone

Extensive seagrass surveys have occurred across the GBR since the early 1980s. This data provides us with information on seagrass presence/absence, spatial extent, and species composition for intertidal and shallow subtidal seagrass, particularly in the coastal zone (Figures 9, 10). Seagrass knowledge outside of this zone is more variable. Of the 68 zones we classified and mapped, 11 were data deficient, and five had <10 sites which limits our ability to describe seagrass within those zones with any confidence, let alone define desired state (Table 3). Eight zones have been surveyed but no seagrass was reported, mainly in estuarine deep subtidal or offshore zones; however four of these zones had <10 sites, so again results should be treated cautiously (Table 3).

The meadow composite represents a total coverage of 450,524 ha of seagrass meadows mapped within the GBRWHA between 1984 and 2014; more than half of which are in the Cape York region (262,158 ha) (Figure 10). The majority of mapped meadow area for all regions occurred in the coastal zone, particulary the intertidal and shallow subtidal (Table 4). Limited mapping, if any, of reef or offshore zones has occurred in each region (Figure 10, Table 4). Estuarine seagrass has been extensively mapped in the Fitzroy and Burnett Mary regions, but limited mapping has occurred between Cape York and the Mackay-Whitsunday regions.

Approximately two-thirds of seagrass site data was within the meadow composite boundaries. Sites outside the meadow composite were mostly in coastal, reef and offshore deep subtidal zones, where mapped spatial extent of meadows is extremely limited. Limited mapping of deep subtidal meadows is due to this zone being dominated by highly variable and low coverage ephemeral *Halophila* species, and the large distances between survey sites. However, site data demonstrated that deep subtidal seagrass is potentially present across a broad area of the GBR lagoon.

In some instances, small portions of mapped meadows were split near their boundary where a zone changed occurred, leaving small remnant edges. The corresponding site data for these remnant edges remained in the adjacent main meadow, and in some cases seagrass was absent from all sites within the same zone as the remnant edge meadow (Table 4).

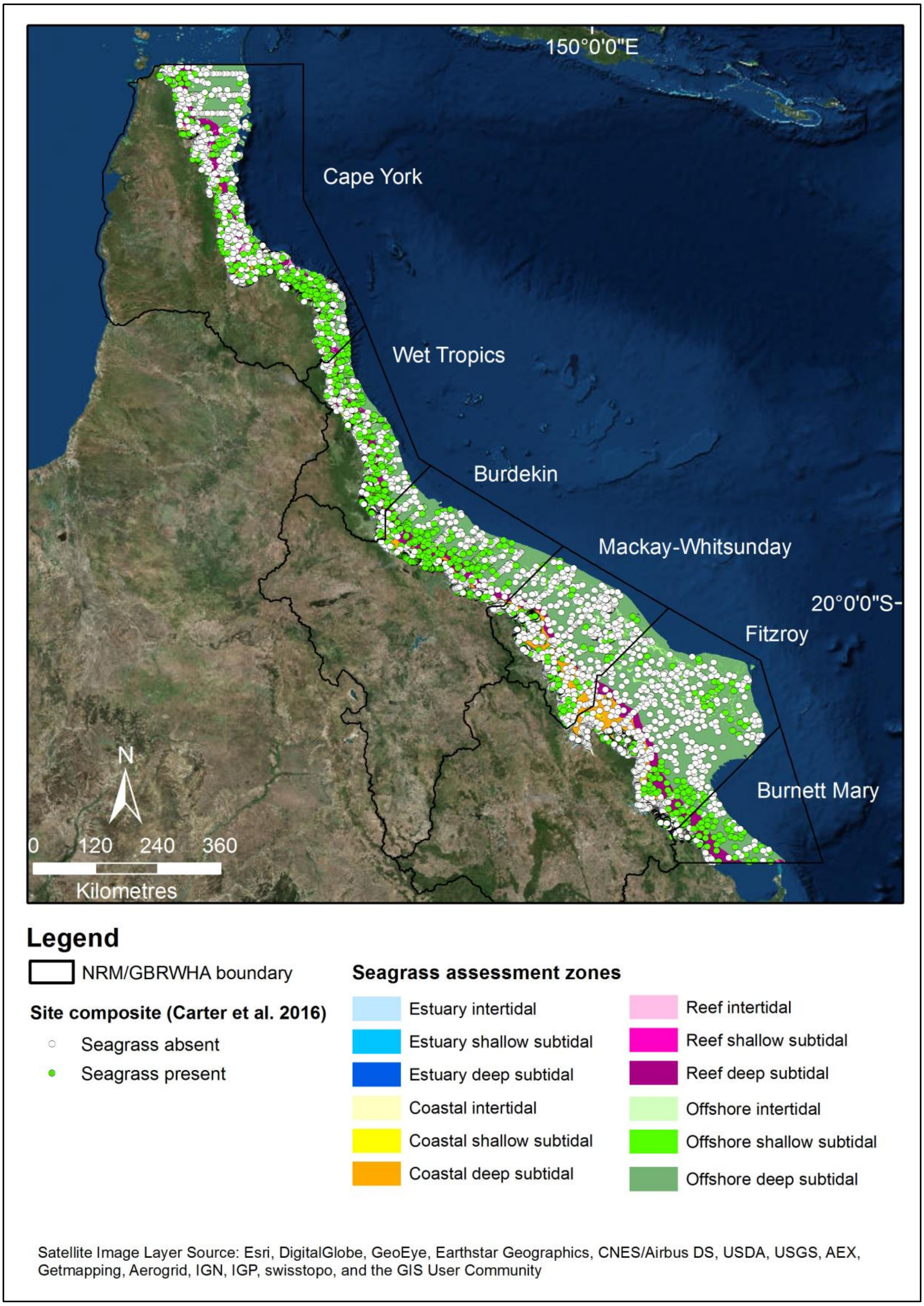


Figure 9: Seagrass presence/absence within the Great Barrier Reef World Heritage Area (GBRWHA) relative to seagrass assessment zones. Number of sites detailed in Table 3

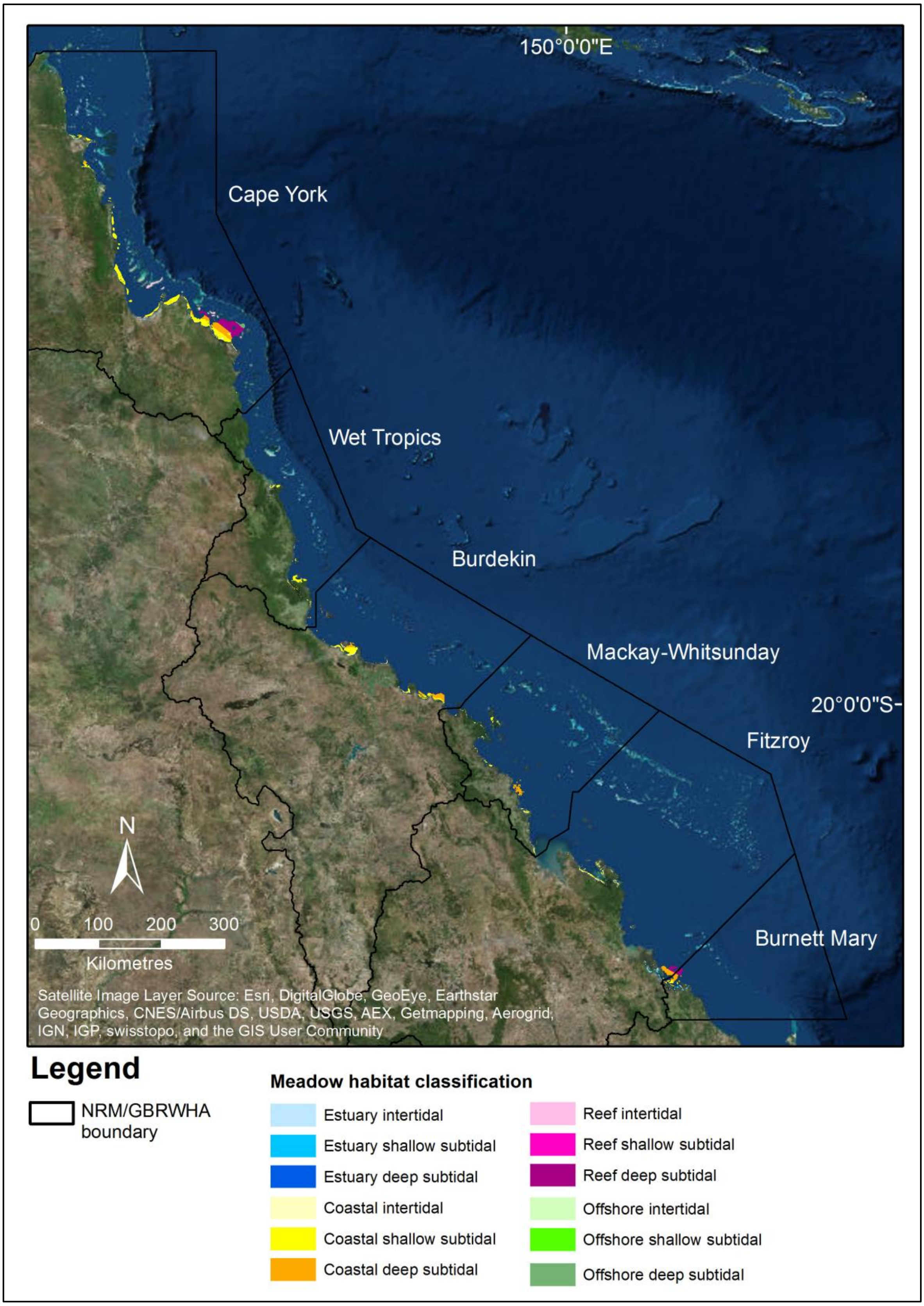


Figure 10: Mapped seagrass meadows (1984-2014; Carter et al. 2016) by zone within the Great Barrier Reef World Heritage Area (GBRWHA). Meadow areas detailed in Table 4

Table 3: Number of seagrass sites (1984-2014; Carter et al. 2016) witihin each assessment zone. SA; seagrass absent from all sites in that zone. ZA; zone absent from NRM region. DD; data deficient - no available data for that zone

Burdekin NRM			
Estuary intertidal	14	Reef intertidal	108
Estuary shallow subtidal	6 (SA)	Reef shallow subtidal	28
Estuary deep subtidal	(ZA)	Reef deep subtidal	128
Coastal intertidal	4477	Offshore intertidal	(DD)
Coastal shallow subtidal	6148	Offshore shallow subtidal	(DD)
Coastal deep subtidal	962	Offshore deep subtidal	253
Burnett Mary NRM			
Estuary intertidal	2346	Reef intertidal	(ZA)
Estuary shallow subtidal	385	Reef shallow subtidal	(DD)
Estuary deep subtidal	2 (SA)	Reef deep subtidal	34
Coastal intertidal	191	Offshore intertidal	(DD)
Coastal shallow subtidal	675	Offshore shallow subtidal	(DD)
Coastal deep subtidal	114	Offshore deep subtidal	68
Cape York NRM			
Estuary intertidal	30	Reef intertidal	1256
Estuary shallow subtidal	25	Reef shallow subtidal	6
Estuary deep subtidal	(DD)	Reef deep subtidal	393
Coastal intertidal	1649	Offshore intertidal	259
Coastal shallow subtidal	709	Offshore shallow subtidal	43
Coastal deep subtidal	165	Offshore deep subtidal	410
Fitzroy NRM			
Estuary intertidal	17032	Reef intertidal	(DD)
Estuary shallow subtidal	2555	Reef shallow subtidal	(DD)
Estuary deep subtidal	81	Reef deep subtidal	78
Coastal intertidal	1207	Offshore intertidal	(DD)
Coastal shallow subtidal	1285	Offshore shallow subtidal	(DD)
Coastal deep subtidal	405	Offshore deep subtidal	333
Mackay-Whitsunday NRM			
Estuary intertidal	108	Reef intertidal	(ZA)
Estuary shallow subtidal	54	Reef shallow subtidal	(ZA)
Estuary deep subtidal	1 (SA)	Reef deep subtidal	22 (SA)
Coastal intertidal	1136	Offshore intertidal	432 (SA)
Coastal shallow subtidal	2632	Offshore shallow subtidal	50 (SA)
Coastal deep subtidal	1317	Offshore deep subtidal	232
Wet Tropics NRM			
Estuary intertidal	3956	Reef intertidal	1163
Estuary shallow subtidal	2217	Reef shallow subtidal	397
Estuary deep subtidal	32 (SA)	Reef deep subtidal	229
Coastal intertidal	2927	Offshore intertidal	(DD)
Coastal shallow subtidal	5068	Offshore shallow subtidal	1 (SA)
Coastal deep subtidal	182	Offshore deep subtidal	179

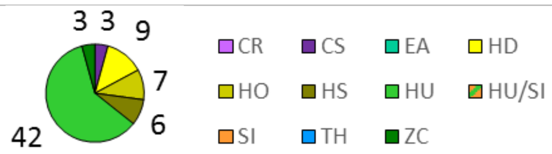
Table 4: Spatial extent (ha) of mapped seagrass meadows (1984-2014; Carter et al. 2016) by assessment zone. SA; seagrass absent from all sites in that zone. ZA; zone absent from NRM region. RE; remnant edge - seagrass absent from all sites in that zone and the mapped meadow is a small remnant edge from an adjacent zone's meadow. DD; data deficient - no available data for that zone. NM; no meadow - seagrass present, but no meadows mapped

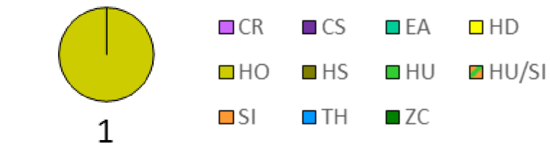
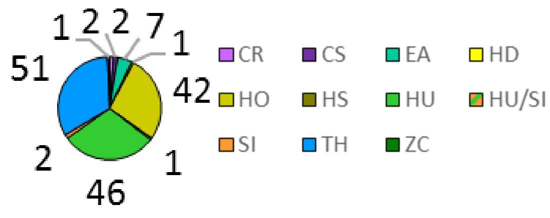
Burdekin NRM			
Estuary intertidal	57	Reef intertidal	414
Estuary shallow subtidal	3 (RE)	Reef shallow subtidal	120
Estuary deep subtidal	(ZA)	Reef deep subtidal	164
Coastal intertidal	6 465	Offshore intertidal	(DD)
Coastal shallow subtidal	36 766	Offshore shallow subtidal	(DD)
Coastal deep subtidal	22 261	Offshore deep subtidal	(NM)
Burnett Mary NRM			
Estuary intertidal	2 815	Reef intertidal	(ZA)
Estuary shallow subtidal	1 354	Reef shallow subtidal	(ND)
Estuary deep subtidal	6 (RE)	Reef deep subtidal	7 223
Coastal intertidal	271	Offshore intertidal	(DD)
Coastal shallow subtidal	4 889	Offshore shallow subtidal	(DD)
Coastal deep subtidal	8 774	Offshore deep subtidal	(NM)
Cape York NRM			
Estuary intertidal	78	Reef intertidal	14 415
Estuary shallow subtidal	525	Reef shallow subtidal	371
Estuary deep subtidal	(DD)	Reef deep subtidal	61 387
Coastal intertidal	10 970	Offshore intertidal	82
Coastal shallow subtidal	124 414	Offshore shallow subtidal	22
Coastal deep subtidal	44 504	Offshore deep subtidal	5 390
Fitzroy NRM			
Estuary intertidal	4 784	Reef intertidal	(DD)
Estuary shallow subtidal	1 391	Reef shallow subtidal	(DD)
Estuary deep subtidal	12	Reef deep subtidal	8 865
Coastal intertidal	8 244	Offshore intertidal	(DD)
Coastal shallow subtidal	9 198	Offshore shallow subtidal	(DD)
Coastal deep subtidal	13 929	Offshore deep subtidal	(NM)
Mackay-Whitsunday NRM			
Estuary intertidal	400	Reef intertidal	(ZA)
Estuary shallow subtidal	207	Reef shallow subtidal	(ZA)
Estuary deep subtidal	0.3 (RE)	Reef deep subtidal	(SA)
Coastal intertidal	4 981	Offshore intertidal	(SA)
Coastal shallow subtidal	10 387	Offshore shallow subtidal	(SA)
Coastal deep subtidal	13 702	Offshore deep subtidal	(NM)
Wet Tropics NRM			
Estuary intertidal	104	Reef intertidal	183
Estuary shallow subtidal	123	Reef shallow subtidal	56
Estuary deep subtidal	(SA)	Reef deep subtidal	64
Coastal intertidal	2 533	Offshore intertidal	(DD)
Coastal shallow subtidal	16 711	Offshore shallow subtidal	(SA)
Coastal deep subtidal	914	Offshore deep subtidal	(NM)

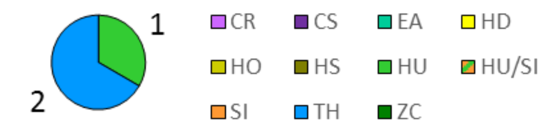
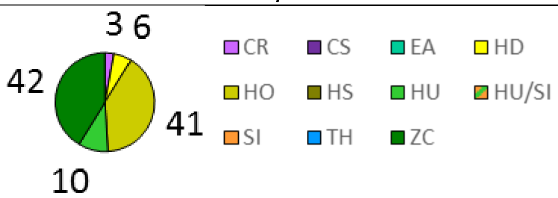
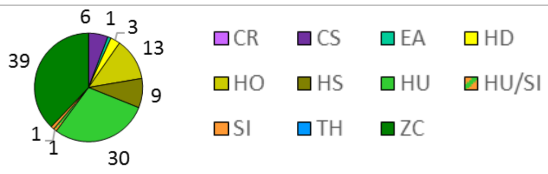
3.3 Seagrass communities by assessment zone

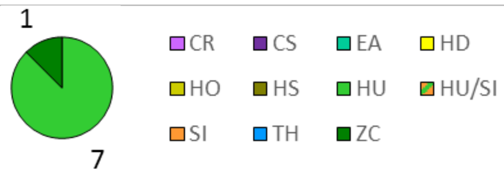
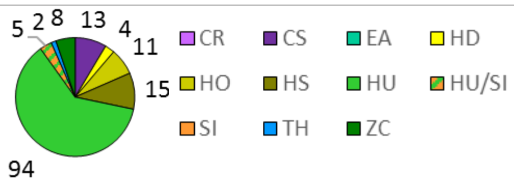
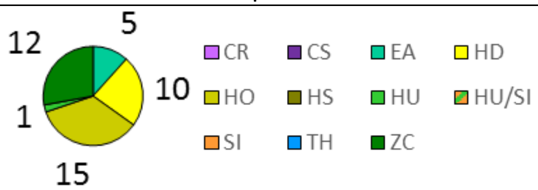
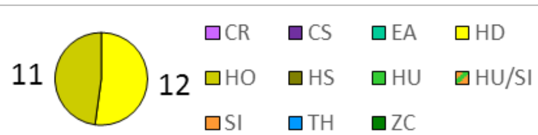
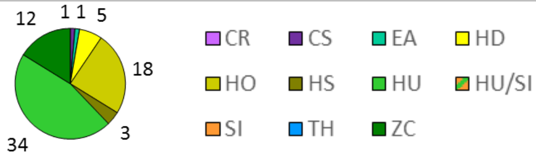
Twelve seagrass species from three families were recorded across the 66,201 sites that form the composite layer. Seagrass community was defined according to the dominant species (i.e. the species that occurred in the greatest proportion of sites) within each mapped meadow for intertidal and shallow subtidal zones, or all sites within each deep subtidal zone. There was rarely only one dominant species among meadows within the same zone; often between two and five different species were dominant across all meadows (Tables 5, 6). For example, in the Burdekin coastal shallow subtidal zone, *H. uninervis* was the dominant species in 42 of the 70 mapped meadows (Table 5). However, meadows were also dominated by *Zostera muelleri* subsp. *capricorni* (3 meadows), *C. serrulata* (3 meadows), *H. spinulosa* (6 meadows), *H. ovalis* (7 meadows), and *H. decipiens* (9 meadows). These species span a cross-section of seagrass life-history attributes and meadow form. Meadow size varied greatly, ranging from <1 ha to >20,000 ha; the commonality of a dominant species among meadows does not necessarily reflect that species' spatial extent. Deep subtidal seagrass communities were nearly always dominated by either *H. spinulosa*, *H. ovalis*, or *H. decipiens*.

Table 5: Intertidal and shallow subtidal dominant meadow community types for each assessment zone. CR: *C. rotundata*; CS: *C. serrulata*; EA: *E. acoroides*; TH: *T. hemprichii*; ZC: *Z. muelleri* subsp. *capricorni*; HU: *H. uninervis*; SI: *S. isoetifolium*; HS: *H. spinulosa*; HO: *H. ovalis*; HC: *H. capricorni*; HD: *H. decipiens*.

Habitat type	Dominant meadow community types (and number of meadows dominated by each species)	Number of meadows	Seagrass species present (alphabetical order)
	Burdekin NRM		
Estuary intertidal		3	ZC
Estuary shallow subtidal	Seagrass absent from all survey sites (n=6)	0	na
Coastal intertidal		52	CR, CS, EA, HD, HO, HS, HU, SI, TH, ZC
Coastal shallow subtidal		70	CR, CS, HD, HO, HS, HU, SI, ZC
Reef intertidal		14	CR, CS, HD, HO, HU, TH
Reef shallow subtidal		5	CR, CS, HD, HO, HS, HU, TH
Offshore intertidal	Data deficient	na	na
Offshore shallow subtidal	Data deficient	na	na
	Burnett Mary NRM		
Estuary intertidal		78	HD, HO, HS, HU, ZC

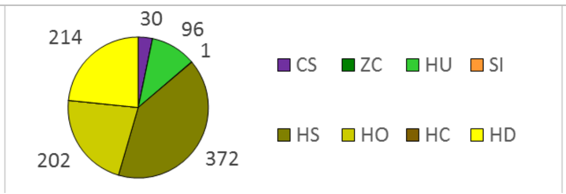
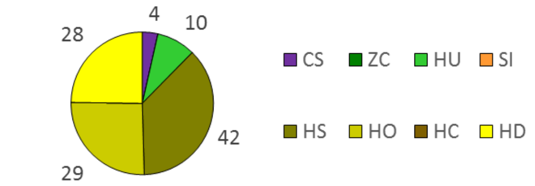
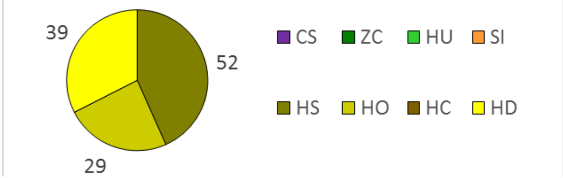
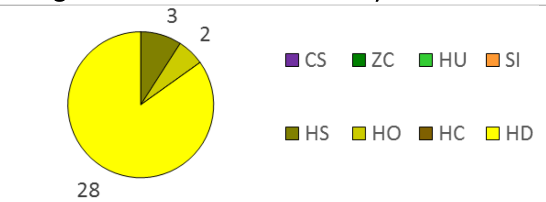
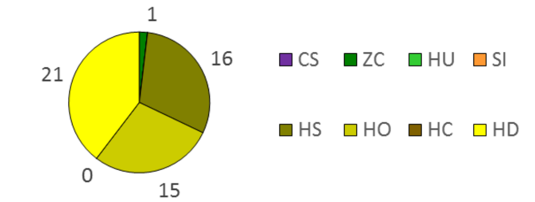
Estuary shallow subtidal		20	HD, HO, HS, HU, ZC
Coastal intertidal		1	HO, ZC
Coastal shallow subtidal		12	HD, HO, HS, HU, ZC
Reef intertidal	Habitat absent	na	na
Reef shallow subtidal	Data deficient	na	na
Offshore intertidal	Data deficient	na	na
Offshore shallow subtidal	Data deficient	na	na
Cape York NRM			
Estuary intertidal		3	HO, HU, TH
Estuary shallow subtidal		5	CS, EA, HO, HS, HU, TH
Coastal intertidal		155	CR, CS, EA, HD, HO, HS, HU, SI, TH, ZC
Coastal shallow subtidal		52	CS, EA, HD, HO, HS, HU, SI, TH

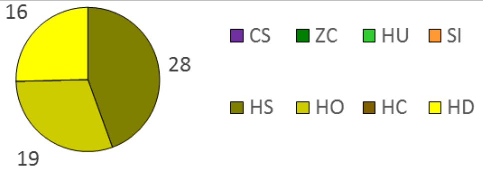
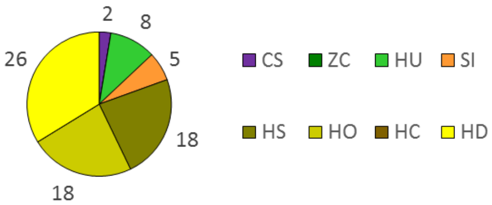
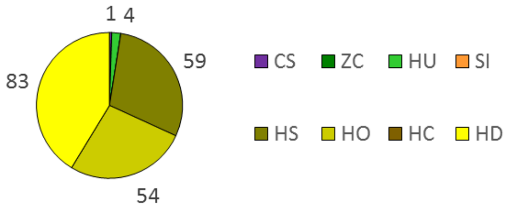
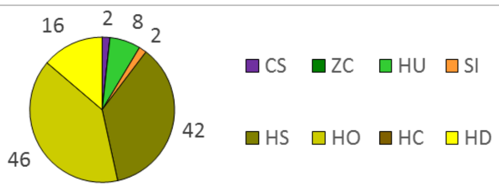
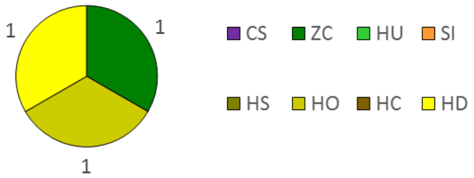
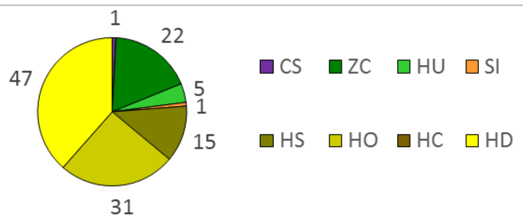
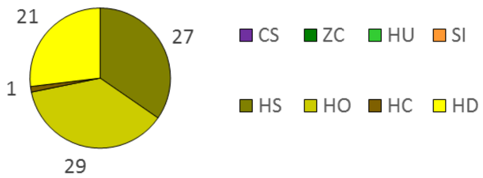
Reef intertidal		31	CR, HO, HU, TH
Reef shallow subtidal		1	HD
Offshore intertidal		9	HO, HU, SI, TH
Offshore shallow subtidal		3	HO, HS, HU, SI, TH
Fitzroy NRM			
Estuary intertidal		102	CR, HD, HO, HS, HU, ZC
Estuary shallow subtidal		30	HD, HO, HS, HU, ZC
Coastal intertidal		110	CS, HD, HO, HS, HU, SI, ZC
Coastal shallow subtidal		103	CS, HD, HO, HS, HU, SI, ZC
Reef intertidal	Data deficient	na	na
Reef shallow subtidal	Data deficient	na	na
Offshore intertidal	Data deficient	na	na
Offshore shallow subtidal	Data deficient	na	na

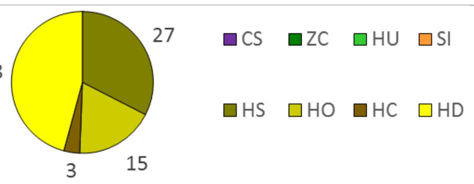
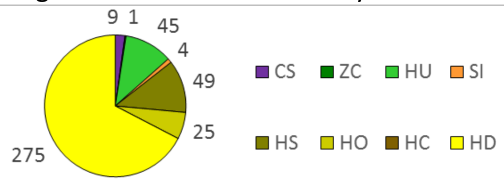
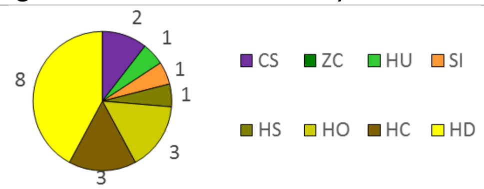
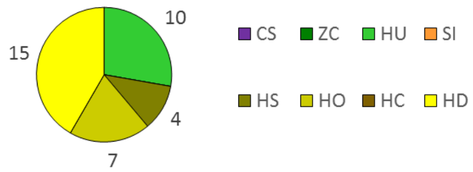
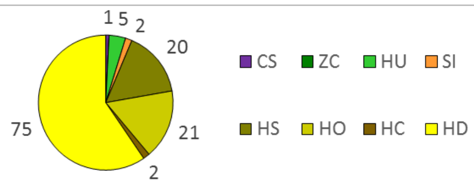
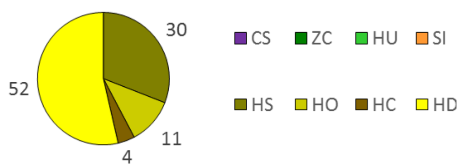
Mackay-Whitsunday NRM			
Estuary intertidal		18	HD, HO, HU, ZC
Estuary shallow subtidal		8	HO, HU, ZC
Coastal intertidal		112	CR, CS, HD, HO, HS, HU, SI, TH, ZC
Coastal shallow subtidal		152	CR, CS, HD, HO, HS, HU, SI, TH, ZC
Reef intertidal	Habitat absent	na	na
Reef shallow subtidal	Habitat absent	na	na
Offshore intertidal	Seagrass absent from all survey sites (n=432)	0	na
Offshore shallow subtidal	Seagrass absent from all survey sites (n=50)	0	na
Wet Tropics NRM			
Estuary intertidal		43	EA, HD, HO, HU, ZC
Estuary shallow subtidal		23	CS, EA, HD, HO, HU, ZC
Coastal intertidal		74	CR, CS, EA, HD, HO, HS, HU, SI, TH, ZC

Coastal shallow subtidal		126	CR, CS, HD, HO, HS, HU, SI, TH, ZC
Reef intertidal		10	CR, CS, EA, HO, HU, SI, TH
Reef shallow subtidal		19	CR, CS, HD, HO, HU, SI, TH
Offshore intertidal	Data deficient	na	na
Offshore shallow subtidal	Seagrass absent from all survey sites (n=1)	0	na

Table 6: Deep subtidal seagrass dominant community type for each assessment zone. CS: *C. serrulata*; ZC: *Z. muelleri* subsp. *capricorni*; HU: *H. uninervis*; SI: *S. isoetifolium*; HS: *H. spinulosa*; HO: *H. ovalis*; HC: *H. capricorni*; HD: *H. decipiens*.

Habitat type	Dominant meadow community types (and number of meadows dominated by each species)	Number of sites	Seagrass species present (alphabetical order)
	Burdekin NRM		
Estuary deep subtidal	No habitat of this type in habitat layer	0	na
Coastal deep subtidal		962	CS, HD, HO, HS, HU, SI
Reef deep subtidal		128	CS, HD, HO, HS HU
Offshore deep subtidal		253	HD, HO, HS
	Burnett Mary NRM		
Estuary deep subtidal	Seagrass absent from all survey sites	2	na
Coastal deep subtidal		114	HD, HO, HS
Reef deep subtidal		34	HD, HO, HS, ZC

Offshore deep subtidal		68	HD, HO, HS
	Cape York NRM		
Estuary deep subtidal	Habitat not surveyed	na	na
Coastal deep subtidal		165	CS, HD, HO, HS, HU, SI
Reef deep subtidal		393	CS, HD, HO, HS, HU
Offshore deep subtidal		410	CS, HD, HO, HS, HU, SI
	Fitzroy NRM		
Estuary deep subtidal		81	ZC, HO, HD
Coastal deep subtidal		405	CS, HD, HO, HS, HU, SI, ZC
Reef deep subtidal		78	HC, HD, HO, HS

Offshore deep subtidal		333	HC, HD, HO, HS
Mackay-Whitsunday NRM			
Estuary deep subtidal	Seagrass absent from all survey sites	1	na
Coastal deep subtidal		1317	CS, HD, HO, HS, HU, SI, ZC
Reef deep subtidal	Seagrass absent from all survey sites	22	na
Offshore deep subtidal		232	CS, HC, HD, HO, HS, HU, SI
Wet Tropics NRM			
Estuary deep subtidal	Seagrass absent from all survey sites	32	na
Coastal deep subtidal		183	HD, HO, HS, HU
Reef deep subtidal		229	CS, HC, HD, HO, HS, HU, SI
Offshore deep subtidal		179	HC, HD, HO, HS,

4.0 DISCUSSION

The representation of habitat, and the ability to capture the diversity of habitat features that support biological diversity, is a major consideration when understanding spatial and temporal change in an ecosystem (Young et al., 2015). Our classification of assessment zones summarizes a large and diverse amount of spatial data into one GIS layer that defines spatial boundaries in water depth and water quality conditions likely to affect seagrass presence and community composition. The total area assigned to a zone in this process was 228,342 km^2, which is considerably higher than the current estimated 35,000 km^2 of mostly deep-water seagrass on the GBR modelled by Coles et al. (2015), or the 4,505 km^2 that has been physically mapped and is presented here. The assessment zones delineated using the current scheme were defined largely based on mega-scale regional variation as a key driver of seagrass diversity, density and distribution. This includes latitudinal scales (e.g. wet tropics, dry tropics, anthropogenic influence), physical scales (e.g. photic light, depth, daytime tidal exposure, salinity, nutrients), and geological scales (e.g. sediment/substrate type). This spatial database provides a framework on which potential seagrass habitats can be further identified using additional attributes. It also underpins the design of a monitoring program representative of the diversity of seagrass habitats that is capable of evaluating natural processes and assessing environmental impacts that affect seagrass at a mega-scale (e.g. cyclones, flood events) and anthropogenic impacts at the meso-scale (e.g. coastal development, dredging, oil spills).

This work is a critical first step in quantifying desired state for GBR seagrasses. Within each zone, diversity in seagrass assemblages was evident. The example we presented in Section 3.3 for coastal shallow subtidal zone in the Burdekin region, where 6 different species occurred as the dominant species across 70 mapped meadows, and these species spanned the range of seagrass life history traits (colonising, opportunistic or persistent), was not unusual (Tables 5, 6). This reflects within-zone diversity, driven by attributes that were not included in our zone classification but that influence seagrass. These include changes in sediment type at finer spatial scales, e.g. the transition from mud to sand in a bay, or sand to rubble on a reef top; and local hydrodynamic conditions driven by coastal geography, e.g. tidal energy, bed sheer stress, wave and wind exposure, and shelter (Coles et al., 2015; Grech et al., 2010; Kilminster et al., 2015). This diversity was particularly evident in intertidal coastal zones: seagrass grows on fringing reef tops, in sandy bays, and on muddy banks, but this diversity is not captured by our current classification system. Within-zone seagrass diversity highlights the importance of updating this analysis with further data on the habitat.

Quantifying desired state of seagrass in the GBR requires adequate data within each zone where seagrass occurs (presence/absence), what is there (species composition), how much is there (biomass/percent cover), and the extent of the resource (meadow area). These attributes are not static, which renders the temporal resolution of the data important. Seagrass growth fluctuates seasonally (Carter et al., 2014; Vermaat, 1996). More significantly, natural and anthropogenic disturbances influence seagrass presence and community structure. Natural disturbances include storms, floods, disease, and overgrazing by herbivores (Fourqurean et al., 2010; McKenna et al., 2015; Robblee et al., 1991). Anthropogenic disturbances include industrial and urban run-off, port and coastal development, and dredging (Grech et al., 2012; York et al., 2015). The timing and severity of disturbances will influence a meadow’s capacity to resist or recover and the recovery trajectory (O'Brien et al., 2017), but so will habitat type, even in the same location (Rasheed et al., 2014), and the genera and species that make up each community (Birch et al., 1984; O'Brien et al., 2017). Seagrass' sensitivity to disturbance events and environmental change make it an ideal indicator for long-term monitoring of marine environmental health (Abal et al., 1996; Dennison et al., 1993; Orth et al., 2006). However, any assessment of seagrass state requires within-zone, community-specific data with sufficient temporal resolution that allows the data to be assessed in the context of disturbance events, recovery trajectories, and seasonal fluctuations.

Robust seagrass desired state analysis will be restricted to locations within zones where continuous data collection has occurred, and for an adequate time span (Figure 11). Two major monitoring programs exist on the GBR with long-term data – the MMP and QPSMP (Figure 12). The seagrass attributes they monitor most relevant to desired state analysis are abundance (percent cover and above-ground biomass in MMP and QPSMP, respectively), meadow area (QPSMP), and species composition (MMP and QPSMP). An "adequate" data time span for desired state analysis may vary among habitats. Transitory meadows, for example, can die-back annually or with longer or shorter time scales due to changes in environmental conditions; these meadows are more likely to occur in variable habitats such as estuarine or deep subtidal habitats (Kim et al., 2014; van Lent et al., 1994; York et al., 2015). Enduring meadows, on the other hand, are defined as being present for five years or more under natural conditions (Kilminster et al., 2015), however, there can be a gradient in the nature of the meadow from transitory to enduring suggesting in some cases a longer time period (e.g. 10 years) may be required (Bryant et al., 2014). The length of continuous data collection for the ranges from 3 to 21 years, and 3 to 25 years for MMP and QPSMP, respectively.

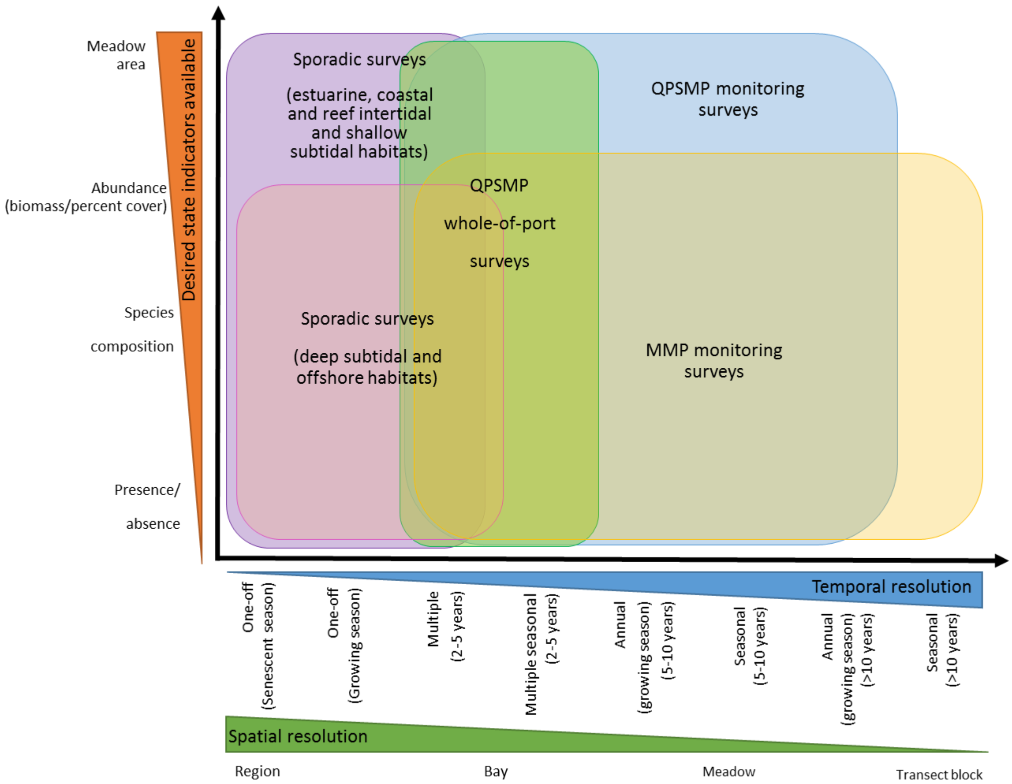


Figure 11: Seagrass desired state analysis requires data with high spatial and temporal resolution. The available data ranges from sporadic broad-scale surveys and meso-scale surveys with moderate spatial low temporal resolution, to small-scale surveys with high spatial high temporal resolution data. The survey method dictates the number of desired state indicators available for analysis.

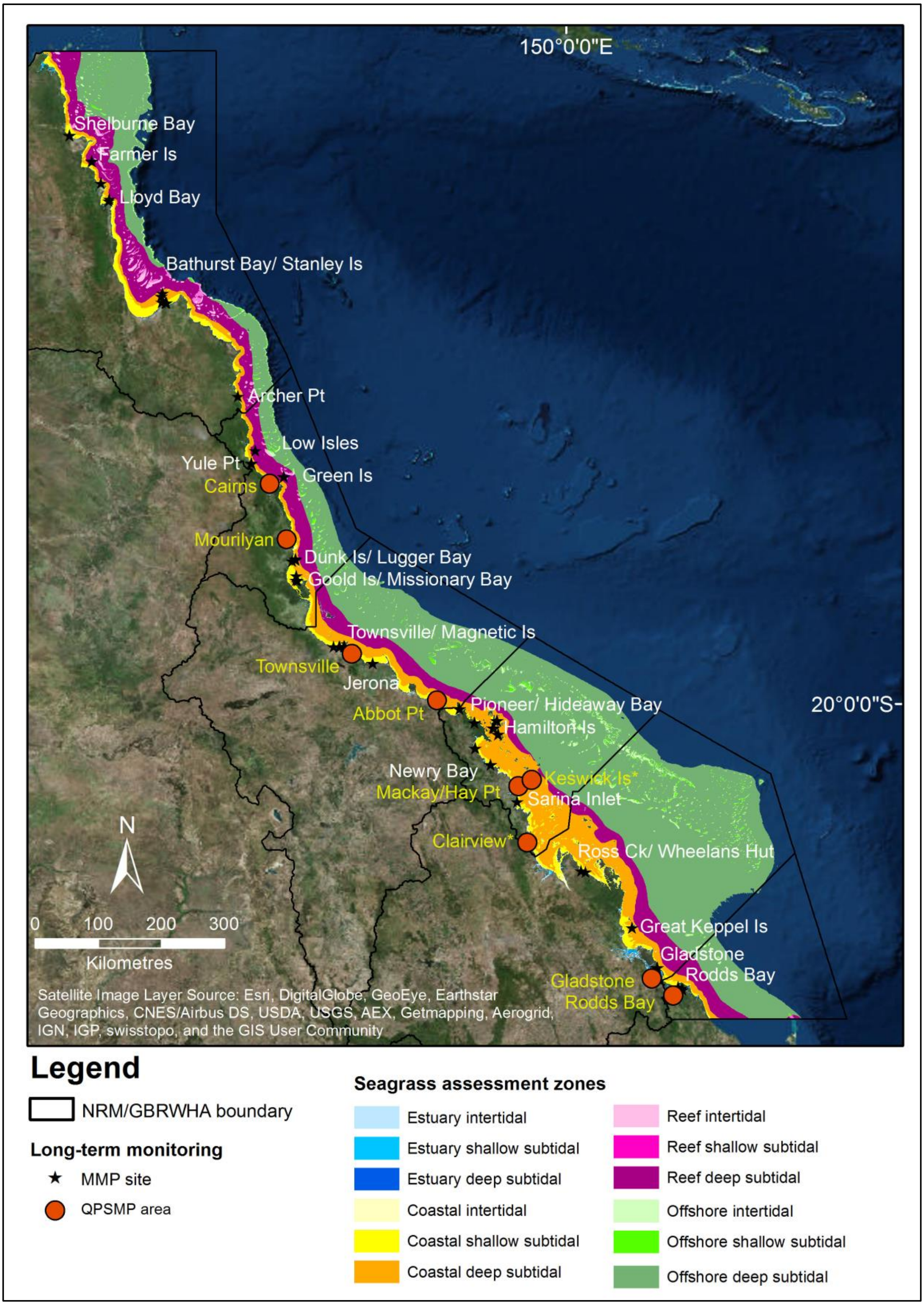


Figure 12: Location of Queensland Ports Seagrass Monitoring Program (QPSMP) areas (multiple meadows per area) and Marine Monitoring Program (MMP) sites (including QPWS drop-camera and Seagrass-Watch sites) within seagrass assessment zones

At the broader GBR scale, considerable temporal gaps exist in data collection, particularly when data is divided by zone (Figure 13). Spatially extensive seagrass surveys began in most NRMs between 1984 and 1987, but were followed by a near-decade long gap in data collection in many regions. Spatially extensive GBR-wide survey data provides the most information on deep subtidal seagrass, particularly in reef and offshore zones, but is ~12-15 years old. Large-scale surveys of coastal and estuarine zones occurred in the mid to late 1980s. Since then, data collection has been more localised, e.g. whole harbour/port surveys every 3-5 years, and the meso-scale intertidal surveys in the Cape York region for the 2011-2014 Oil Spill Response Atlas. This lack of temporal resolution may limit our ability to use this data for desired state analysis (Figure 11), particularly where there is little historical context to explain how potential impacts and recovery trajectories may have influenced these seagrass “snapshots”.

Where sufficient temporal information exists, desired state should ideally take into account a seagrass community’s history, encompassing its state across a range of environmental conditions. This is preferable to applying a generalised condition derived from other locations, as this may result in unrealistic expectations of desired state for many meadows due to the myriad of localised factors that act to constrain seagrasses to a particular range of states. In reality, this will not be possible across the extensive range of GBR habitats and seagrass communities, meaning a combination of using specific long-term site data for locations (where it exists) and a process of extrapolation into areas with only limited or no historical data, will be required.

Desired state analysis also will be dictated by the spatial resolution of the data. Existing long-term monitoring locations are inconsistent across NRM regions and do not cover the entire range of assessment zones identified here, focusing predominately on intertidal and shallow subtidal depths in estuarine, coastal and, to a smaller extent, reef zones. Seagrass extent (meadow area) will be the most problematic desired state indicator to quantify as temporal and meadow-scale mapping surveys are limited to QPSMP locations, and remain biased to estuarine and coastal intertidal and shallow subtidal zones (Figure 12). Historical site data demonstrates that deep subtidal seagrass occurs across the GBR lagoon (Figure 9), with communities dominated by *Halophila* (Table 6); the species most commonly found in subtidal waters due to their low light requirements (Freeman et al., 2008). However, few deep subtidal meadows have been mapped, particularly in the reef and offshore zones. Where deep subtidal meadows are mapped, it is often as an extension of adjacent shallow subtidal meadows, and meadow boundaries often follow a survey boundary rather than the meadow’s natural/full extent.

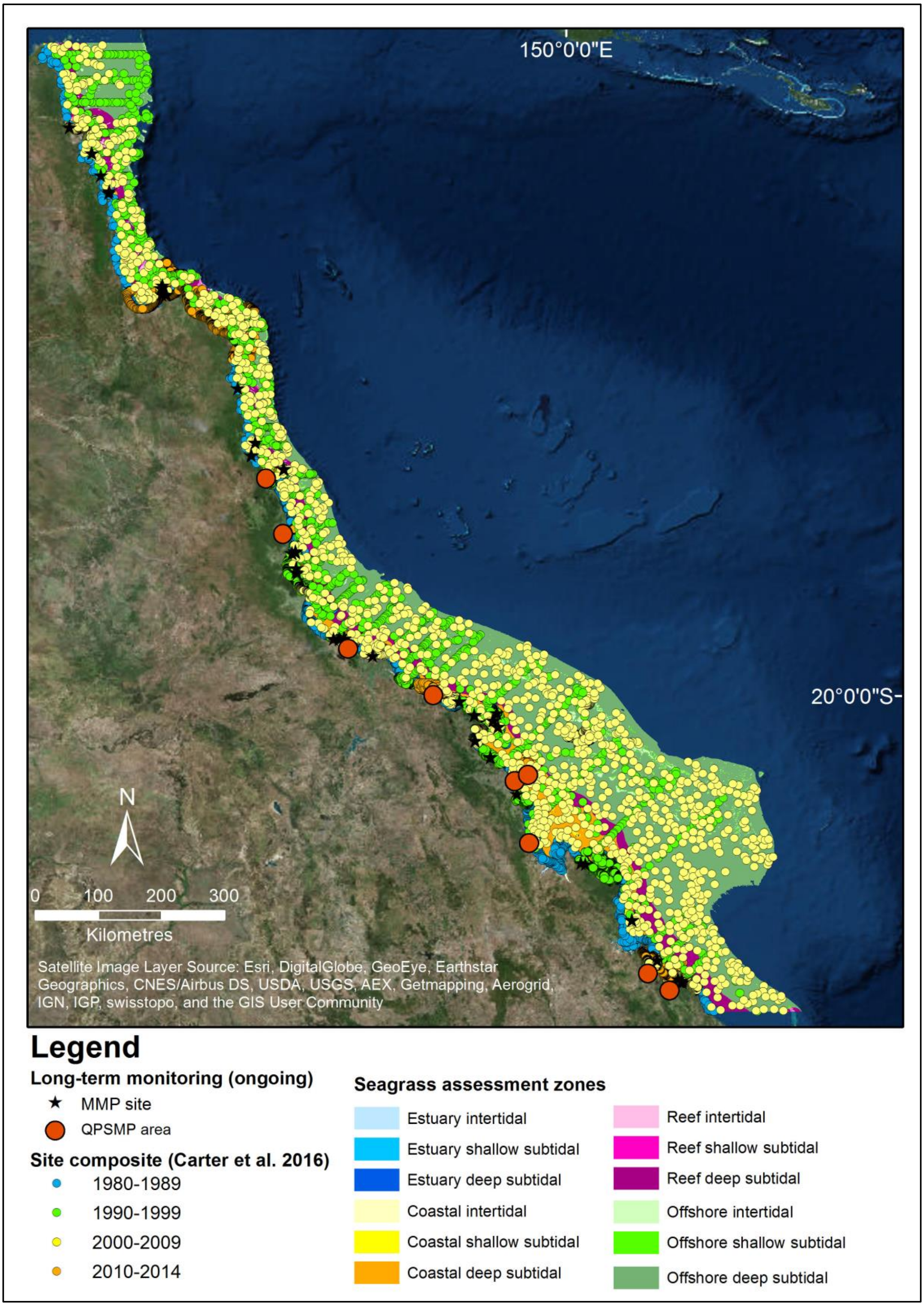


Figure 13: Age of seagrass site data by assessment zone. Ongoing data collection occurs at the long-term monitoring locations

5.0 CONCLUSION

We present a seagrass assessment scheme for the GBR that summarizes a large amount of spatial data into zones within one GIS layer. Our results and analysis of existing datasets provides a framework that categorises habitats across the GBR based on dominant pressures that are known to impact on seagrass presence/absence, species, and abundance. The assessment zones can be used to differentiate seagrass habitat at a broad regional scale, from intertidal to deep subtidal waters, and distance from land-based influence. This provides a framework for the design of assessment and monitoring programs that are representative of the range of seagrass habitats in the Great Barrier Reef. The high variability in community composition identified by the current study demonstrates that further separation into major seagrass species assemblage types within the broader physical/water body zones will be required to produce attributes of desired seagrass state that will be useful to managers. This additional analysis (NESP TWQ Hub Project 5.4, 2019-2010) will build on the framework outlined in this report, by incorporating additional habitat data and seagrass data.

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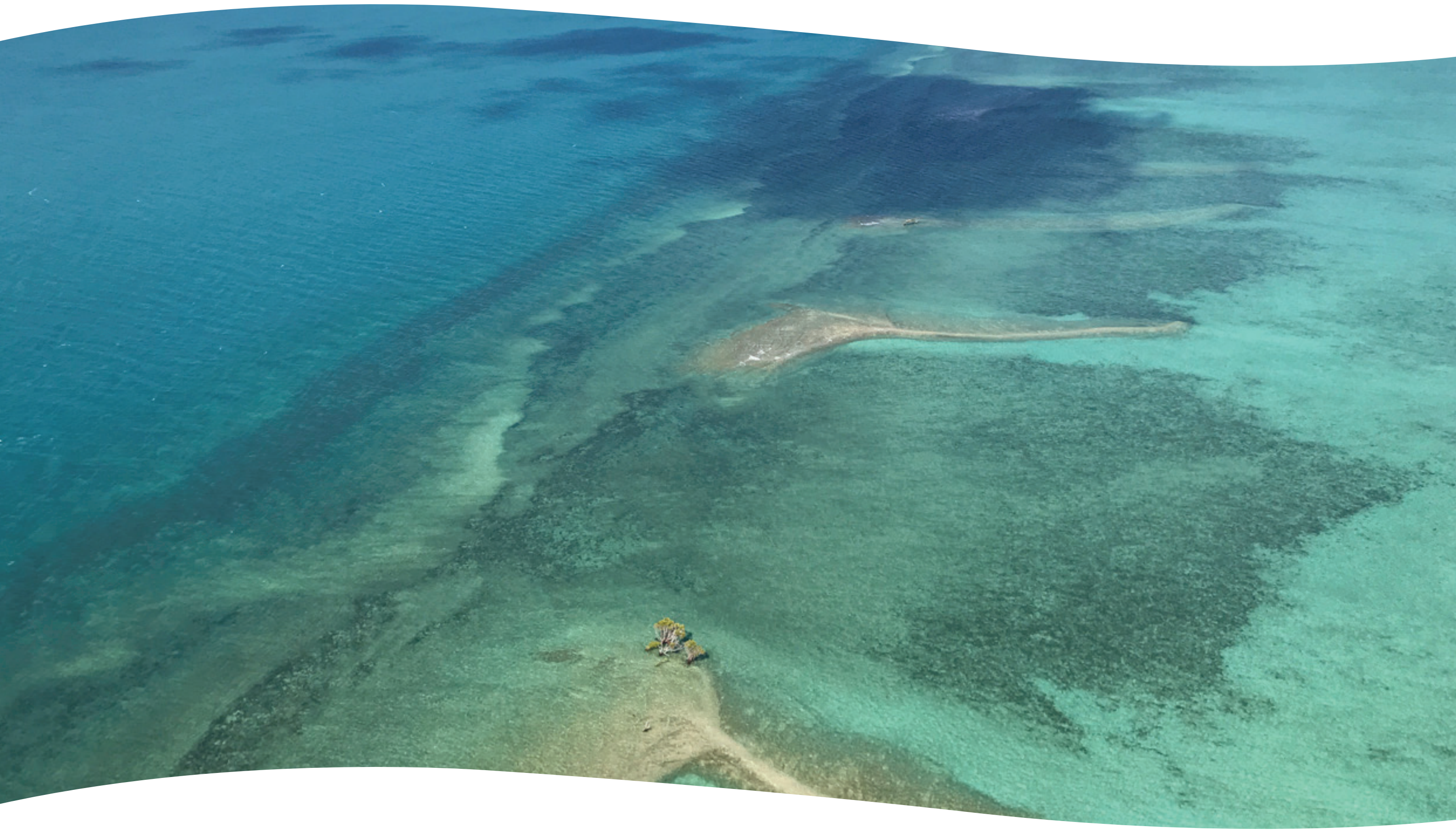

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