

POST-FLOOD SEAGRASS MONITORING IN THE GREAT SANDY MARINE PARK - 2023

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EXECUTIVE SUMMARY

Extensive flooding of the Mary River over two consecutive events in early 2022 resulted in persistent flood plumes in the Great Sandy Marine Park (GSMP), alerting marine managers to potential impacts on seagrass meadows and subsequent declines in the health of dependent species including dugongs and green sea turtles. In response, the former Queensland Department of Environment and Science commissioned post-flood assessments of seagrasses in Hervey Bay and the Great Sandy Strait (both within the GSMP) funded by the joint Australian-Queensland government funded Disaster Recovery Funding Arrangements Environmental Recovery Program. Surveys were conducted in May 2022 (York et al. 2022, Bryant et al. 2023) during a typical low seagrass growth period, and again in October/November 2022 (Bryant et al. 2023) during a typical high seagrass growth period. It had been more than 20 years since the last broad-scale mapping of seagrasses in the region so the state of seagrass resources prior to the flood event was not well known. These surveys aimed to quantify the state of seagrasses in the region at three months and at nine months following the flood events to help inform management decisions and future seagrass monitoring.

Results of the initial post-flood surveys showed that the distribution and abundance of seagrass was significantly reduced compared to historical levels. In Hervey Bay, seagrass distribution three months after the flood (744 km²) was less than a third of the distribution found during historical (1998) surveys (2,307 km²) and where seagrass existed, density was extremely low (York et al. 2022). In October 2022, nine months after the flood, seagrass distribution had increased significantly (1343 km²), mainly due to an expansion in the large deep-water meadow in the centre of the bay. Despite signs of recovery, total seagrass distribution was only 58% of that mapped in 1998, and where seagrass did occur, especially intertidally, it remained sparse with very low density compared to historical levels (Bryant et al. 2023). In the Great Sandy Strait, intertidal seagrass distribution three months after the flood (~12 km²) was only 22% of the area found during historical (1998) surveys (~53 km²) and abundance was extremely low (< 0.1 g DW m⁻² and < 1 % cover) compared to historical levels. Follow up surveys at four seagrass assessment areas in October 2022 found that very little recovery had occurred (Bryant et al. 2023).

Given the significance of seagrass to the region, based on the results of these initial surveys, Bryant et al. (2023) recommended resurveying the entire region in 2023 to track the recovery of seagrass resources. A range of other measures were also recommended to improve the understanding of seagrass dynamics and recovery in the region. These included monitoring light (Photosynthetically Active Radiation) and temperature at key locations in the region, assessing the status of a seed bank to assist with recovery, and investigating impacts of megaherbivore (dugong and turtle) grazing on the rate of seagrass recovery in the region. This report presents findings of the most recent post-flood survey conducted from August to November in 2023 as well as the results of these other complimentary monitoring and research programs.

In August to November 2023, total seagrass distribution in Hervey Bay (1700 ± 404 km²) had increased a further 26% over the 12 months since the October/November 2022 survey and was almost 75% of the 1998 distribution. The increase in area was again mostly due to the colonisation of *Halophila decipiens* around the periphery of the large deep-water meadow in the middle of the bay. Average seagrass biomass and percent cover had increased significantly at subtidal and deep-water meadows, but the majority of intertidal seagrass remained low in density and density overall was lower than historical (1998) levels. In the Great Sandy Strait, the total area of intertidal seagrass mapped from August to November 2023 (53 km²) had more than tripled since the first post-flood survey in May (12 km²) and was very similar to the total area of seagrass mapped in December 1998 (53 km²), although there was very little subtidal seagrass and the distribution of meadows had changed with very little seagrass present from the Mary River to the Moonboom Islands compared with historical surveys. The

assessment meadow at Moon Point increased significantly in area and density (both biomass and percent cover) and there were significant increases in percent cover at assessment meadows at Urangan, Poona and Tin Can Bay. However overall, average biomass remained low compared to historical (1998) levels. There had been a species shift at many of the meadows along the mainland coast from *Zostera muelleri* to *Halodule uninervis* dominated communities although it is possible that both species co-occur in these areas.

PAR monitoring in Hervey Bay indicates that light levels were above the minimum light requirements for *Halophila* species for at least part of the 2023 seagrass growing season at all locations and has likely contributed to the further recovery of *Halophila* communities in the region. Light was well below growth requirements for other species in these subtidal areas (*H. uninervis* and *Z. muelleri*).

Results of megaherbivore exclusion studies at Moon Point indicate that herbivory does structure the seagrasses there, however site effects made it difficult to understand more about these patterns. Given the recovery of seagrass in the Moon Point meadow and more broadly throughout the survey area, it is likely that by the time of these studies herbivory was not driving seagrass declines or significantly contributing to impeding seagrass recovery.

The numbers of *H. uninervis* and *Z. muelleri* seeds found in Hervey Bay are low (0.8 - 6.4 seeds m⁻²) compared to studies in some other areas of Queensland. While the presence of some seeds was a positive sign, the low numbers indicate they had not yet reached levels that would convey significant long-term resilience through a large and persistent seed bank should another catastrophic loss of seagrass occur in the near future.

The seagrass assessments and monitoring during 2023 revealed positive outcomes for seagrasses and associated fauna with substantial strides toward recovery. That recovery should continue with the maintenance of favourable growing conditions and the absence of major flooding. While some resilience has returned to the system it could be several years before the system achieves a truly resilient seagrass community with a replenished seed bank and fully recovered adult seagrass population.

We have recommended a long-term monitoring approach that incorporates monitoring at key intertidal meadows and some larger spatial assessments of deep-water seagrass on a regular (at least annual) basis. We have also suggested a range of other measures that could be implemented to improve the understanding of seagrass dynamics and recovery in the region and ensure that management of seagrasses and associated fauna are well informed in the future.

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INTRODUCTION

Study area

The Great Sandy Marine Park on the eastern subtropical coast of Australia, extends from Baffle Creek in the north to Double Island Point in the south. It encompasses the Bundaberg Coast, Hervey Bay, Great Sandy Strait, Tin Can Inlet and the waters seaward to three nautical miles off the east coast of K'gari (Figure 1). The marine environments are among the most biodiverse in Australia and in 2009 contributed to the recognition by UNESCO of the globally significant Great Sandy Biosphere (Ribbe 2014). The region also hosts the east coast's largest dugong population south of Torres Strait and six of the world's seven species of endangered and vulnerable marine turtles. Of these, loggerhead, green and flat-back turtles regularly nest along the region's foreshores.

Hervey Bay extends from the relatively narrow opening of the Great Sandy Strait in the south at Urangan and is bound by the Queensland coast on the western side north to Bundaberg and by K'gari (Fraser Island) on the eastern side with an opening of about 80 km width in the north (Figure 1). The average depth of the bay is approximately 20 m (Ribbe 2014). There are four main river catchments that influence the marine waters of Hervey Bay; the Mary, Burrum, Elliott and Burnett (Figure 1). These rivers discharge turbid flood waters during major flood events that establish a frontal structure along the western region of the bay with a recovery time of approximately 2 months (Ribbe 2014). Hervey Bay contains one of the largest expanses of deep-water (> 10 m) seagrasses on the east coast of Queensland (Lee Long et al. 1993), which support large numbers of dugongs (Preen and Marsh 1995, Sheppard et al. 2006, Sheppard et al. 2007) and green turtles (Hazel and Gyuris 2006).

The Great Sandy Strait is a sand passage estuary that encompasses an area of around 930 km² between the mainland and K'gari, from Urangan in the north to Tin Can Inlet in the south (Figure 1). The Mary River flows into the northern section of the Great Sandy Strait and the smaller catchments of Boonooroo Creek, Kauri Creek and Tin Can Estuary flow into the southern section (Figure 1). The Great Sandy Strait is the largest area of tidal swamps within the South East Queensland bioregion, consisting

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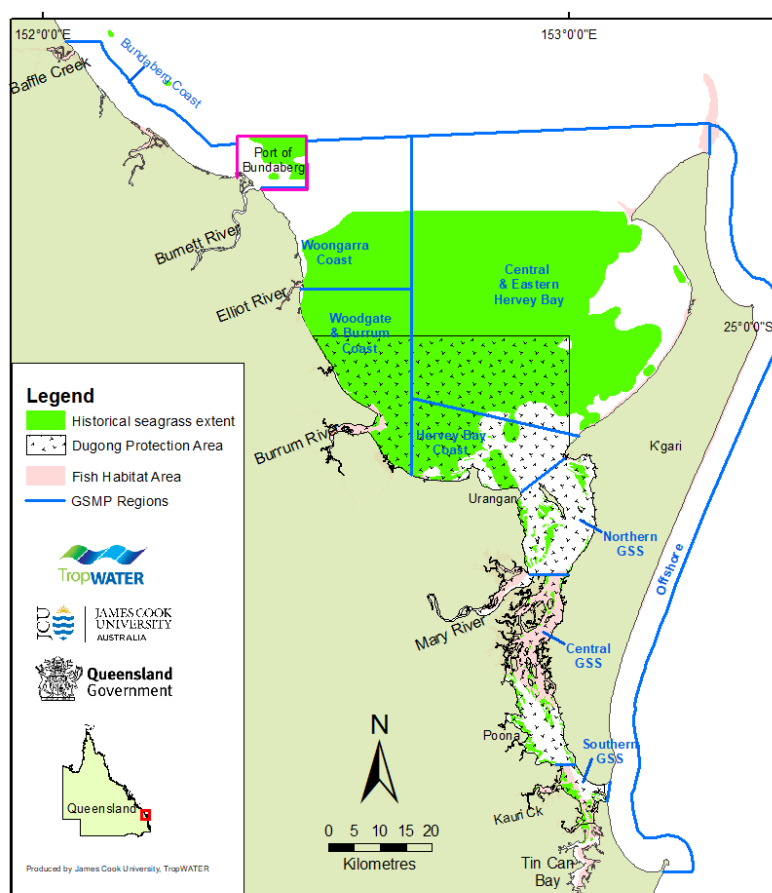


Figure 1. Map of the Great Sandy Marine Park.

of intertidal sand and mud flats, extensive seagrass beds, mangroves, salt flats and saltmarshes. The region supports a wide range of migratory and other birds, fish, crustaceans, dugong, turtle and dolphins and in 1999 was listed as a Wetland of International Importance under the Ramsar agreement (RAMSAR 1999).

Seagrasses of the Great Sandy Marine Park

Hervey Bay

Historically, seagrass meadows in the bay are extensive with the distribution dominated by deep-water communities of the colonising species *Halophila spinulosa*, *Halophila ovalis* and *Halophila decipiens* (Figure 2). Intertidal meadows also occur predominately on sand banks between Urangan and Burrum Heads and generally contain low-biomass assemblages of *Zostera muelleri* (syn. *Zostera capricorni*), *Halodule uninervis* and *H. ovalis* (Preen et al. 1995, McKenzie 2017, McKenzie 2000). Seagrass Watch intertidal monitoring transects on the southwestern shore of the bay show fluctuations in seagrass abundance over the past 20 years. Seagrass at Burrum Heads fluctuated with peaks of around 30-40% cover and was <10% in December 2021 prior to the 2022 flood event. Adjacent to the Hervey Bay township at Dundowran, seagrass cover has remained <1% since at least 2015 (Seagrass Watch 2023).

Great Sandy Strait

Seagrasses in the Great Sandy Strait were first mapped in 1973 with six species observed including extensive dense meadows of *Cymodocea serrulata* on the western shore to the west of the Tin Can Bay and *Z. muelleri*, *H. uninervis* and *H. ovalis* dominating meadows along intertidal mudflats (Dredge 1977). A series of broad-scale seagrass mapping surveys in the 1990s and early 2000s using aerial photography, aerial and dive surveys combined with long-term monitoring transects found dynamic meadows that at their peak included dense *Z. muelleri* with *H. ovalis* meadows on the mud/sand banks throughout the region (McKenzie and Campbell 2003). Seagrass Watch intertidal monitoring transects throughout the Great Sandy Strait also show fluctuating seagrass abundance since 1999. Seagrass monitored at Urangan has come and gone on an irregular basis with a peak of around 80% cover but has remained low (<5% cover) for several years prior to the 2022 flood event. Seagrass cover at Boonooroo and Tinnanbar has also fluctuated over the course of monitoring, but abundance was low (<1% cover) in December 2021 prior to the 2022 flood event (Seagrass Watch 2023).

	<i>Zostera muelleri ssp capricorni</i> • Narrow and wide leaf blades • 5 longitudinal veins and cross veins which form a mesh across the leaf blade • Rounded leaf tip • Leaf grows straight from the rhizome i.e. no shoots
	<i>Halodule uninervis</i> • Narrow leaf blades 0.25-5mm wide • Trident leaf tip ending in three points • 1 central longitudinal vein which does not usually split into two at the tip • Usually pale ivory rhizome, with clean black leaf scars along the stem • Dugong preferred food
	<i>Halophila spinulosa</i> • Fern like • Leaves arranged in opposite pairs • Erect shoot up to 15cm long • Found at subtidal depths
	<i>Halophila ovalis</i> • Small oval shaped leaves (0.5 - 2cm long) • 8 or more cross-veins on leaf • No hairs on leaf surface • Dugong preferred food
	<i>Halophila decipiens</i> • Small oval leaf blade (1-2.5cm long) • 6-8 cross veins • Leaf hairs on both sides • Found at subtidal depths
	<i>Cymodocea serrulata</i> • Flat, strap-like leaves 5-9mm wide • Serrated leaf tip • Robust strong rhizome • 13-17 longitudinal veins • Leaves 6-15cm long
	<i>Syringodium isoetifolium</i> • Cylindrical in cross section (spaghetti like) • Leaf tip tapers to a point • Leaves 7-30cm long • Found on shallow subtidal reef flats and sand banks

Figure 2: Seagrass species found in the Great Sandy Marine Park. *C. serrulata* and *S. isoetifolium* have not been observed in the region since 1998 and 2002 respectively (McKenzie and Campbell 2003).

Impacts to seagrasses of the Great Sandy Marine Park

Light

Light is essential for seagrasses as it enables photosynthesis which is fundamental in enabling carbon fixation, growth and biomass production (Collier and Waycott 2009, Collier et al. 2016a). Seagrasses have relatively high light requirements as they invest in building and maintaining non-photosynthetic structures such as rhizomes and roots (Dennison et al. 1993). The availability of light determines the spatial distribution and depth range seagrasses will inhabit (Duarte 1991). Limitations in light can cause a change in plant physiology as the plant adjusts the rates of growth by metabolic changes such as balancing carbon supply and respiratory requirements (Ralph et al. 2007, Collier et al. 2012, O'Brien et al. 2018). Major flood events and associated river flows deliver large volumes of highly turbid water to shallow coastal areas often resulting in increased concentrations of silt, organic matter and nutrients (Kamp-Nielsen et al. 2002) and reducing levels of light available to seagrasses.

The Mary River in the south, as well as the other smaller estuaries along the western coast of Hervey Bay and in the Great Sandy Strait discharge turbid flood waters during major flood events (e.g., 1992, 1999, 2011, 2013 and 2022 – see Figure 3). Whilst no consistent long term seagrass monitoring spans this same period, reported declines in seagrass distribution and abundance coincide with major flow events. Declines have been reported in 1992 (Preen et al. 1995), 1999 (McKenzie et al. 2000), and 2022 (Bryant et al. 2023). No broad scale seagrass assessments occurred in 2010/2011 or 2013 but monitoring at seagrass watch sites also detected declines in seagrass abundance over this period (Seagrass Watch 2023). The flooding and associated seagrass loss with La Niña cycles generally coincide with increased strandings of dugong and green turtles which both rely on seagrass as a major component of their diet (Meager and Limpus 2014, Flint et al. 2017).

Herbivory

Seagrass meadows are well adapted to grazing by megaherbivores and have evolved under intense grazing pressure. This grazing by dugongs and green turtles shapes many of the meadow characteristics and can drive seagrass productivity (Scott et al. 2018). However, grazing can exacerbate meadow declines that are driven by environmental conditions, as herbivores continue to feed in seagrass meadows that have been impacted by flooding or cyclones. This dynamic presents a problem for both the seagrass meadows themselves and the herbivores which rely on seagrass as a food source.

Overgrazing by megaherbivores has led to seagrass meadow loss in some locations worldwide. Overgrazing often occurs where numbers of herbivores increase due to effective conservation programs, but their predators are declining or where seagrass management has not kept pace with turtle conservation (Heithaus et al., 2014). This mismatch means herbivores can reach densities greater than the seagrass meadow can support. If excessive grazing pressure is sustained over a long period, it may lead to the loss of one or many meadows in an area; such losses have been observed in Bermuda, Indonesia and the Indian Ocean (Christianen et al., 2014; Fourqurean et al., 2019; Gangal et al., 2021). The effect of grazing pressure on seagrasses in the Great Sandy Marine Park is not well understood but overgrazing has the potential to exacerbate declines in flood effected meadows in the Great Sandy Marine Park.

Seed bank

A key aspect in understanding the resilience of seagrass meadows to stressors is their capacity to recover from impact (Kenworthy 2000). Seagrass recovery predominantly occurs through the dispersal of sexual propagules (seeds, fruits and flowers), and/or asexual vegetative extension of plants at the

periphery and replacement of above-ground structures (Rasheed 2004; 1999; Rollón et al. 1998) or the dispersal of vegetative fragments to new environments (Thomson et al. 2015; McMahon et al. 2014). Some species are also capable of producing relatively long-lived seeds stored in the sediment. This seed bank may be especially important for the recovery of seagrass meadows following natural widespread losses from events such as flooding. Knowledge of the seed bank status in the Great Sandy Marine Park will help to determine the resilience of these meadows to ongoing environmental pressures.

Flood events in 2022

In early 2022 two significant flood events in January and February-March dispersed suspended sediments from the Mary River and other catchments into Hervey Bay and Great Sandy Strait (Figure 3). The first event was driven by a rain depression brought by the remnants of tropical cyclone Seth with discharge in the Mary River at Home Park peaking at 663,655 ML day⁻¹ on 9th January 2022. The second flood event saw river discharge in the Mary River at Home Park peak at 657,944 ML day⁻¹ on 28th February 2022 (Figure 3). Processed satellite images in January, February and March using Forel-Ule colour classes show the flood plume from the Mary River was fairly constrained to the mainland coast and Great Sandy Strait during January and extended further offshore into the southern and western regions of Hervey Bay during March (Lewis et al. 2022) (Figure 4).

This raised concerns for the ongoing health of seagrass communities in the region and the dugong and green turtle populations that rely on them as a food source. The former Queensland Department of Environment and Science entered into a collaborative agreement with James Cook University's Centre for Tropical Water & Aquatic Ecosystem Research to map and monitor the post-flood seagrass distribution in Hervey Bay and Great Sandy Strait in May 2022 (York et al. 2022, Bryant et al. 2023) October/November 2022 (Bryant et al. 2023) and between August and November 2023 to track recovery in the region. This report presents findings from the most recent assessment of seagrasses in the Great Sandy Marine Park conducted from August to November in 2023.

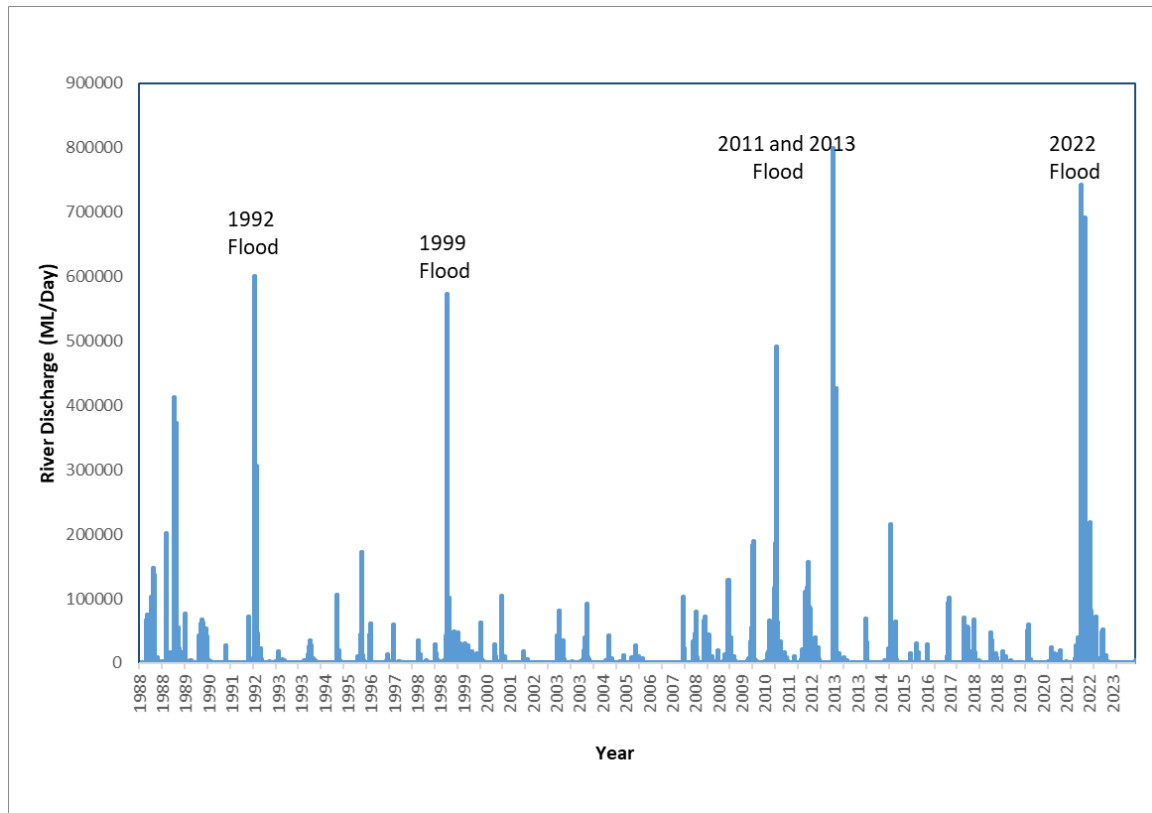


Figure 3. Daily discharge at Home Park gauge (138014A) in the Mary River from 1988 to December 2023. Data sourced from the Queensland Government (<https://water-monitoring.information.qld.gov.au/>).

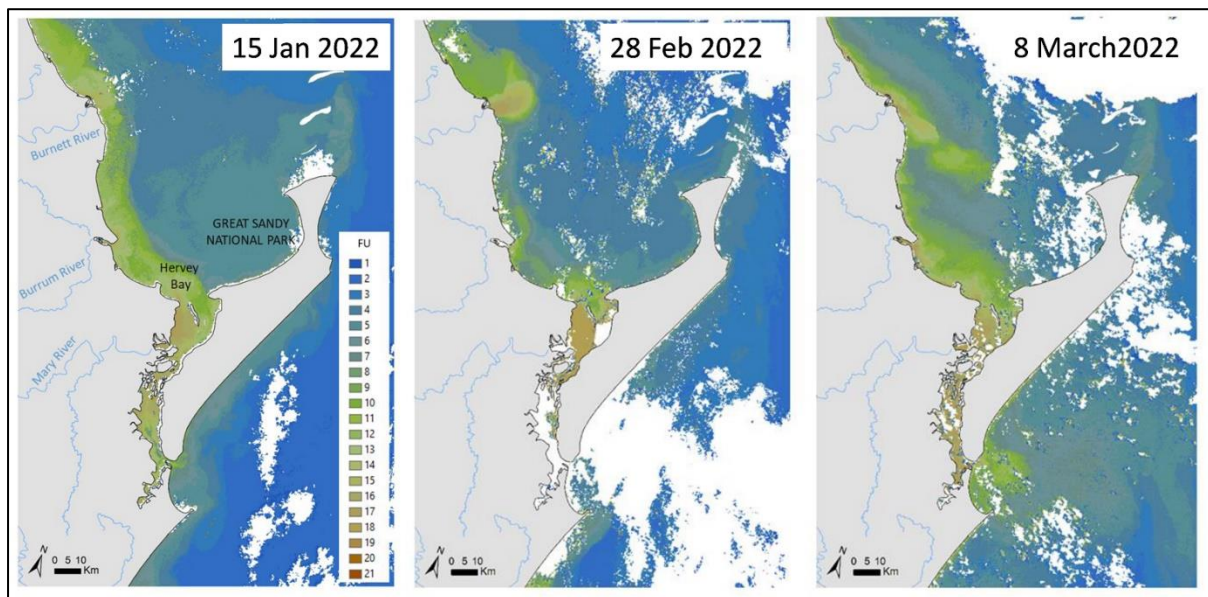


Figure 4. Processed satellite images (to the Forel Ule (FU) colour classes) from January, February and March following flood events of the Mary River-Hervey Bay region. Images sourced (Lewis et al. 2022).

METHODS

Site description

Our study area was bound in the north by a line connecting Bargara on the mainland to just north of Rooney Point on K'gari, and encompassed the area between the mainland and K'gari to the southern extent of the Great Sandy Strait including Tin Can Bay (Figure 5). A line between Urangan on the mainland and Moon Point on K'gari defined waters belonging to Hervey Bay (to the north) and Great Sandy Strait (to the south).

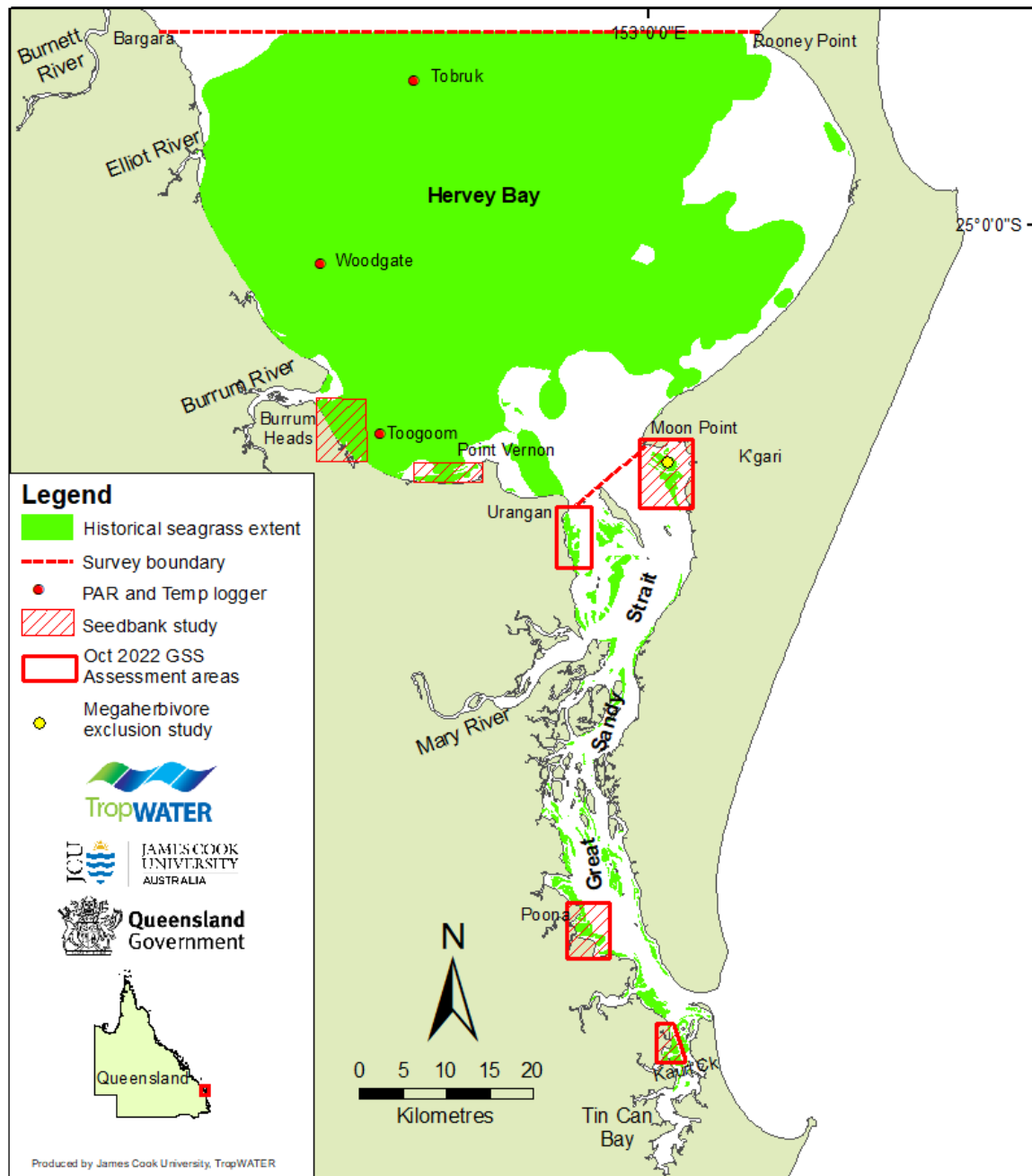


Figure 5. Location of 2022/2023 post-flood seagrass assessments. Historical seagrass extent from Lee Long et al. 1992 and McKenzie 2017.

Seagrass monitoring, habitat mapping and Geographic Information System

Site selection

Sampling intensity during post-flood seagrass assessments has varied slightly during each survey. The first post-flood survey (May 2022) covered all intertidal, shallow subtidal and deep-water areas of Hervey Bay (York et al. 2022) as well as intertidal areas of Great Sandy Strait (Bryant et al. 2023). The survey did not cover subtidal areas of Great Sandy Strait which were thought to contain minimal seagrass habitat.

The second post-flood survey (October/November 2022) again covered all intertidal, shallow subtidal and deep-water areas of Hervey Bay but focused on a subset of intertidal areas in Great Sandy Strait (Bryant et al. 2023). Based on the distribution of seagrass meadows in May 2022, four locations were selected to track intertidal seagrass recovery during peak seagrass growth in October 2022; Moon Point, Urangan, Poona and Tin Can Bay (Figure 5). These locations encompassed a large portion of the seagrass remaining in the Great Sandy Strait following the flood event in the May 2022 survey and represented the main community types in the region.

During the final post-flood survey (August to November 2023), all seagrass habitat in both Hervey Bay and Great Sandy Strait was assessed, including intertidal, shallow subtidal and deep-water areas. The most recent survey covered the same extent as the 1998 survey, and provides a direct comparison to historical pre-flood levels of seagrass in the region.

In intertidal areas, survey sites were spread throughout the banks in a stratified way with a higher intensity of sites around seagrass meadow boundaries or changes in species composition with a random/haphazard allocation of sites within meadow boundaries. Where seagrass meadows extended into subtidal areas, sites continued along a seaward transect to map the subtidal edge of the meadow. In offshore deep-water areas in Hervey Bay, sites were spaced at equal intervals in a grid pattern (Figure 6).

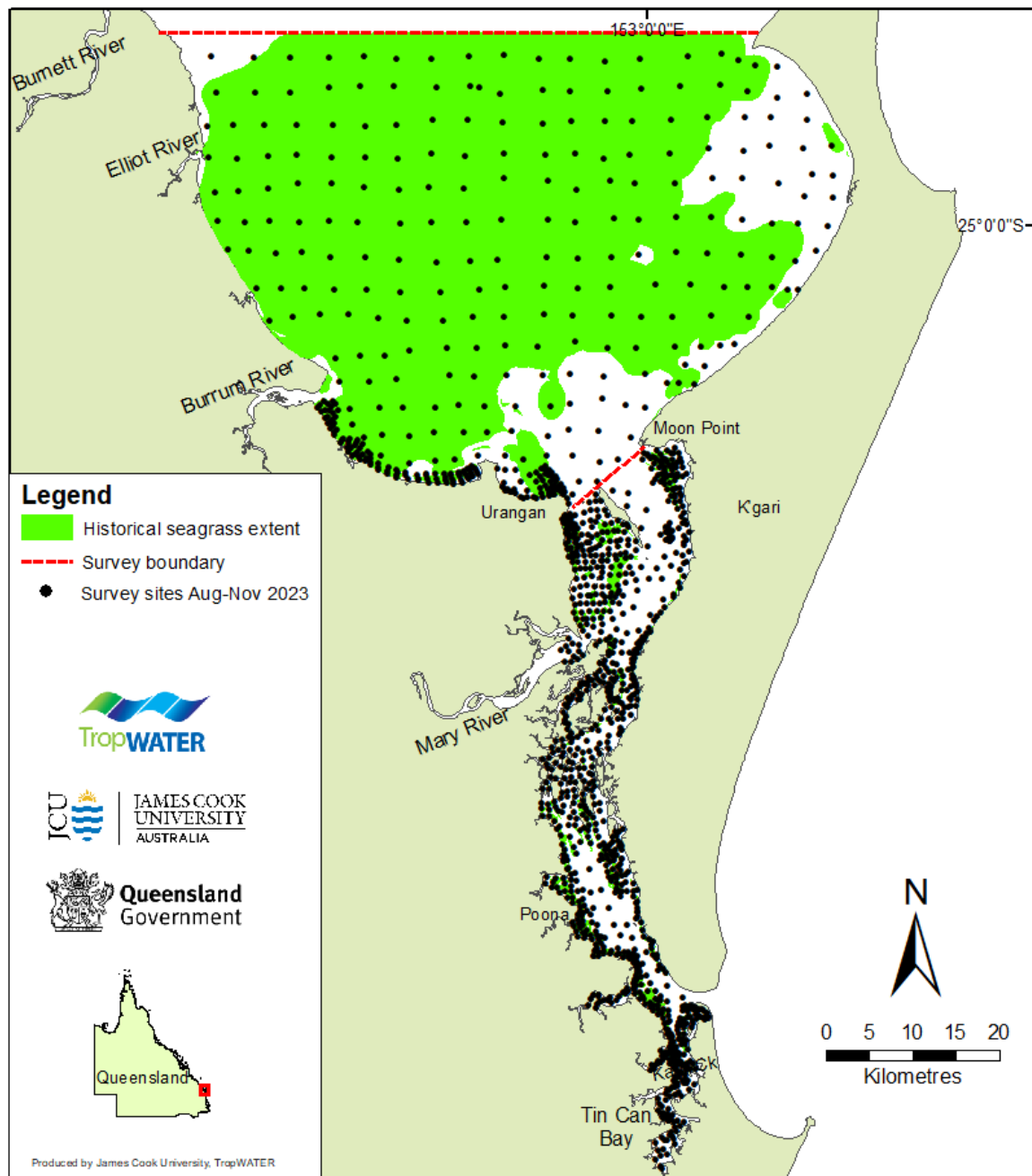


Figure 6. Location of seagrass assessment sites during post-flood surveys in August to November 2023. Historical seagrass extent from Lee Long et al. 1992 and McKenzie 2017.

Methods and equipment

Methods for seagrass assessment followed previous surveys and employed standard and extensively reviewed techniques applied for baseline assessments and monitoring of seagrasses and benthic communities in Queensland. Techniques also take into account logistical issues associated with naturally high water turbidity and the presence of dangerous marine animals. Sampling methods were based on existing knowledge of benthic habitats and physical characteristics of the location such as depth, visibility and logistical and safety constraints.

Two sampling techniques were used (Figure 7):

1. Intertidal areas: Helicopter surveys at low tide;
2. Subtidal areas: Boat based underwater digital camera mounted on a drop frame.



Figure 7. Methods for mapping and monitoring seagrass for subtidal meadows using (A, B) digital camera mounted on a drop frame connected to CCTV, and for intertidal meadows (C) helicopter aerial surveillance.

At each survey site, seagrass habitat observations were recorded using TropWATER’s standard coastal benthic survey data sheet adapted to be compatible with the Queensland Intertidal and Subtidal Ecosystem Classification Scheme (DEHP 2017). Data recorded included seagrass species composition, above-ground biomass, seagrass percent cover, percent algal cover, depth below mean sea level (MSL), substrate composition and % consolidation, time and position (GPS). The percent cover of other major benthos at each site was also recorded (Appendix 1).

Where seagrass was present, seagrass above-ground biomass was measured using a “visual estimates of biomass” technique (Kirkman 1978, Mellors 1991). At camera drop and helicopter sites this technique involved an observer ranking seagrass biomass within three randomly placed 0.25m² quadrats at each site (Figure 7A-C). Percent cover of seagrass and species composition was also recorded for each quadrat.

A photo/video record of quadrats for seagrass sites was also collected and for subtidal sites a van-veen sediment grab was used to collect a sediment sample for visual classification as well as to confirm species viewed on the screen (Figure 8). For subtidal sites in addition to the 3 quadrat assessments the camera was set within a few metres of the bottom and allowed to drift for approximately 20m to pick up the presence of any sparsely distributed seagrass at the site. For the intertidal helicopter survey, seagrass species were confirmed using a rake dragged through the sediment to collect a sample (Figure 8).

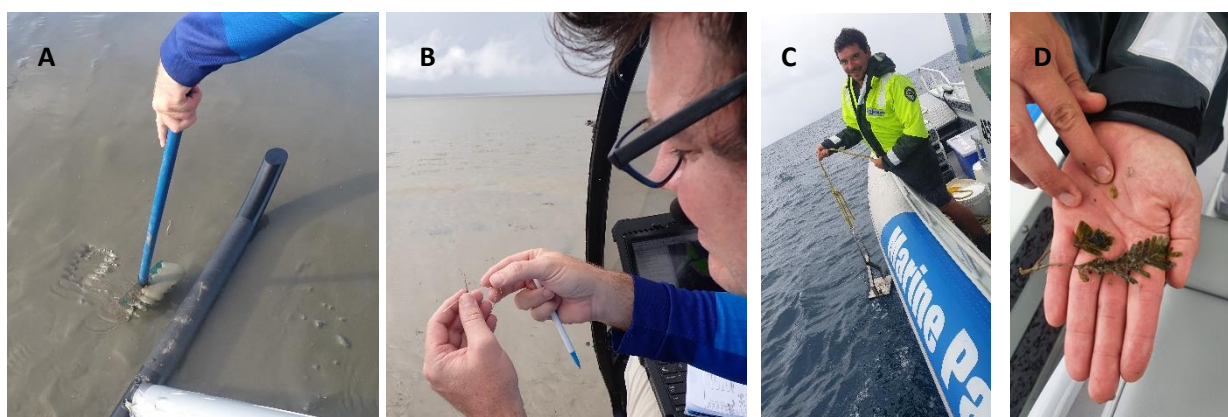


Figure 8. Collecting seagrass and sediment samples for species confirmation in Hervey Bay and Great Sandy Strait from a helicopter using a rake (A & B) and from a boat using a Van veen grab (C & D)

Analysis

Survey data were entered into a Geographic Information System (GIS) using ArcGIS 10.8®. Four GIS layers were created to describe seagrass in the survey area: a site layer, meadow layer, biomass interpolation layer and percent cover interpolation layer.

- **Site Layer:** The site (point) layer contains data collected at each site, including:
 - Site number
 - Temporal details – Survey date and time.
 - Spatial details – Latitude, longitude, depth below mean sea level (dbMSL; metres) for subtidal sites.
 - Habitat information – Sediment type; seagrass information including presence/absence, percentage cover, above-ground biomass (total and for each species) and biomass standard error (SE); dugong feeding trail (DFT) presence/absence.
 - Sampling method and any relevant comments.
- **Meadow layer:** The meadow (polygon) layer provides summary information for all sites within each meadow, including:
 - Meadow ID number – A unique number assigned to each meadow to allow comparisons among surveys
 - Temporal details – Survey date.
 - Habitat information – Mean meadow biomass $\pm$ standard error (SE), mean meadow percent cover, meadow area (hectares) $\pm$ reliability estimate (R) (Table 3), number of sites within the meadow, seagrass species present, meadow community type and density (Tables 1 & 2), meadow landscape category (Figure 9).
 - Sampling method and any relevant comments.

- **Interpolation layers:** The interpolation (raster) layers describe spatial variation in seagrass biomass or percent cover across each meadow and were created using an inverse distance weighted (IDW) interpolation of seagrass site data within each meadow.

Seagrass meadow boundaries were determined from a combination of techniques. Exposed inshore boundaries were guided by recent satellite imagery of the region (Source: ESRI; Google Earth). Subtidal boundaries were interpreted from a combination of subtidal survey sites and the distance between sites, field notes, depth contours and recent satellite imagery.

Meadow area was measured using the calculate geometry function in ArcGIS®. Meadows were assigned a mapping precision estimate (in metres) based on mapping methods used for that meadow (Table 3). Mapping precision ranged from 20 – 100 m for intertidal seagrass meadows with boundaries mapped by helicopter where visible, to 100 – 1000 m for subtidal meadows with boundaries mapped by distance between sites with and without seagrass. The mapping precision estimate was used to calculate a buffer around each meadow representing error; the area of this buffer is expressed as a meadow reliability estimate (R) in square kilometres.

Table 1. Nomenclature for Queensland seagrass community types.

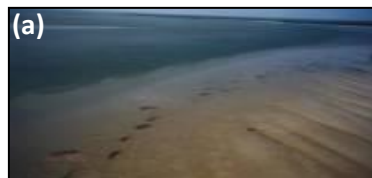
Community type	Species composition
Species A	Species A is 90-100% of composition
Species A with Species B	Species A is 60-90% of composition
Species A with Species B/Species C	Species A is 50% of composition
Species A/Species B	Species A is 40-60% of composition

Table 2. Density categories and mean above-ground biomass ranges for each species used in determining seagrass community density in Hervey Bay and the Great Sandy Strait.

Density	Mean above-ground biomass (g DW m ⁻²)				
	<i>H. uninervis</i> (narrow)	<i>H. ovalis</i> <i>H. decipiens</i>	<i>H. uninervis</i> (wide)	<i>H. spinulosa</i>	<i>Z. muelleri</i>
Light	< 1	< 1	< 5	< 15	< 20
Moderate	1 - 4	1 - 5	5 - 25	15 - 35	20 - 60
Dense	> 4	> 5	> 25	> 35	> 60

Isolated seagrass patches

The majority of area within the meadow consists of unvegetated sediment interspersed with isolated patches of seagrass.



Aggregated seagrass patches

The meadow consists of numerous seagrass patches but still features substantial gaps of unvegetated sediment within the boundary.



Continuous seagrass cover

The majority of meadow area consists of continuous seagrass cover with a few gaps of unvegetated sediment.



Figure 9. Seagrass meadow landscape categories: (a) Isolated seagrass patches, (b) aggregated seagrass patches, (c) continuous seagrass cover.

Table 3. Mapping precision and methodology for boundary mapping in Hervey Bay and Great Sandy Strait.

Mapping precision	Mapping methodology
20 - 100 m	Intertidal meadow boundaries determined from helicopter in meadows at low tide; Relatively high density of survey sites; Recent aerial photography aided in mapping.
100 – 300 m	Smaller subtidal meadow boundaries determined from underwater CCTV camera drops; Moderate density of survey sites.
1000 m	Larger deep subtidal meadow with boundaries determined from underwater CCTV and camera drops; All meadows subtidal; Relatively low density of survey sites.

Statistical analyses

The effects of time on a) seagrass biomass (g DW m^{-2}) and b) seagrass percent cover of individual seagrass meadows were analysed using a generalised linear model (GLM) with a Poisson distribution in R v3.5.2 (R core team, 2019). Analysis of deviance was used to determine significance levels of main effects. For each model a post-hoc Bonferroni test was conducted to compare differences at each sampling time. Residual and q-q plots of normalised results were inspected for heteroscedasticity and non-normality. Data were plotted using the ggplot2 package (Wickham, 2016). The effect of time on

seagrass biomass at each depth zone; intertidal (0-2m), shallow subtidal (2-10m) and deep-water (>10m), in both Hervey Bay and Great Sandy Strait was analysed using the same methodology.

Monitoring of Benthic Photosynthetically Active Radiation (PAR)

Site selection

Benthic light and temperature monitoring equipment was initially deployed at a subtidal site offshore from Toogoom just south of Burrum Heads in May 2022 (Figure 5 above). The equipment was deployed over bare sediment in shallow subtidal waters that have historically supported patchy high biomass *H. spinulosa* and *H. ovalis* seagrasses. The station is also located near existing shallow subtidal *H. uninervis* meadows. Two additional benthic PAR and temperature monitoring stations were added to the monitoring program in June 2023, in deep-water offshore from Woodgate and Tobruk (Figure 5). The Woodgate monitoring site was established at the periphery of the deep-water meadow where *H. decipiens* had recolonised after flood related losses in 2022 (Bryant et al. 2023). The Tobruk monitoring site was established in deeper water near seagrass (*H. spinulosa*) biomass hot spots detected in November 2022 (Bryant et al. 2023).

Methods and Equipment

Submersible OdysseyTM photosynthetic irradiance autonomous loggers (light loggers) were deployed with automatic wiper units which clean the optical surface of the sensor every 15 minutes to prevent marine organisms fouling the sensors (Figure 10). At each location, two independent light loggers and wiper units were deployed on the seabed in two separate deployment cradles connected to a surface float. The presence of dual loggers reduces the risk of data loss through unit malfunction, fouling or disturbance during the three months between equipment exchange and download. Equipment was changed out and downloaded approximately every three months.



Figure 10. Deploying continuously logging PAR equipment in Hervey Bay May 2022.

Odyssey loggers logged a cumulative reading at 15 minute intervals, which was calibrated and summed to gain total daily benthic light ($\text{mol m}^{-2} \text{ day}^{-1}$). The raw data captured by the loggers required calibrating to a known light value. Sensors were calibrated against a certified reference irradiance sensor (LI-CORTM LI-192SB Underwater Quantum Sensor) in controlled laboratory conditions. A custom built calibration device held the light loggers a consistent distance from the source light and excluded all external light. To allow for the differences in light absorption properties between air (calibration medium) and water (deployment media), a multiplication factor of 1.33 was applied to data. Following retrieval from the field, a report on the condition and appearance of each data logger was made to identify any fouling of the sensor or issues with the wiping apparatus.

Analysis

After downloading, the data was adjusted using the most recent calibration factor for each logger and adjusted for submersion (see methods above). The adjusted data was used to calculate a total daily benthic light value for each logger.

At each site loggers A & B were compared to determine if there were any significant differences (>20%) in total daily light value. This comparison was initially undertaken for 15 minute increments however, for some sites the distance between loggers meant that differences in excess of 20% were common. Even a distance of 10 m can cause loggers to differ substantially during exposure and submersion events. Where failures of one unit were obvious, data was removed from the record (e.g. where a logger failed to record data or where there were exceptionally high readings outside of possible light levels). Data was also removed when fouling had occurred. If both loggers were deemed to be recording accurately and loggers agreed (difference <20%), a mean total daily light value was calculated. Where there were no obvious malfunctions and units disagreed by more than 20% in one day, the data for the unit recording the higher value was used as it is more likely to be reading within the 5% error margin for that logger. The lower of the two was considered more likely to have been affected by physical disturbances such as shading by floating debris.

Seed bank assessment

Site selection

Sampling of the seagrass seed bank (seeds stored in the sediments) was conducted in 5 blocks within Hervey Bay at Burrum Heads, Point Vernon, Moon Point, and in the Great Sandy Strait at Poona and Tin Can Bay (Figure 5 above). These sites were selected based on existing seagrass assessment areas in Great Sandy Strait and expanded to include coastal intertidal meadows in Hervey Bay.

Methods and equipment

A Van Veen sediment grab (0.0625m²) was used to collect 20 samples at sites haphazardly scattered throughout the sampling block. All samples were geo- referenced with a GPS, placed in labelled bags and stored on ice. Samples were sieved through a 710 µm micron particle size grade sieve on site to reduce the weight of the sample for shipping.

In the laboratory, sediment samples were sorted by passing the sample through a 1.4 mm and a 710 µm sieve with fresh water and seeds/pericarps of *Z. muelleri* and *H. uninervis* were inspected using a dissecting microscope, quantified and photographed (Figure 11). The 710 µm mesh size was small enough to retain seeds/pericarps of *Z. muelleri* and *H. uninervis* and fruits and flowers were noted if present. Seeds of *H. ovalis* are not routinely measured in this fraction because their small size allows them to pass through the sieve mesh and requires a microscope to locate them. If *H. ovalis* seeds were present in the sample they were counted.

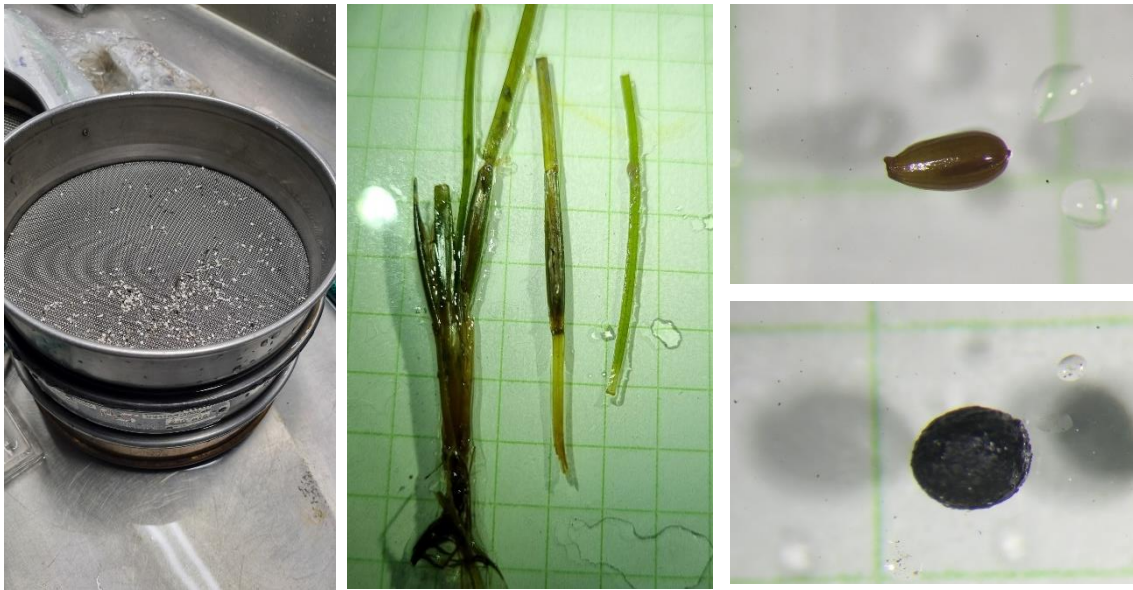


Figure 11. a) Sorting sediment through test sieves to separate out seagrass seeds, b) *Z. muelleri* spathe, c) *Z. muelleri* seed, d) *H. uninervis* seed.

Analysis

All data were entered into a Geographic Information System (GIS) for presentation of seagrass seed bank species distribution and abundance. Seagrass seed bank GIS layers were created in ArcMap and contained information on seed and pericarp density (for each species), latitude and longitude from GPS fixes and comments. Seed density data were delineated by species and reported as mean number of seeds per m⁻² for each monitoring block.

Megaherbivore exclusion experiments

Site selection

We used a short-term field study to investigate the role of megaherbivore grazing in structuring seagrass at Moon Point (Figure 5 above). This location was selected based on observed declines in the meadow here and evidence of megaherbivore grazing. This study adapts methods applied in seagrass meadows throughout the Great Barrier Reef (Scott et al., 2020, 2021a, 2021b, 2022, York et al., in prep).

Methods and equipment

Megaherbivore exclusion cages were used to prevent green turtles and dugong grazing on small areas of seagrass within the meadow at Moon Point. Eight steel megaherbivore exclusion cages 2 x 2 x 0.5 m were deployed in the seagrass meadow and secured with steel pegs, eight control plots 2 x 2 m were established adjacent to exclusion cages and corners were marked with star pickets (Figure 12).

Within all plots three individual 0.25m² quadrats were marked with pegs (Figure 12). Seagrass metrics (biomass, percent cover and canopy height) inside cages and adjacent control plots were measured at the beginning (2nd September 2023), during the experiment at three months (28th November 2023) and seven months, (25th March 2024) to understand the grazing pressure on seagrass meadows in both locations.

Four canopy height measurements were taken from each of the three quadrats. Seagrass aboveground biomass was measured in each quadrat using assessments in the field or photos from the field and post-field calibrations following the methods described in Mellors (1991) and seagrass percent cover was also recorded. Previous studies using the same exclusion cages have shown that experimental cages do not impact the light environment (Scott et al. 2020, 2021).

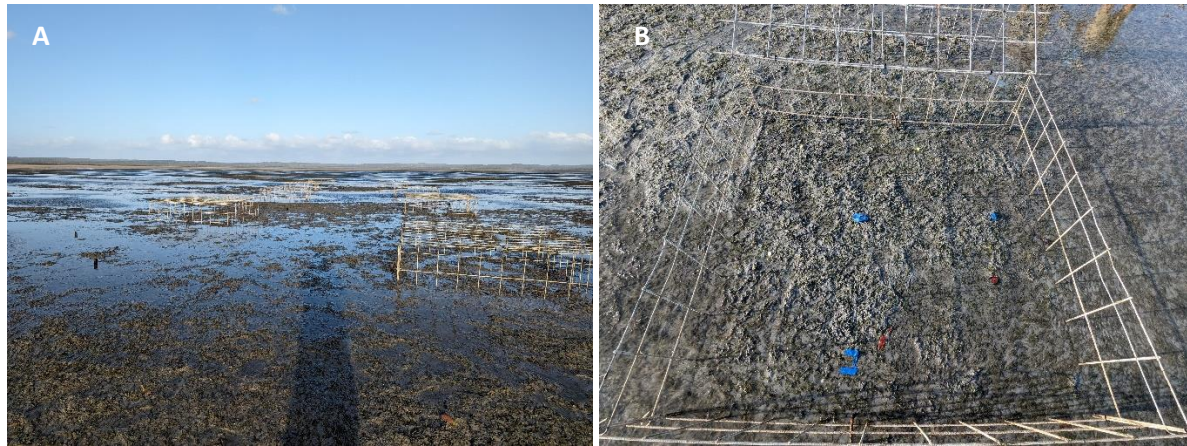


Figure 12. A) Megaherbivore exclusion cages and controls at Moon Point. B) Quadrats marked with pegs inside megaherbivore exclusion cage.

Analysis

The effects of time and treatment (and their interaction) on (1) canopy height (2) seagrass biomass and (3) seagrass percent cover were analysed using a generalised linear model (GLM) with a poisson distribution in R v3.5.2 (R core team, 2019). Analysis of deviance was used to determine significance levels of main effects and F statistics are presented for each model. For each model a post-hoc Tukey test was conducted to compare differences between caging treatments at each sampling time using the emmeans package (Lenth, 2019). Residual and q-q plots of normalised results were inspected for heteroscedasticity and non-normality. Data were plotted using the ggplot2 package (Wickham, 2016).

RESULTS

Seagrass monitoring, habitat mapping and Geographic Information System

Hervey Bay

Comparison with historical seagrass distribution, species and density

Seagrasses in Hervey Bay were first extensively mapped in 1988 (Lee Long et al. 1992 and 1993) with a dive based survey that covered the western, southern and south eastern regions of the bay. During this survey, approximately 1026 km² of seagrasses were mapped (Figure 13a). However, a large section of the north-western section of the bay was not surveyed so this likely underestimated the total seagrass extent. Relatively dense (>50% cover) intertidal meadows were identified on the coast at Burrum Point and in the estuaries of Coonaar and Theodolite Creeks. In the Hervey Bay coast region and in Platypus Bay, intertidal meadows were less dense (majority <10% cover). Seagrass in the shallow subtidal region in Hervey Bay was 10-50% cover. A large, relatively dense (>50% cover) deep-water *H. spinulosa* dominated meadow extended from the shallow subtidal zone across much of the western and central area of the bay to depths of over 20m (Lee Long et al. 1992 and 1993).

The entire Bay was resurveyed in 1992, and again in 1993 following two major floods and a cyclone which occurred within a three week period in early 1992 (Preen et al. 1995). The 1992 survey revealed a loss of around 1000km² of seagrass with the remaining meadow restricted to the central deep area of the bay (Figure 13a). Deep-water *H. spinulosa* dominated communities likely died as a result of light deprivation under a persistent flood plume and shallow seagrasses were uprooted by wave action during the weather events (Preen et al. 1995). By 1993, almost two years after the impact, there had been significant recovery in the deep-water meadow with the pioneering *H. decipiens* dominating the majority of sites and some areas returning to pre disturbance condition (Preen et al. 1995), however intertidal and shallow subtidal meadows had not recovered (Figure 13a). Recovery of the deep-water meadow was likely from a seed bank. The lack of recovery at intertidal meadows was thought to be through the lack of viable seeds (Preen et al. 1995).

In December 1998 a broad scale predominately dive and remote video based survey found seagrass to be once again widely distributed across the bay, from the western shoreline to deeper water covering a total area of 2,307 ± 279 km² (Figure 13a) (McKenzie 2017). Nearly half of this area was comprised of continuous deep-water meadows made up of medium to high biomass *Halophila spinulosa* with *Halophila ovalis* and *Halophila decipiens* (McKenzie 2017). Shallow subtidal banks were covered with low biomass *H. spinulosa*/*H. decipiens* and intertidal *H. uninervis* and *Z. muelleri* dominated meadows had returned in the Woodgate Burrum and the Hervey Bay Coast regions (McKenzie et al. 2017). The 1998 survey was undertaken near the peak of the seagrass growing season and prior to a significant flood event in February 1999 and likely represented seagrasses in a relatively good condition, although very little baseline data are available to confirm this. There were no broad scale assessments of seagrasses in Hervey Bay for the period from 1998 to 2022 (24 years). This time period was punctuated by significant flooding of the Mary or Burrum Rivers in 1999, 2010, 2012, 2013 and 2017 (Figure 5 above). Post-flood monitoring was conducted at a subset of sites in 1999 (McKenzie et al. 2000) and 2002 (McKenzie et al. 2003) but seagrasses were not mapped across the entire bay during these periods.

In May 2022, three months after significant flooding in the region, the total area of seagrass mapped (744 ± 212 km²) was 68% lower than the 1998 distribution (Figure 13b). A follow up survey occurred

in October/November 2022, at a similar time of year as the 1998 survey when seagrasses are naturally near their peak distribution and abundance. The total extent of seagrass in October/November 2022 ($1343 \pm 339 \text{ km}^2$) had increased significantly ($\sim 80\%$) over the nine months since May but remained 42% lower than the 1998 distribution (Figure 13b). During the most recent surveys conducted from August to November 2023, the total extent of seagrass ($1700 \pm 404 \text{ km}^2$) continued to increase ($\sim 26\%$) over the 12 months since the October/November 2022 survey but remained 26% lower than the 1998 distribution when seagrass extended to the shoreline along the western coastal area of the bay (Figure 13b).

The six species of seagrass present in Hervey Bay have remained the same as those present during historical surveys. Deep-water meadows are comprised of *H. spinulosa*, *H. ovalis* and *H. decipiens*, with the colonising *H. decipiens* more abundant following periods of disturbance (Preen et al. 1995, Bryant et al. 2023). Shallow subtidal meadows have historically been comprised of *H. spinulosa*/*H. decipiens* (McKenzie 2000) although post flood surveys in 2022 and 2023 found the little seagrass present in the shallow subtidal zone was predominantly *H. uninervis* (York et al. 2022, Bryant et al. 2023). Intertidal meadows continue to be dominated by *Z. muelleri* or *H. uninervis* (Figure 14 and 19-21).

Seagrass density (both above ground biomass and percent cover) has changed markedly since the original surveys particularly in subtidal and deep-water meadows. In 1988 over three quarters of the seagrass mapped consisted of dense meadows of greater than 50 % cover (Lee Long et al. 1992). During the 1998 survey, nearly half of the mapped seagrass were large continuous deep-water meadows of medium-high biomass *Halophila* species usually > 50 % cover and with mean biomass of 20-35 g DW m^{-2} (McKenzie et al. 2000). Subtidal meadows in the south west of Hervey Bay were patchy medium to high biomass ($\sim 20 \text{ g DW m}^{-2}$ and 50-100% cover) and shallow subtidal seagrass on Dayman Bank off Urangan was low biomass *H. spinulosa/decipiens* ($\sim 20 \text{ g DW m}^{-2}$ and 10-50% cover) (McKenzie et al. 2000). Post flood surveys in 2022 and 2023 show that both average biomass and percent cover are significantly lower than historical levels (see below).

In May 2022, following the flood event, there were a higher proportion of sites where the dominant sediment was classified as mud compared with subsequent surveys in October/ November 2022 and August 2023 (Figure 17). The muddier sites were concentrated in the north east section of the bay. Nine months later however, during the October/November 2022 surveys, the dominant sediment type for most sites had returned to sand (Figure 17). The most recent surveys in August to November 2023 also found that the dominant sediment type at most sites in Hervey Bay was sand (Figure 17).

Seagrass in August to November 2023

A total of 403 sites were surveyed from August to November 2023 in the Hervey Bay region (Figure 18). Approximately two thirds were subtidal sites surveyed by boat and one third were intertidal sites surveyed by helicopter. Seagrass was present at ~46 % of all sites (184 sites) compared with ~37 % of sites in October/November 2022 and ~20 % in May 2022 (Figure 18). Seagrass was present at ~48 % of subtidal sites and ~42 % of intertidal sites. The majority (~86 %) of subtidal seagrass sites were in deep-water (> 10 m), however seagrass was also found at 18 shallow (<10 m) subtidal sites compared to twelve in October/November 2022 and only one in May 2022. Seagrass was located from the intertidal zone to a depth of 28 m which was similar to October/November 2022. The total area of seagrass in Hervey Bay had increased 26 % since October/November 2022 ($1343 \pm 339 \text{ km}^2$ to $1700 \pm 404 \text{ km}^2$) with an overall increase of 128 % since the initial post-flood survey in May 2022 ($744 \pm 212 \text{ km}^2$ to $1700 \pm 404 \text{ km}^2$).

The seagrass species assemblages found in the seagrass meadows of Hervey Bay remained typical of those found for coastal and offshore meadows in the Hervey Bay region and more broadly in central Queensland (Figure 2). Offshore deep-water assemblages in the middle of Hervey Bay contained a light cover of *Halophila spinulosa*, with *Halophila ovalis* and *Halophila decipiens*, two small shallow subtidal coastal meadows contained a dense cover of the narrow-leafed morph of *Halodule uninervis* and a light cover of *Zostera muelleri* and the intertidal meadows contained isolated patches of very light cover of *Zostera muelleri* (thin leaf morphology) (Figure 21). Due to the very sparse and low cover of above ground seagrass for the two thin-leaf species found in the survey (*Z. muelleri* and *H. uninervis*), rapid differentiation of the species was difficult in the field, and it is possible that they may be co-occurring in these coastal meadows with only one species positively identified at a site. The dominant sediment type at all seagrass sites was sand (Figure 17).

Post-flood recovery

Deep-water (>10m dbMSL) meadows (Meadows 1 and 56)

The majority of the increase in seagrass area in Hervey Bay was due to the expansion of the deep-water meadow in the middle of the bay (Meadow 1, Figure 21 and 22). The footprint of Meadow 1 increased another 22% since October/November 2022 (from 1326 ± 331 to $1619.2 \pm 380.3 \text{ km}^2$) with the further colonisation and expansion of *H. decipiens* around the periphery of the meadow, particularly in the western section of the bay (Figure 14). *H. spinulosa* had also expanded into the north western corner of the bay and new isolated patches of *H. ovalis* were detected in the eastern section of the bay (Figure 14).

Mean biomass ($4.2 \pm 0.4 \text{ g DW m}^{-2}$) had increased significantly ($p = 0.001$) since the previous survey ($3.2 \pm 0.4 \text{ g DW m}^{-2}$) (Figure 22, Table 4) but remained low compared to reported mean biomass for deep-water meadows in 1998 ($20 - 35 \text{ g DW m}^{-2}$) (McKenzie et al. 2000). Biomass hot spots had extended further south into the central region of the bay with a maximum of $16.24 \pm 1.7 \text{ g DW m}^{-2}$ (Figure 15).

Mean percent cover ($11.5 \pm 0.9 \%$) was similar to the previous survey ($12.1 \pm 1.3 \%$) but significantly higher than May ($5.5 \pm 0.9 \%$) ($p < 0.001$) (Figure 16; Figure 22 and Table 4). Mean percent cover remains low compared with 1998 when cover was usually >50% (McKenzie et al. 2000).

One new isolated patch of *H. ovalis* was also detected in deep-water (~12m) on the eastern side of the bay (Figure 22; Meadow 56).

The deep-water meadow was once again dominated by *H. spinulosa* (72.8 % of species composition) although *H. ovalis* (18.5 % of species composition) was more prevalent than in October/November 2022 (Figure 14). *H. spinulosa* was found at a wider depth range than previous (2022) post-flood surveys (9.2 to 28.8m) (Figure 24).

Shallow subtidal (2-10m dbMSL) meadows (Meadows 2, 7, 27, 55 and 57)

The shallow subtidal meadow near Burrum Heads (Meadow 2, Figure 21 and 22) covered a similar area as the previous survey ($5.4 \pm 2.9 \text{ km}^2$). Species composition remained exclusively *H. uninervis* (narrow), however average biomass (9.4 g DW m^{-2}) had increased significantly ($p < 0.05$) resulting in dense seagrass cover (Figure 23 and Table 4). Mean percent cover (14.3 %) had also increased significantly since October/November 2022 ($1.3 \pm 0.5 \%$) ($p = 0.0001$) (Figure 23 and Table 4).

The dense subtidal meadow near Urangan (Meadow 7; Figure 21) covered a similar area as the previous survey ($2.0 \pm 0.7 \text{ km}^2$) however average biomass ($11.6 \pm 3.5 \text{ g DW m}^{-2}$) and percent cover ($16.3 \pm 6.0 \%$) had both increased significantly ($4.3 \pm 1.1 \text{ g DW m}^{-2}$ and $3.8 \pm 0.9 \%$) ($p < 0.0001$) (Figure 22 and Table 4). Species composition had shifted from *H. uninervis* to exclusively *Z. muelleri* (Figure 21) although *Z. muelleri* and *H. uninervis* in their sparse narrow leaf form are very similar and difficult to differentiate during rapid visual surveys and both species may coexist in the meadow.

Three new shallow subtidal meadows had appeared in the Hervey Bay region since the previous survey; an isolated patch of light *H. uninervis* (0.5 g DW m^{-2} and 1.6% cover) was found to the north of Burrum Heads (Meadow 27; Figure 21), an isolated patch of light *H. spinulosa* (13.5 g DW m^{-2} and 20% cover) was found nearshore north of Moon Point (Meadow 55; Figure 21) and aggregated patches of light *H. decipiens* (0.2 g DW m^{-2} and 1.2% cover) covered an area of $48.9 \pm 9.0 \text{ km}^2$ at the entrance to Great Sandy Strait (Meadow 57; Figure 21). Interestingly, Meadow 57 lies outside the footprint of historical (1988 and 1998) seagrass distributions (Figure 21).

The mean biomass of all sites within mapped shallow subtidal (2 to 10m dbMSL) meadows ($4.8 \pm 1.8 \text{ g DW m}^{-2}$) has increased since the initial post-flood survey in May 2022 (0.6 g DW m^{-2}) (Figure 23 and table 5) but remains low compared to 1998 ($23.24 \pm 1.8 \text{ g DW m}^{-2}$) although this was within a designated subtidal monitoring site (McKenzie et al. 2000).

All five species were found in the shallow subtidal zone in August to November 2023, however *H. spinulosa* were found less frequently in the shallow subtidal zone compared to 1998 when subtidal meadows in the south west of the bay were dominated by *H. spinulosa* (McKenzie et al. 2000). *H. uninervis* and *Z. muelleri* were found at greater depths during the recent survey compared to the 2022 post-flood surveys (8.9m and 7.1m cf 5.4m and 2.5m respectively) (Figure 24).

Intertidal (0-2m dbMSL) meadows (Meadows 3-6 and 8)

Five intertidal meadows were located from Burrum Heads to Urangan (Meadows 3-6 and 8; Figure 21). These meadows covered a combined area of approximately $14.04 \pm 4.3 \text{ km}^2$ compared to $11.01 \pm 3.6 \text{ km}^2$ during the previous survey. Most of the increase in area was due to the appearance or expansion of *Z. muelleri* dominated meadows south of Burrum Heads (Meadows 3 and 4; Figure 21). All intertidal meadows were comprised almost exclusively of isolated patches of light *Z. muelleri*

except at Meadow 3 where *H. uninervis*, *H. ovalis* and *H. decipiens* were also present (Figure 21). Mean biomass and percent cover increased significantly at Meadow 8 (2.0 ± 0.9 g DW m⁻² and 6.5 ± 2.4) ($p = 0.01$) since the previous survey (0.1 ± 0.04 g DW m⁻² and 0.9 ± 0.5 %) but remained low (Figure 22, Table 4). The highest average meadow biomass and percent cover was found at the *Z. muelleri* meadow on the exposed sand bar off Urangan (Meadow 8; Figure 21) at 2.0 ± 0.9 g DW m⁻² and 6.5 ± 2.4 % cover respectively (Figure 22).

The mean biomass of all sites within mapped intertidal (0-2m) meadows (1.3 ± 0.5 g DW m⁻²) has increased significantly since October/November 2022 (0.3 ± 0.1 g DW m⁻²) (Table 5) but is well below the mean biomass for the vast majority of meadows assessed in 1998 (McKenzie 2017).

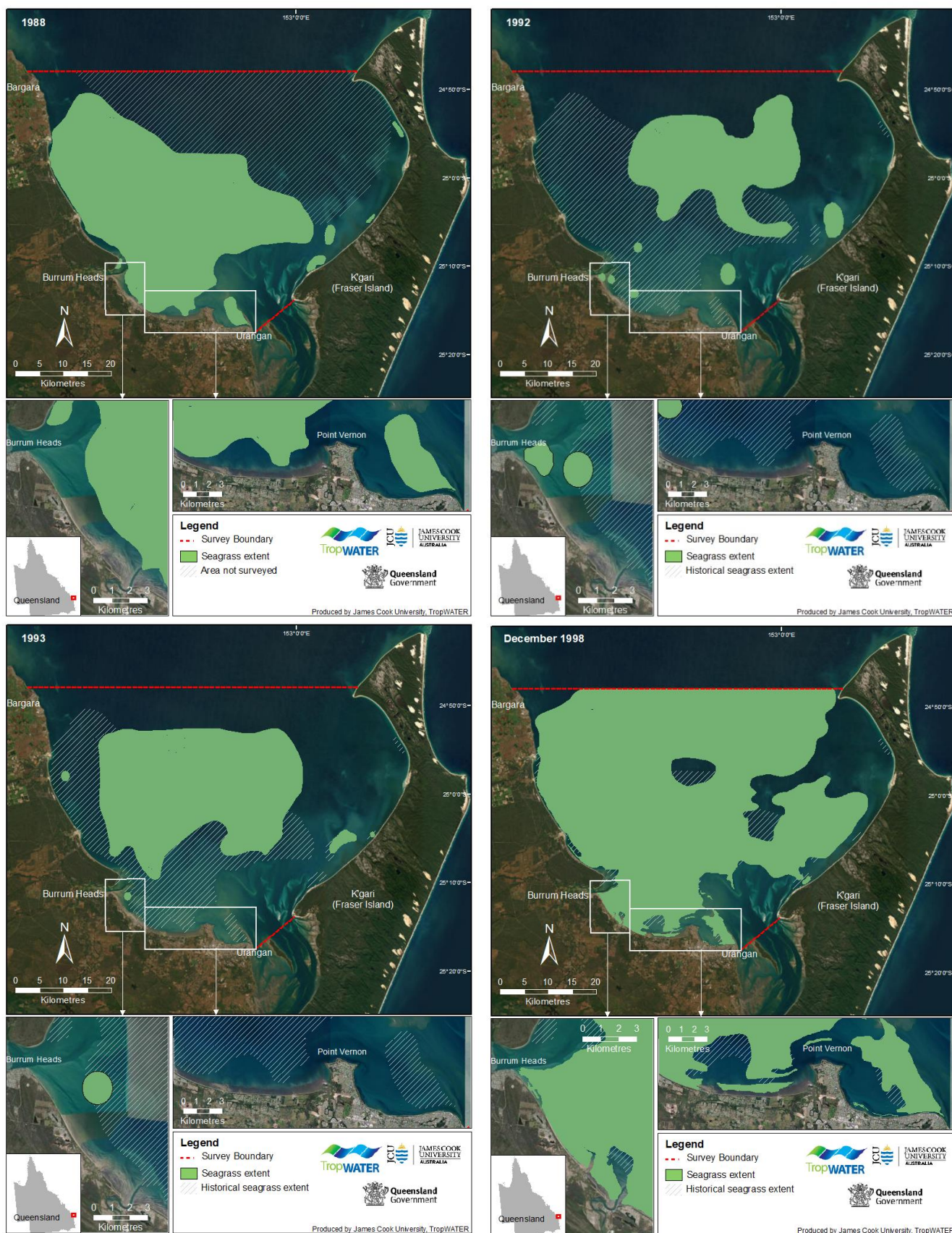


Figure 13a. Total seagrass extent in Hervey Bay in December 1988, 1992, 1993 and 1998. Data sources: Lee Long et al. 1992, Preen et al. 2015, McKenzie 2017.

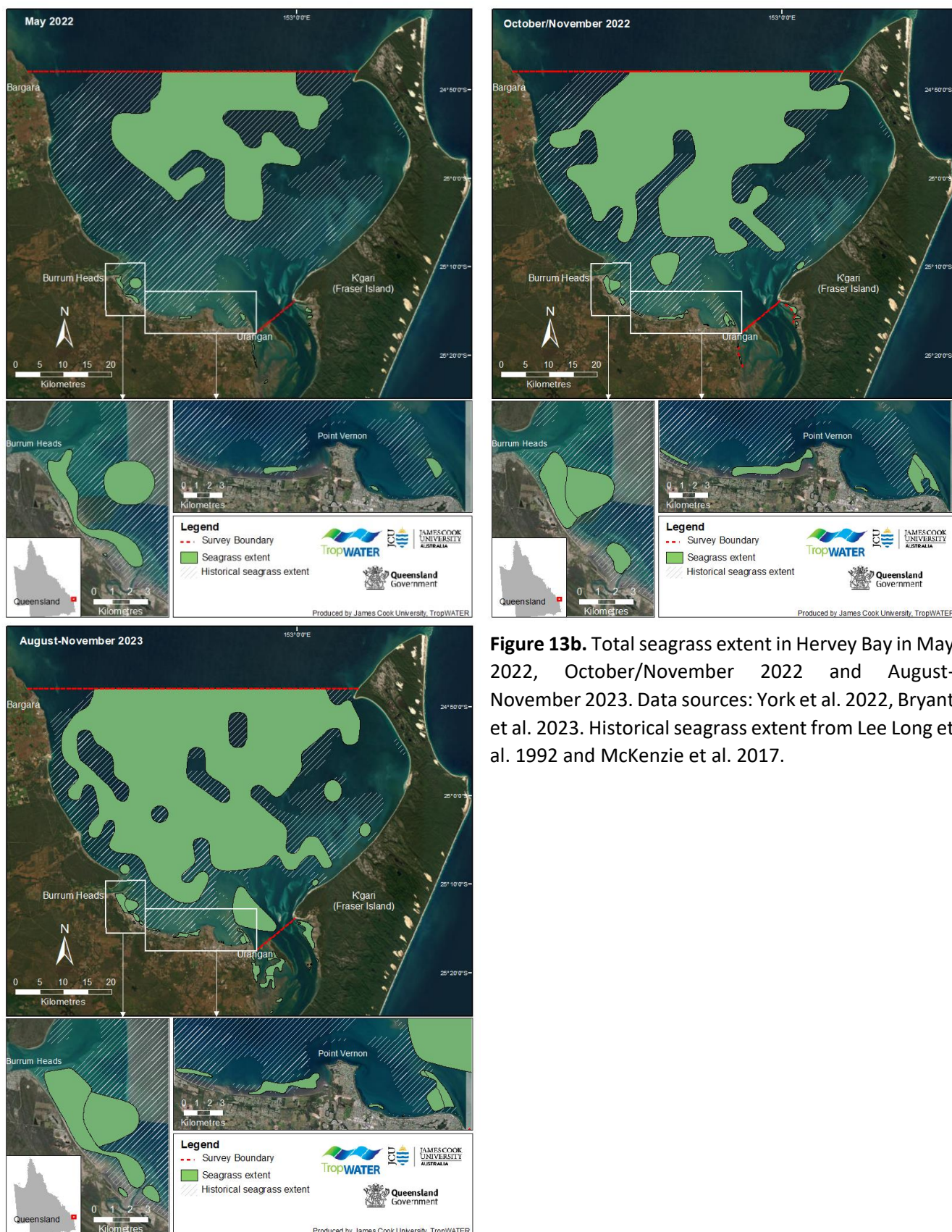


Figure 13b. Total seagrass extent in Hervey Bay in May 2022, October/November 2022 and August-November 2023. Data sources: York et al. 2022, Bryant et al. 2023. Historical seagrass extent from Lee Long et al. 1992 and McKenzie et al. 2017.

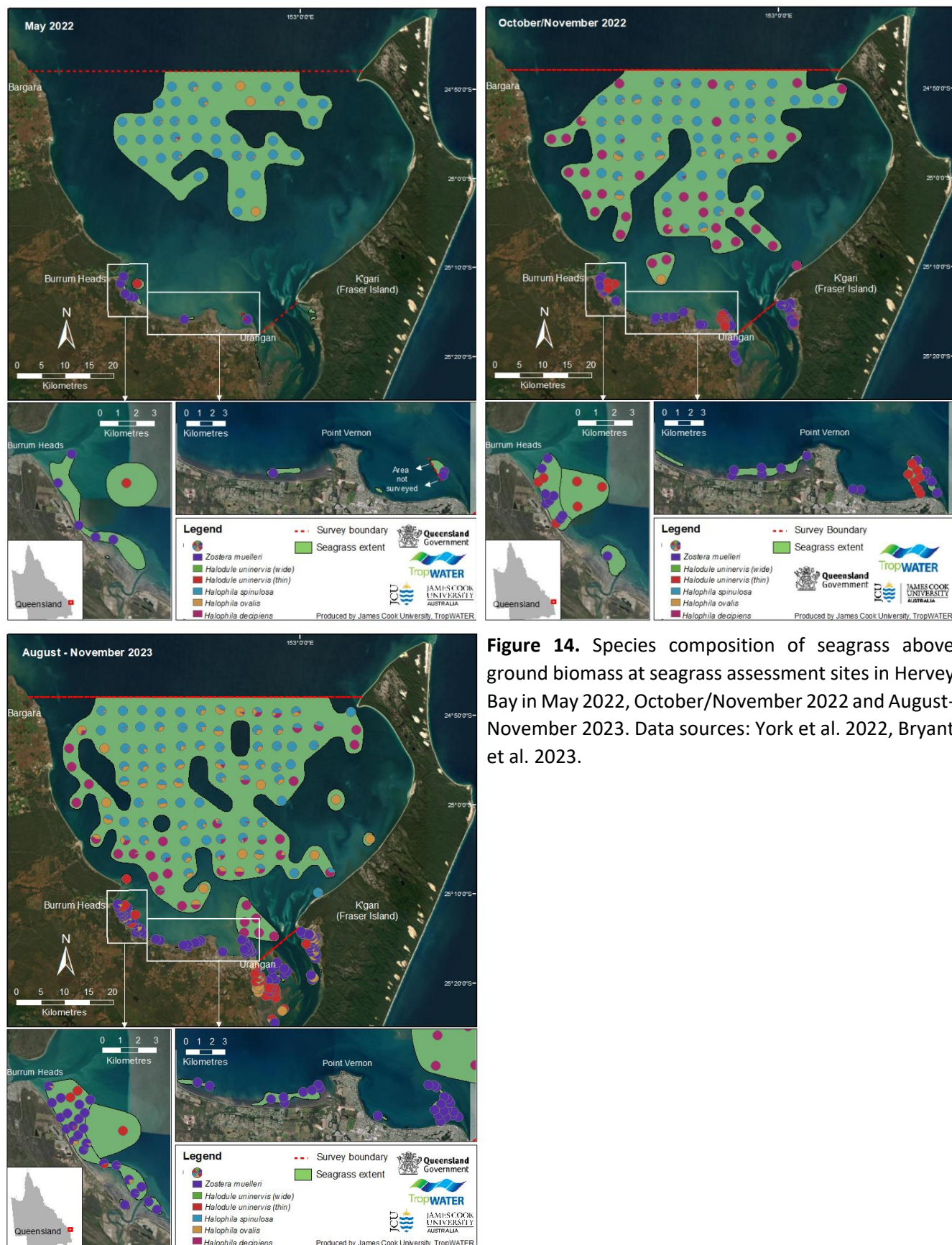


Figure 14. Species composition of seagrass above ground biomass at seagrass assessment sites in Hervey Bay in May 2022, October/November 2022 and August-November 2023. Data sources: York et al. 2022, Bryant et al. 2023.

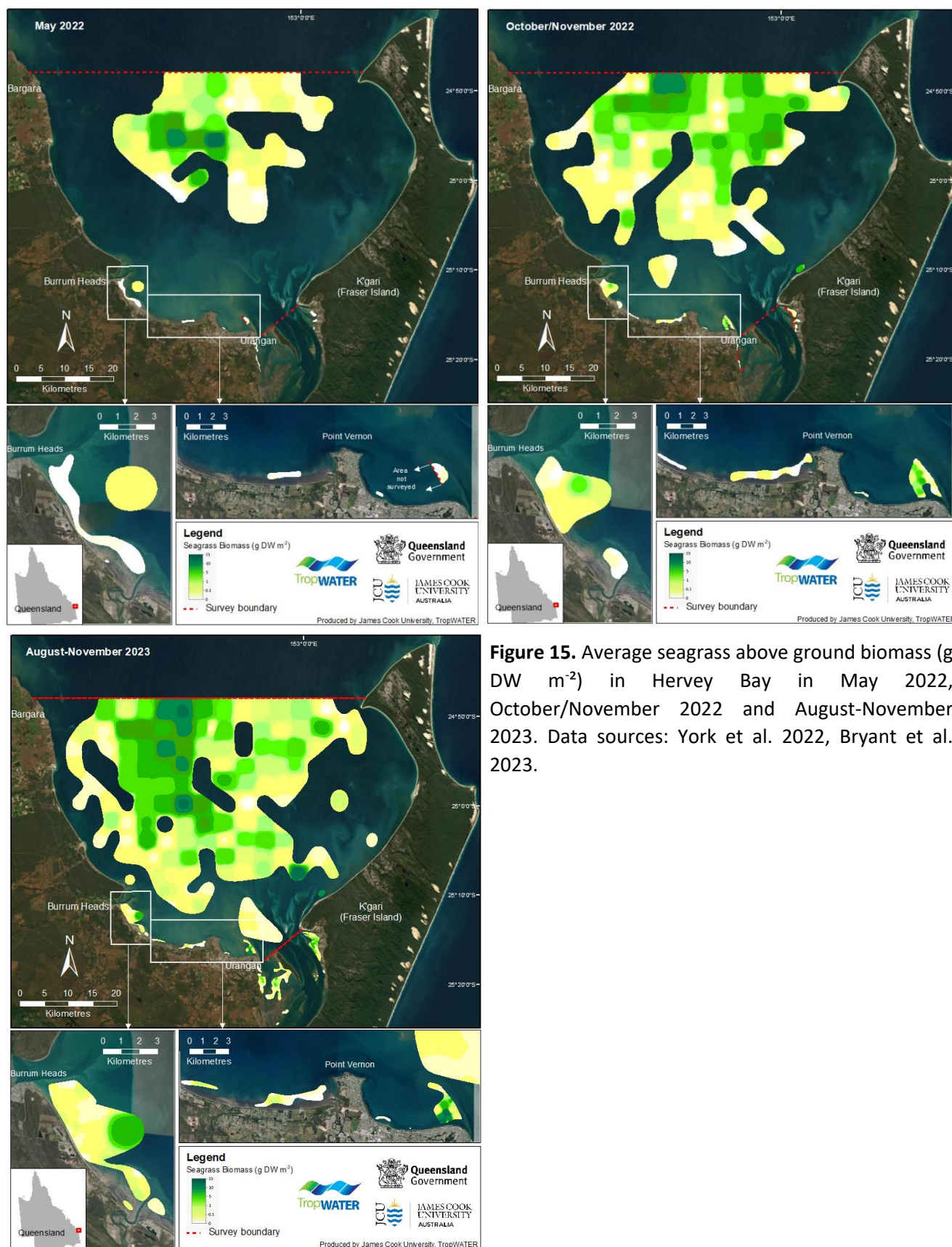


Figure 15. Average seagrass above ground biomass (g DW m⁻²) in Hervey Bay in May 2022, October/November 2022 and August-November 2023. Data sources: York et al. 2022, Bryant et al. 2023.

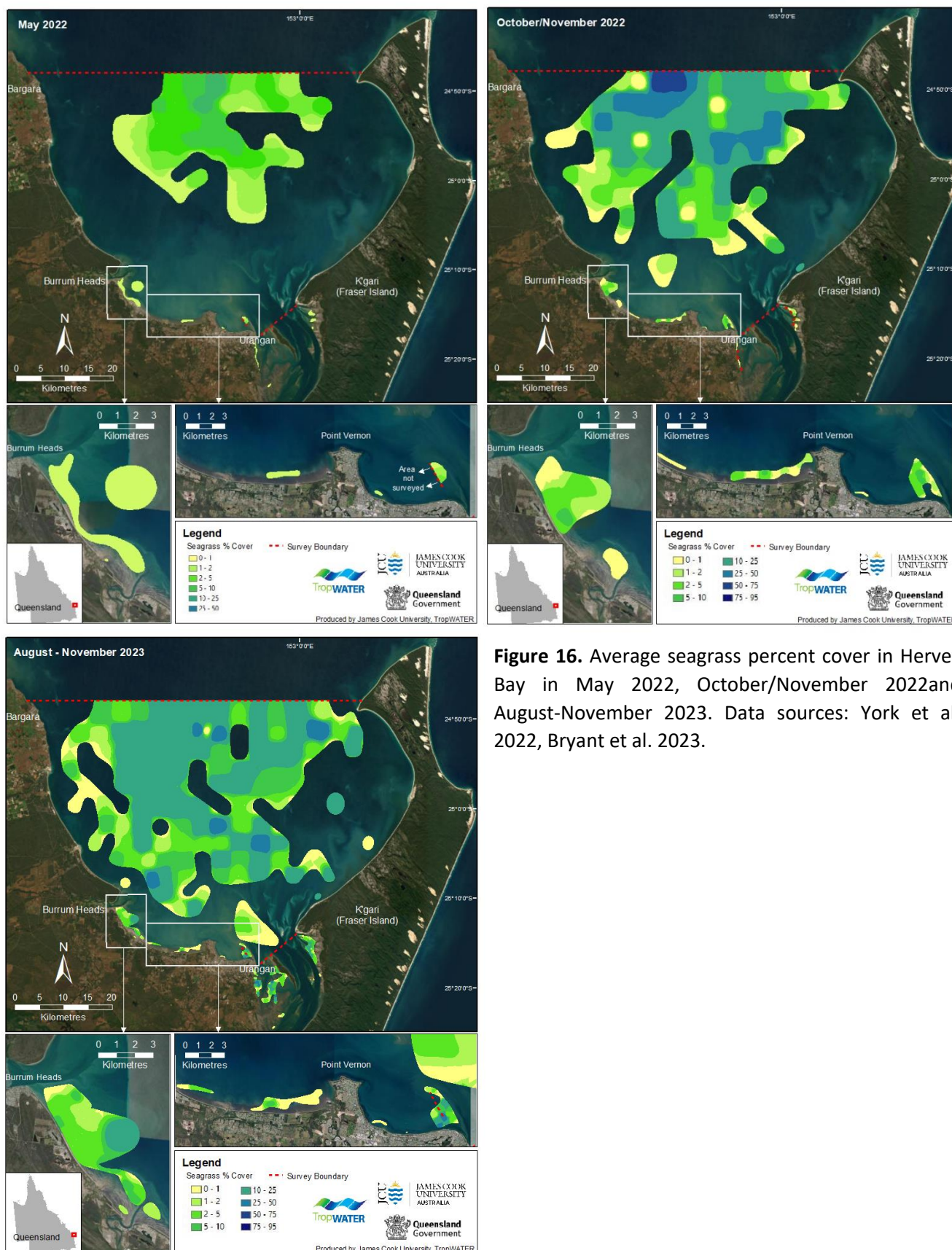


Figure 16. Average seagrass percent cover in Hervey Bay in May 2022, October/November 2022 and August-November 2023. Data sources: York et al. 2022, Bryant et al. 2023.

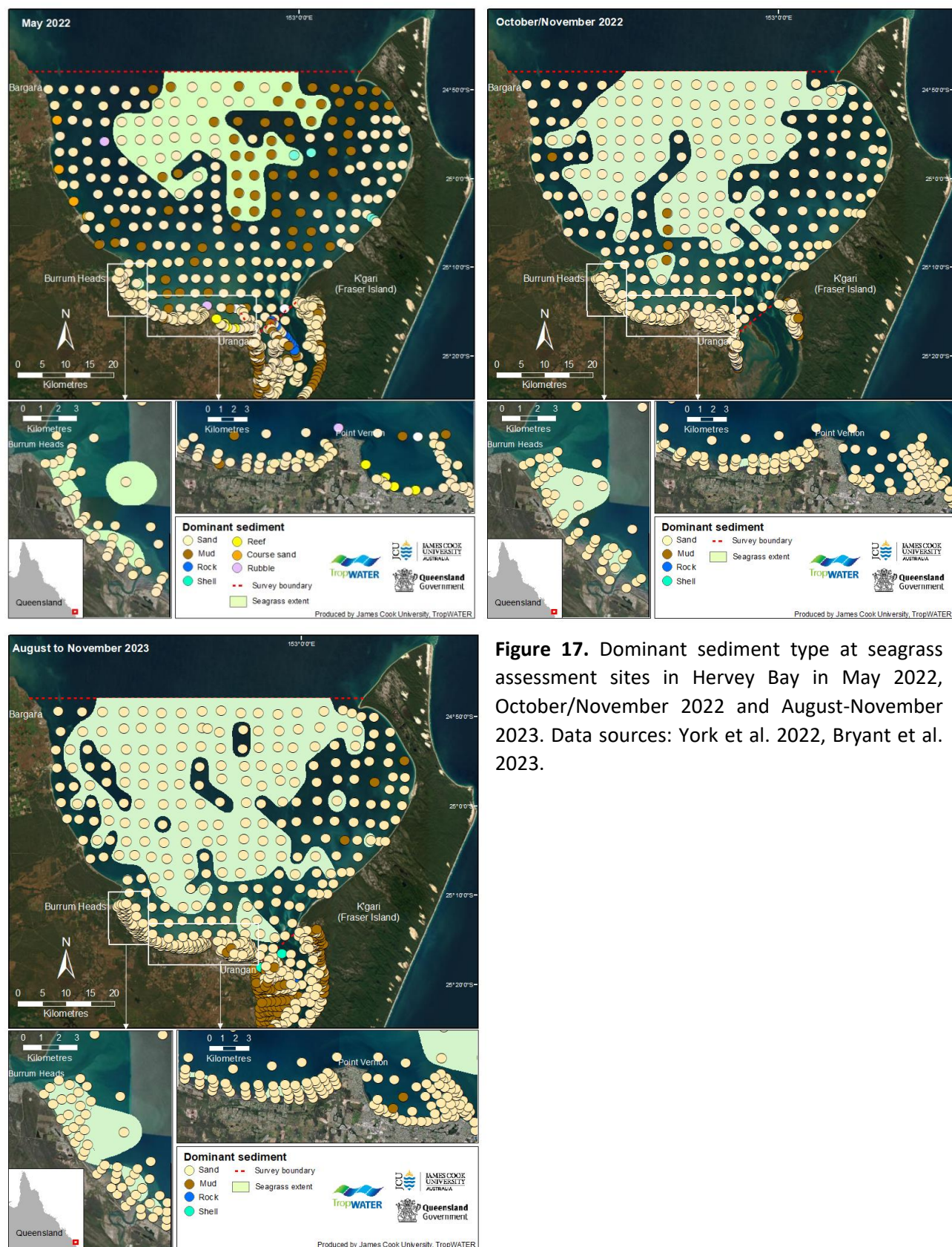


Figure 17. Dominant sediment type at seagrass assessment sites in Hervey Bay in May 2022, October/November 2022 and August-November 2023. Data sources: York et al. 2022, Bryant et al. 2023.

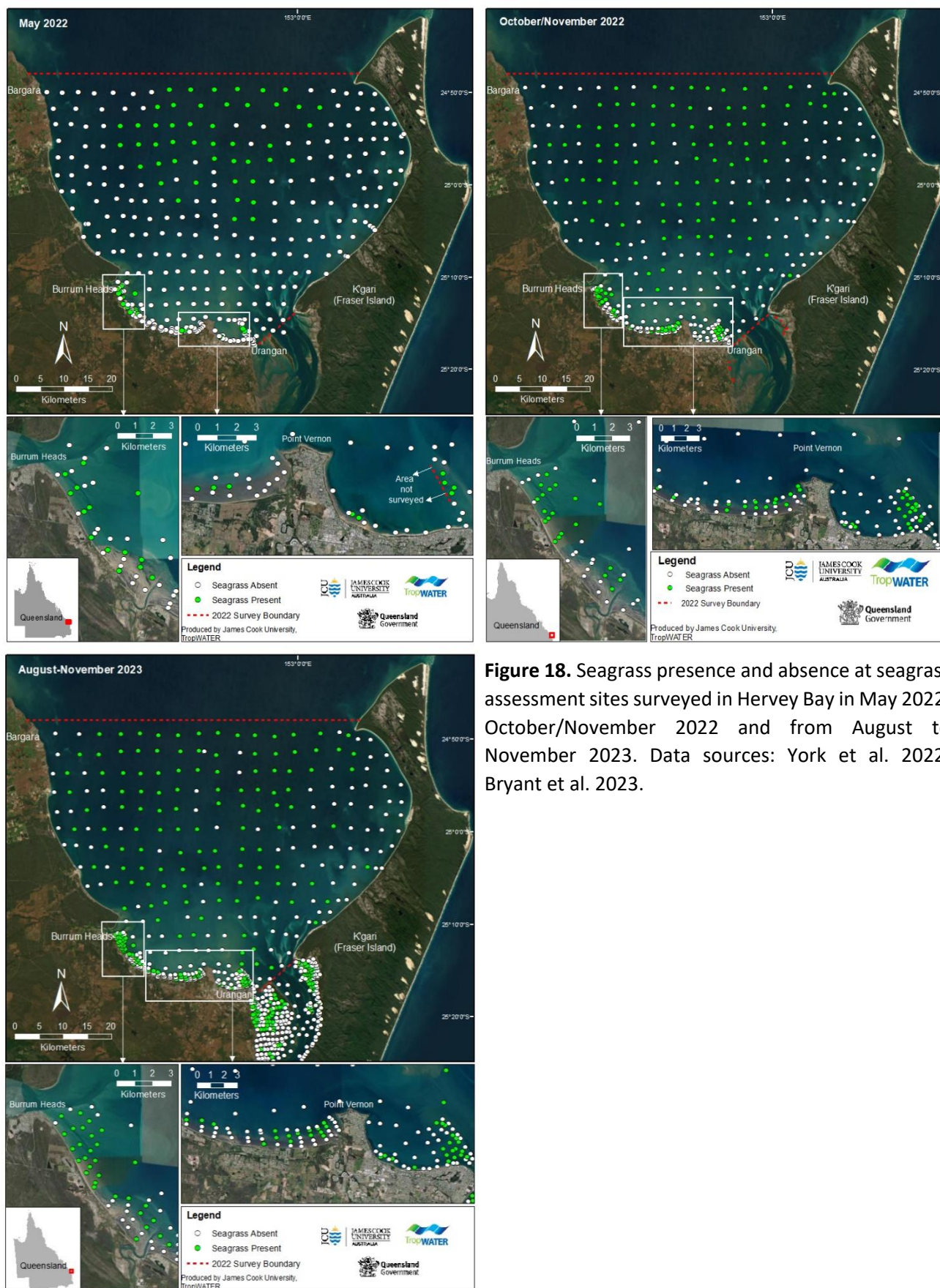


Figure 18. Seagrass presence and absence at seagrass assessment sites surveyed in Hervey Bay in May 2022, October/November 2022 and from August to November 2023. Data sources: York et al. 2022, Bryant et al. 2023.

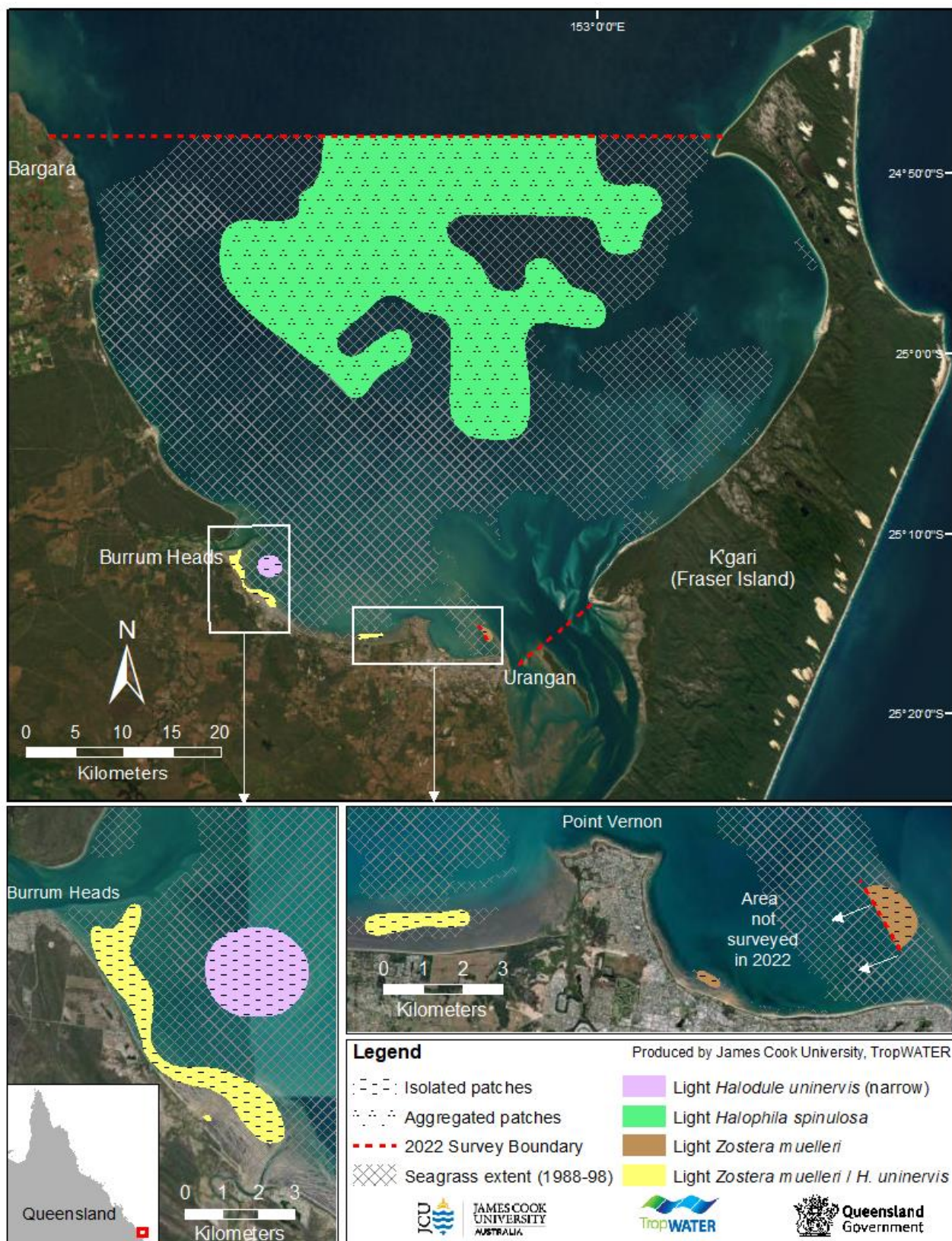


Figure 19. Meadow community and landscape types for seagrass meadows surveyed in Hervey Bay in May 2022 (York et al. 2022). Historical seagrass extent: Lee Long et al. 1992, McKenzie 2017.

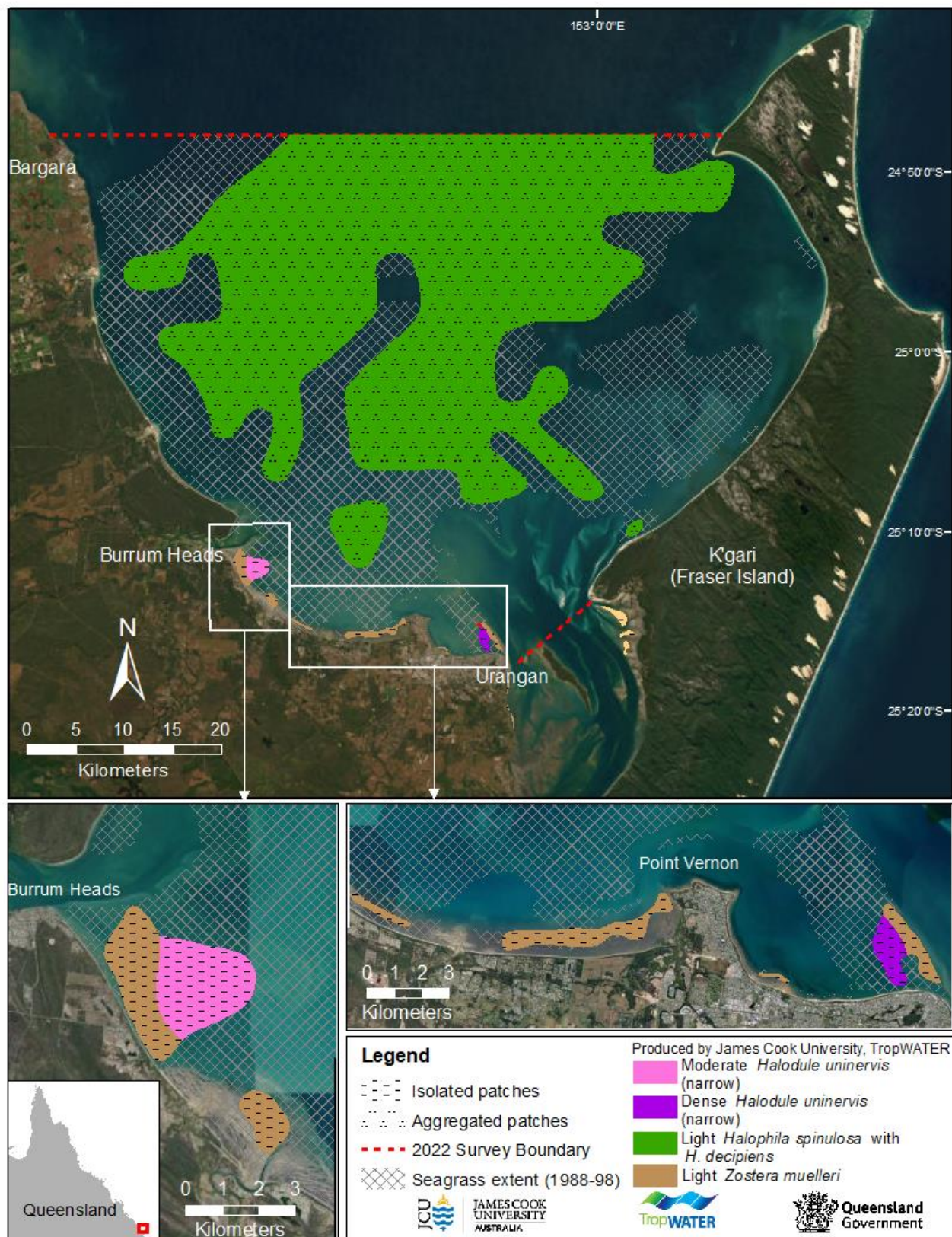


Figure 20. Meadow community and landscape types for seagrass meadows surveyed in Hervey Bay in October/November 2022 (Bryant et al. 2023). Historical seagrass extent: Lee Long et al. 1992, McKenzie 2017.

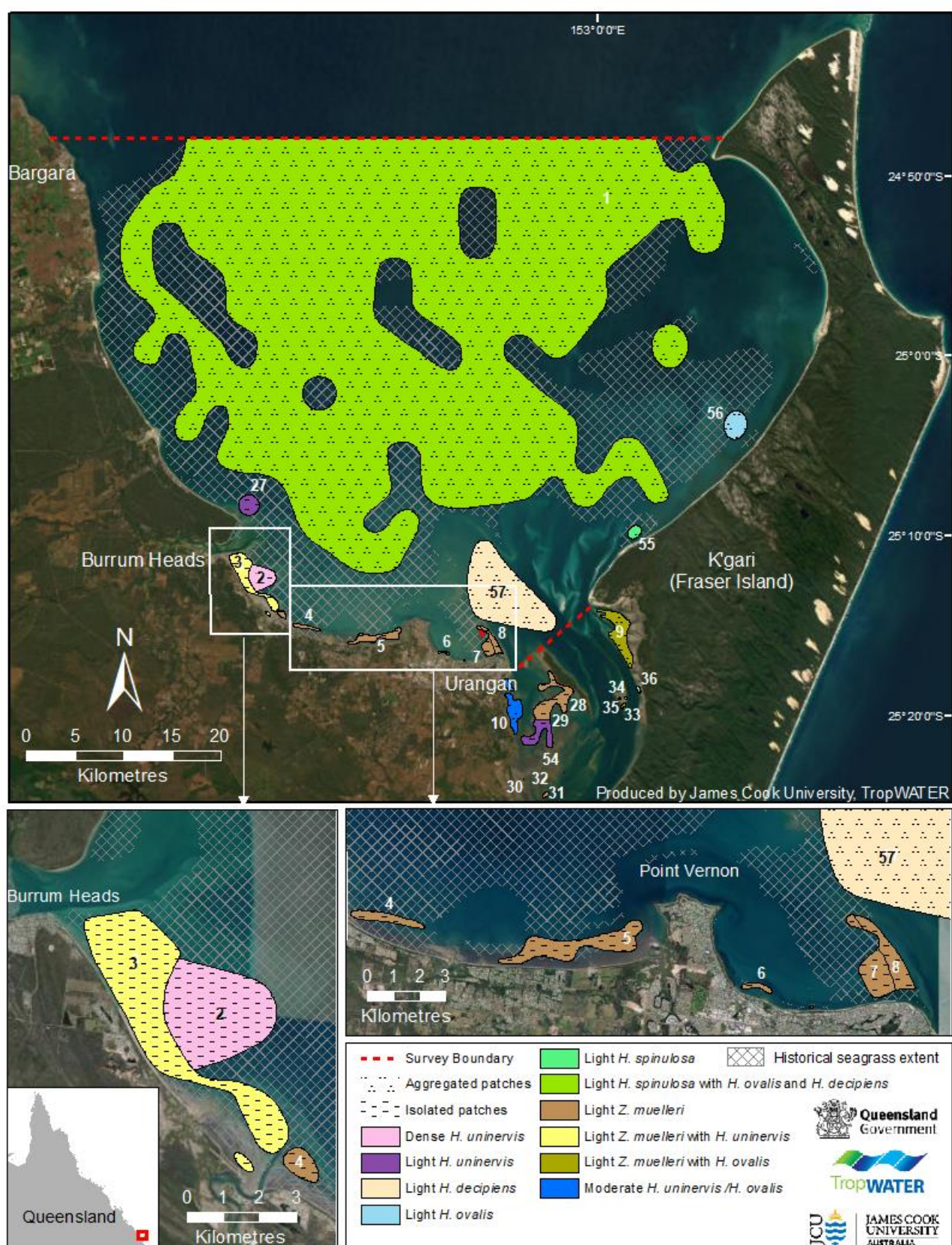


Figure 21. Meadow community and landscape types for seagrass meadows surveyed in Hervey Bay in August-November 2023. Historical seagrass extent: Lee Long et al. 1992, McKenzie 2017.

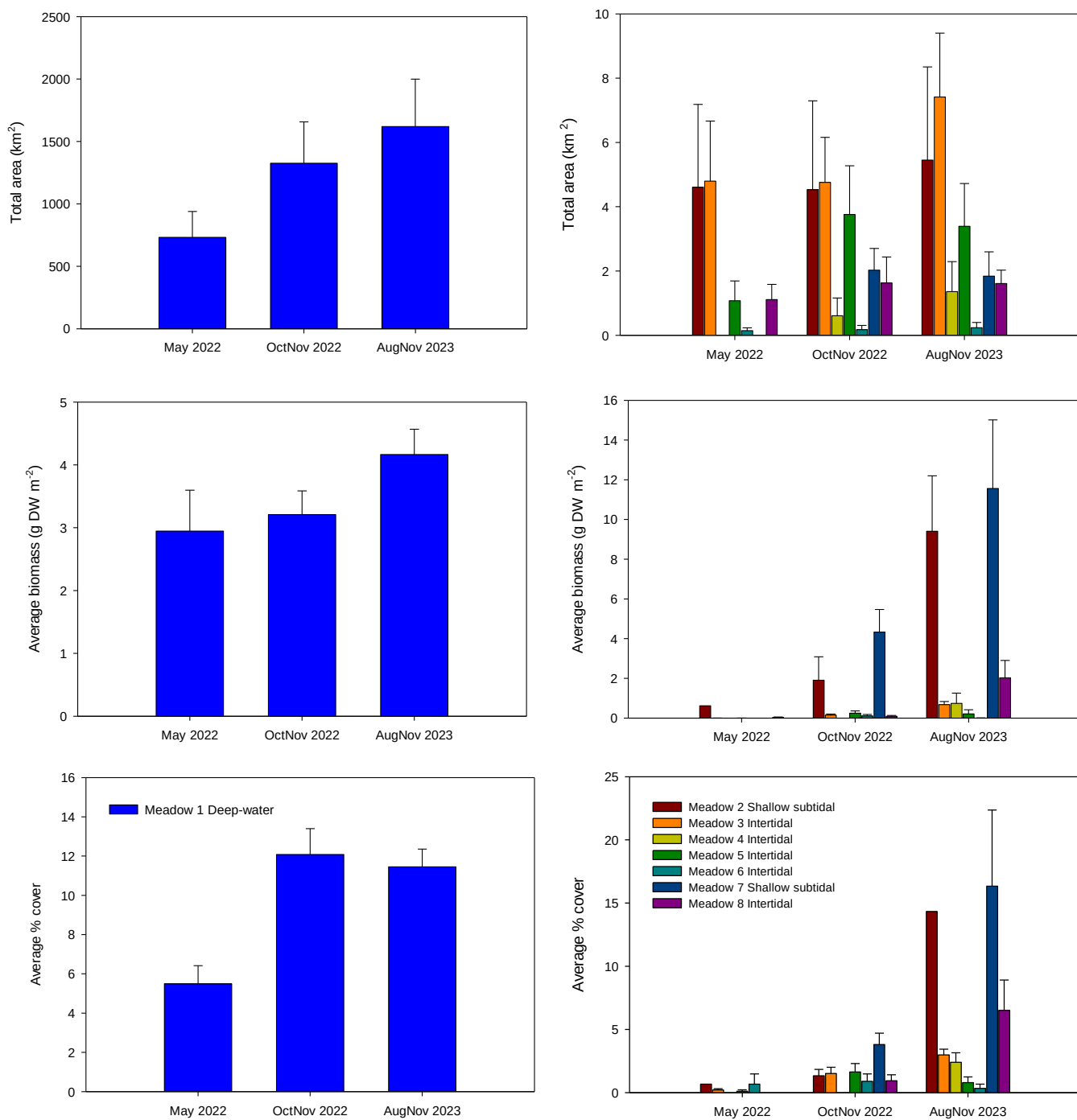


Figure 22. Total area (km²), average biomass (g DW m⁻²) and average percent cover of seagrass at meadows mapped in Hervey Bay in May 2022 and October/November 2022 and August to November 2023.

Table 4. Total area (km²), mean biomass (g DW m⁻²) and mean percent cover of seagrass at meadows mapped in Hervey Bay in May, October/November 2022 and August to November 2023.

Meadow	Total Area (km ²)			Mean Biomass (g DW m ⁻²)			Mean % Cover		
	May 2022	Oct/Nov 2022	Aug to Nov 2023	May 2022	Oct/Nov 2022	Aug to Nov 2023	May 2022	Oct/Nov 2022	Aug to Nov 2023
1	732.4 ± 206.4	1325.8 ± 331.3	1619.2 ± 380.3	2.9 ± 0.7	3.2 ± 0.4	4.2 ± 0.4	5.5 ± 0.9	12.1 ± 1.3	11.5 ± 0.9
2	4.6 ± 2.6	4.5 ± 2.8	5.4 ± 2.9	0.6	1.9 ± 1.2	9.4	0.7	1.3 ± 0.5	14.39
3	4.8 ± 1.9	4.8 ± 1.4	7.4 ± 2.0	<0.001	0.1 ± 0.1	0.7 ± 0.2	0.2 ± 0.1	1.5 ± 0.5	3.0 ± 0.4
4	not present	0.6 ± 0.6	1.4 ± 0.9	not present	not calculated	0.7 ± 0.5	not present	not calculated	2.4 ± 0.7
5	1.1 ± 0.6	3.8 ± 1.5	3.4 ± 1.3	<0.001	0.2 ± 0.1	0.21 ± 0.20	0.1 ± 0.1	1.6 ± 0.7	0.8 ± 0.4
6	0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.16	not calculated	0.1 ± 0.1	0.01 ± 0.01	not calculated	0.9 ± 0.6	0.3 ± 0.3
7	not surveyed	2.0 ± 0.1	1.8 ± 0.8	not surveyed	4.3 ± 1.1	11.5 ± 3.5	not surveyed	3.8 ± 0.9	16.3 ± 6.0
8	1.1 ± 0.5	1.6 ± 0.8	1.6 ± 0.4	<0.01	0.1 ± 0.04	2.0 ± 0.9	0.7 ± 0.4	0.9 ± 0.5	6.5 ± 2.4
27	not present	not present	3.5 ± 2.3	not present	not present	0.5	not present	not present	1.7
55	not present	not present	1.5 ± 1.5	not present	not present	13.5	not present	not present	20
56	not present	not present	5.4 ± 2.8	not present	not present	0.08	not present	not present	0.3
57	not present	not present	48.9 ± 9.0	not present	not present	0.2 ± 0.1	not present	not present	1.2 ± 2.4

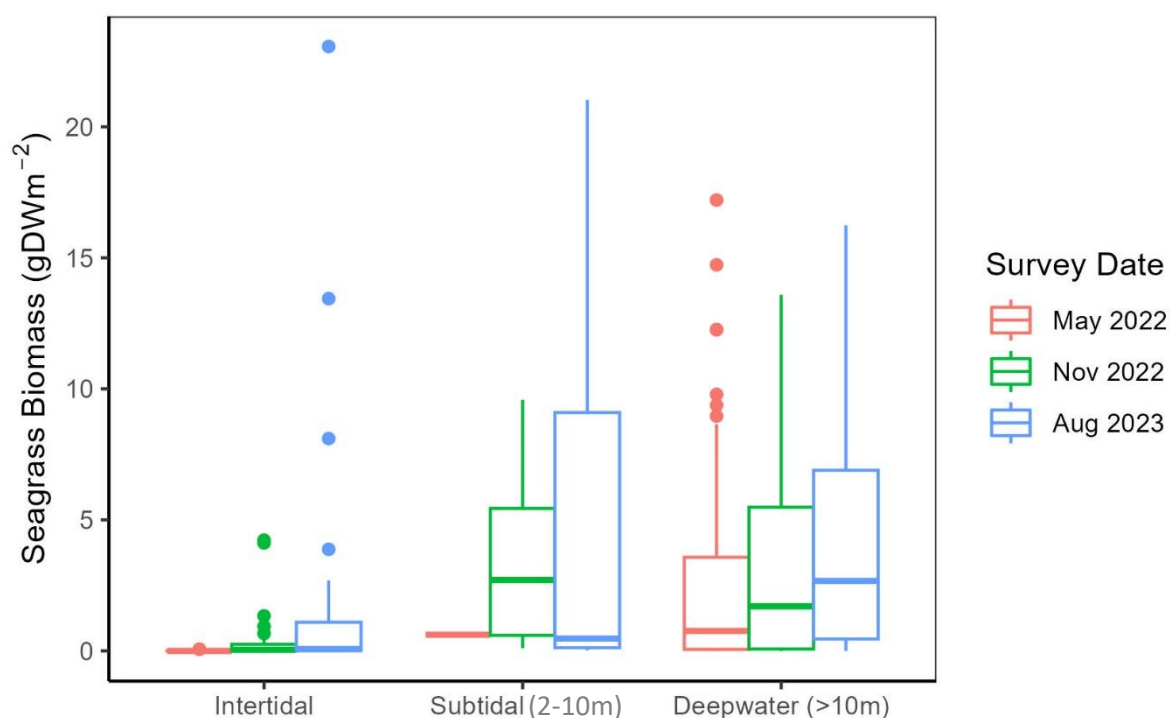


Figure 23. Seagrass biomass (gDWm⁻²) at sites all within mapped seagrass meadows at three depth zones in Hervey Bay in May 2022, October/November 2022 and August 2023. Box plots show the minimum, maximum, median and 25th and 75th percentiles. Data sources: Bryant et al. 2023.

Table 5. Mean biomass of seagrass (g DWm⁻²) of all sites within mapped seagrass meadows at three depth zones in Hervey Bay in May 2022, October/November 2022 and August 2023. Data sources: Bryant et al. 2023.

Depth	SURVEY	Mean	SE	Max	Min	SD	CV	n
Intertidal (0-2m)	May 2022	0.01	0.004	0.06	0.00	0.02	2.97	22
	Oct/Nov 2022	0.33	0.13	4.22	0.00	0.87	2.66	46
	Aug 2023	1.33	0.46	23.07	0.00	3.55	2.68	60
Subtidal (2-10m)	May 2022	0.62	NA	0.62	0.62	NA	NA	1
	Oct/Nov 2022	3.67	1.13	9.58	0.10	3.58	0.98	10
	Aug 2023	4.75	1.78	21.03	0.02	6.88	1.45	15
Deep-water (>10m)	May 2022	2.95	0.65	17.21	0.00	4.42	1.50	46
	Oct/Nov 2022	3.18	0.38	13.59	0.00	3.62	1.14	91
	Aug 2023	4.14	0.41	16.24	0.00	4.25	1.03	110

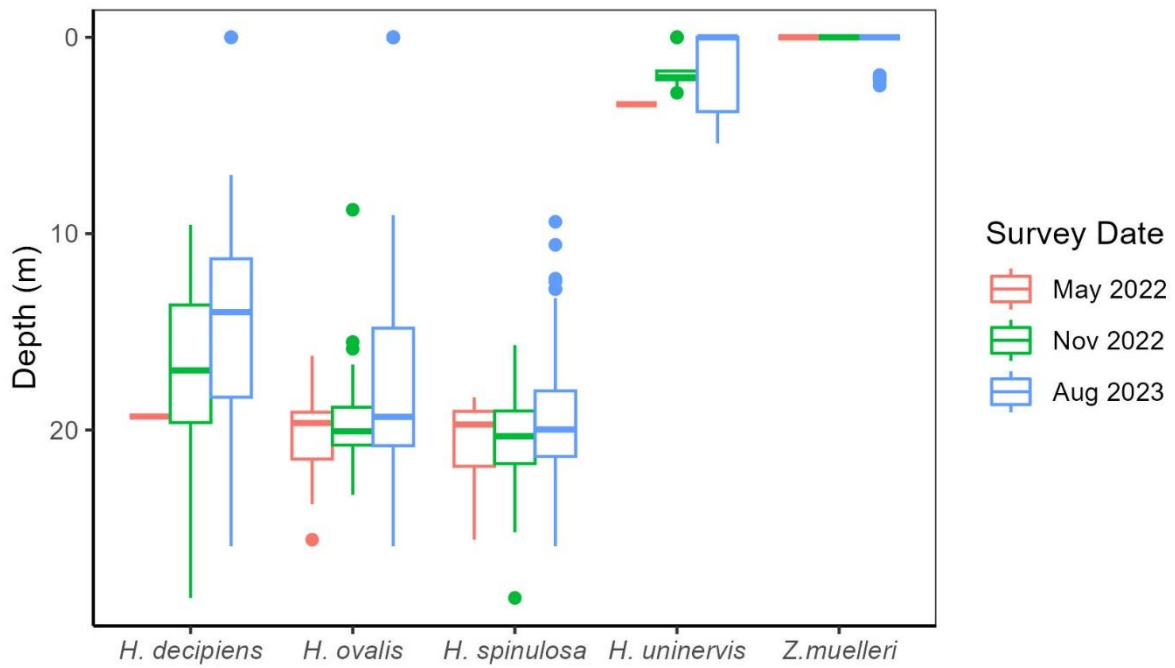


Figure 24. Depth distribution of each species present in Hervey Bay during seagrass surveys in May 2022, October/November 2022 and August 2023. Data sources: Bryant et al. 2023.

Great Sandy Strait

Comparison with historical distribution, species and density

Due to significant differences in mapping techniques and the extent of ground truthing in historical surveys, it is difficult to accurately quantify absolute changes in seagrass resources in the Great Sandy Strait prior to 1998 (McKenzie et al. 2000).

A broad scale predominantly dive and video based assessment of seagrass in December 1998 found $55 \pm 14.5 \text{ km}^2$ of seagrass, predominantly in the northern and central regions of the Great Sandy Strait (Figure 25, McKenzie 2017). Dense *Z. muelleri* with *H. ovalis* meadows dominated the intertidal banks, except at Kauri Creek, which was dominated by *Cymodocea serrulata*. Shallow subtidal meadows contributed 5% to the total distribution. Subtidal meadows occurred mostly in the northern and southern regions along the edge of intertidal banks, or extending across the large subtidal banks, and were dominated by *Halophila* species (*H. spinulosa*, *H. decipiens*, *H. ovalis*) or *Z. muelleri* and (McKenzie 2017). *Syringodium isoetifolium* was also identified during the survey. The distribution mapped in 1998 likely represents seagrass in a relatively healthy state, although there are no baseline data to confirm this.

Following a significant flood event in February 1999, surveys from 1999 to 2002 tracked seagrass recovery using a combination of aerial photographs combined with ground truthing via helicopter or on foot (McKenzie et al. 2000 and 2003). Seagrass area declined approximately 50% from February to November 1999 with losses occurring mainly in the northern region and at Kauri Creek and Tin Can Inlet (Figure 25, McKenzie et al. 2003). The 2002 survey, which occurred 36 months after the flood event, found intertidal seagrass had increased to $70.1 \pm 19.5 \text{ km}^2$ which was greater than pre-flood (1998) levels (McKenzie et al. 2003) and average biomass had recovered at most meadows to similar or slightly lower levels except for the *C. serrulata* meadow at Kauri Creek which had not recovered (McKenzie et al. 2003). Subtidal seagrass was not assessed during the 1999 to 2002 post-flood surveys.

No broad-scale mapping of seagrass occurred in the Great Sandy Strait over the following 20 years. The 1998 survey covered both intertidal and subtidal areas of the Great Sandy Strait whereas subsequent (1999 to 2002) broadscale surveys did not. Given the similarities in survey methodologies and survey area, the 1998 seagrass distribution provides a good pre-flood comparison to our current 2023 survey results.

In May 2022, three months after significant flooding in the region, the total area of intertidal seagrass ($12.1 \pm 4.1 \text{ km}^2$) was only 23% of the 1998 intertidal seagrass distribution ($52.9 \pm 17.25 \text{ km}^2$) and 17% of the 2002 distribution ($70.1 \pm 19.5 \text{ km}^2$) (Figure 25). During the most recent surveys conducted from August to November 2023, the total area of seagrass mapped ($53.04 \pm 11.41 \text{ km}^2$) had more than tripled since the first post-flood survey in May and was very similar to the total area of seagrass mapped in 1998 and 76% of the distribution mapped in 2002 (Figure 26). In 2023, there was very little seagrass present in the shallow subtidal zone compared to 1998 and there was very little seagrass in the central region from the Mary River South to Moonboom Islands compared to 1998 and 2002 (Figure 25 and 26).

The species of seagrass present in Great Sandy Strait have changed since historical surveys. In both 1998 and 2002 surveys, *Z. muelleri* dominated meadows on both the mainland and K'gari side. During the initial post-flood survey in 2002, *Z. muelleri* dominated meadows on both the mainland and *H. uninervis* was more prevalent on the K'gari coast (Figure 27 a). During the most recent (2023) survey however, *H. uninervis* (narrow) dominated meadows along the mainland coast and *Z. muelleri*

dominated those on the K’gari coast (Figure 27c). In 1998, a dense *Cymodocea serrulata* meadow was present south of Kauri creek and *Syringodium isoetifolium* occurred on the southern tip of K’gari. *C. serrulata* has not been reported in the region since 1998 but *S. isoetifolium* was also present during 2002 (McKenzie et al. 2003). *H. spinulosa* was also present on the deeper edge of meadows in these original surveys (McKenzie 2017 and McKenzie et al. 2003). *C. serrulata* and *S. isoetifolium* have not been detected in the 2022 and 2023 surveys (Figure 27a-c).

Seagrass density (average biomass) has changed markedly since the 1998 survey when average meadow biomass was up to 46.9 g DW m⁻² at some individual meadows (McKenzie et al. 2017). Following the 2022 flood event, biomass was extremely low (majority < 0.1 g DW m⁻² and <1 % cover) (Figure 28a). The most recent survey highlights some increase in biomass since the flood event but overall seagrass density remains extremely low with a maximum mean meadow biomass of only 3.3 ± 1.1 g DW m⁻² (Figure 28c).

In 1998, the dominant substrate at the vast majority of meadows was sand (McKenzie 2017). In May 2022 however, following the flood event, there were a higher proportion of sites where the dominant sediment was classified as mud. The most recent surveys in August to November 2023 also found that the dominant sediment type at most sites in Great Sandy Strait was mud (Figure 30a-c).

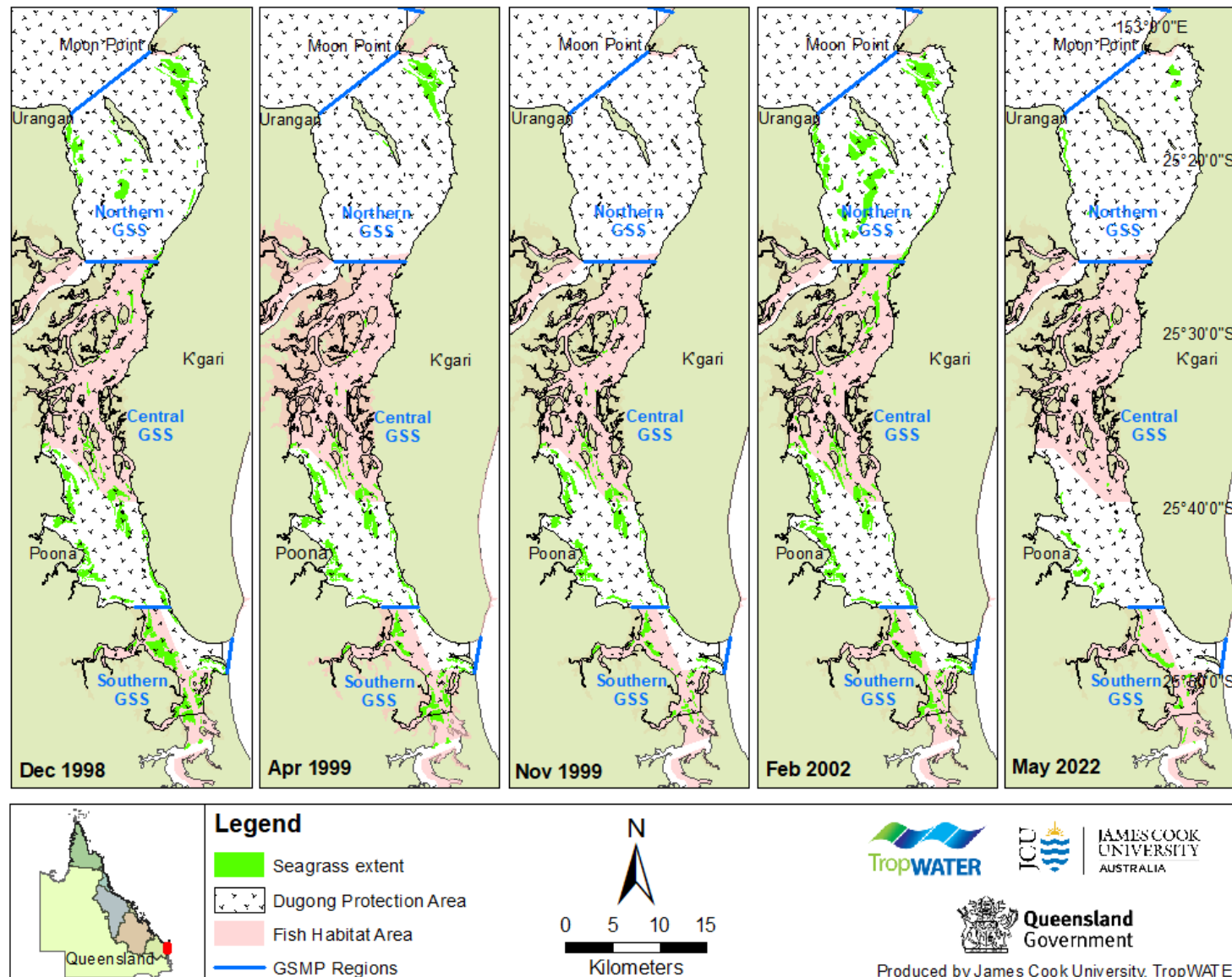


Figure 25. From Rasheed et al. 2023 - Total seagrass extent mapped during broad scale assessments of seagrass in Great Sandy Strait from 1988 to 2022. Data sources: McKenzie 2017, McKenzie et al. 2000, Campbell and McKenzie 2001, McKenzie and Campbell 2003, Bryant et al. 2023.

Seagrass in August to November 2023

A total of 992 sites were assessed in the Great Sandy Strait from August–November 2023 including 830 exposed sites surveyed by helicopter and 162 subtidal sites surveyed by boat. Seagrass was present at 30% of the exposed intertidal sites (248 sites) compared to only 10 % (111 sites) in May 2022 (Figure 31). Seagrass was found at only 4% of the subtidal sites (7 sites) and all of these were at relatively shallow (majority <2 m) depths, most of which may expose on extreme low tides. The majority of seagrass sites were once again concentrated north of Turkey Island and south of the Moonboom Islands (Figure 26).

The total area of intertidal seagrass mapped from August to November 2023 ($53.04 \pm 11.41 \text{ km}^2$) had more than tripled since the first post-flood survey in May ($12.1 \pm 4.1 \text{ km}^2$) and was very similar to the total area of intertidal seagrass mapped in December 1998 ($52.9 \pm 17.25 \text{ km}^2$; McKenzie et al. 2017), although a wider distribution of seagrass is now present from Urangan to Woody Island and very little seagrass is present from the Mary River South to Moonboom Islands (Figure 26).

The seagrass species found were typical of those previously reported in the Great Sandy Strait (Dredge et al. 1977, McKenzie and Campbell 2003) and more broadly in central Queensland (Figure 2). *Z. muelleri*, *H. uninervis* (narrow leaf morphology), *H. ovalis* and *H. decipiens* were all observed during the survey (Figures 27c). As noted for narrow-leaved seagrasses in Hervey Bay it is difficult to differentiate between *Z. muelleri* and *H. uninervis* in these environments during rapid field surveys and both species may be co-occurring in intertidal environments in the Great Sandy Strait.

Forty three individual meadows comprised of sixteen community types were identified during the recent survey compared to only twenty eight meadows and six community types in May 2022 (Table 6). The majority of seagrass mapped was classified as light *Z. muelleri*, followed by light *H. uninervis* with *H. ovalis*, light *Z. muelleri* with *H. ovalis* and light *H. uninervis* communities (Table 6). Ten other community types covered a combined area of $3.6 \pm 2.1 \text{ km}^2$ (Table 6). Average biomass and percent cover had increased since May for those community types present during both surveys. Average biomass was highest for light *Z. muelleri* with *H. ovalis* communities but remained low over most community types ($<1 \text{ g DW m}^{-2}$ biomass) (Table 6).

Table 6. Total mapped area (km²), mean biomass (g DW m⁻²) and mean percent cover of different seagrass community types found in the Great Sandy Strait in May 2022 and August to November 2023.

	May 2022			August to November 2023		
Seagrass community type	Area (km ²)	Biomass (g DW m ⁻²)	% Cover	Area (km ²)	Biomass (g DW m ⁻²)	% Cover
Light <i>Zostera muelleri</i>	6.7 ± 2.6	0.14 ± 0.04	1.0 ± 0.2	13.7 ± 3.2	0.74 ± 0.18	3.6 ± 0.7
Light <i>Halodule uninervis</i> with <i>H. ovalis</i>	---	---	---	9.2 ± 1.7	0.39 ± 0.12	5.2 ± 0.9
Light <i>Zostera muelleri</i> with <i>H. ovalis</i>	1.9 ± 0.5	0.001 ± 0.001	0.3 ± 0.1	8.3 ± 0.9	3.22 ± 0.05	8.6 ± 1.2
Light <i>Halodule uninervis</i>	2.3 ± 0.7	0.01 ± 0.01	0.5 ± 0.1	7.2 ± 1.3	0.33 ± 0.11	4.6 ± 1.1
Moderate <i>Halodule uninervis</i>	---	---	---	6.2 ± 1.4	0.4 ± 0.2	4.2 ± 1.4
Moderate <i>Halodule uninervis</i> / <i>H. ovalis</i>	---	---	---	4.7 ± 0.7	1.1 ± 0.3	10.4 ± 2.5
Light <i>Halophila ovalis</i> / <i>Halodule uninervis</i>	---	---	---	1.7 ± 1.0	0.3 ± 0.1	4.4 ± 1.8
Light <i>Halophila ovalis</i> with <i>H. decipiens</i>	---	---	---	1.0 ± 0.7	0.1 ± 0.02	1 ± 0
Light <i>Halophila ovalis</i>	0.1 ± 0.02	0.002	0.5 ± 0.2	0.6 ± 0.2	0.03 ± 0.01	1.8 ± 0.4
Light <i>Halophila decipiens</i> / <i>H. uninervis</i>	---	---	---	0.4 ± 0.1	0.2 ± 0.1	4.2 ± 1.6
Light <i>Halophila ovalis</i> with <i>H. uninervis</i>	---	---	---	0.2 ± 0.05	0.02 ± 0.01	1.7 ± 0.3
Moderate <i>Halophila decipiens</i>	---	---	---	0.2 ± 0.04	1.5 ± 1.2	6.8 ± 3.4
Light <i>Halophila ovalis</i> with <i>Z. muelleri</i>	0.6 ± 0.1	0.15 ± 0.03	1.0 ± 0.3	0.1 ± 0.02	0.6 ± 0.02	1.6 ± 0.2
Light <i>Halodule uninervis</i> / <i>H. decipiens</i>	---	---	---	0.002 ± 0.005	NA	1
Light <i>Halophila decipiens</i>	---	---	---	0.002 ± 0.001	0.6	1
Light <i>Halophila uninervis</i> / <i>H. ovalis</i>	---	---	---	0.002 ± 0.001	NA	1
Light <i>Halodule uninervis</i> with <i>Z. muelleri</i>	0.5 ± 0.2	0.02 ± 0.01	0.5 ± 0.1	---	---	---

Northern Section

On the intertidal sand/mud banks at K'gari between Moon Point and Blackfellow Point (Meadow 9, Figure 32c), aggregated patches to continuous cover of light *Zostera muelleri* with *H. ovalis* (3.2 ± 0.6 g DW m⁻² and 7.4 ± 1.3 % cover) covered a total area of 8.1 ± 0.9 km² extending to the shallow subtidal zone at one site. On the mainland coast, on the mud banks from the marina at Urangan south to Mangrove point (Meadow 10, Figure 32c), aggregated patches of moderate *Halodule uninervis*/*H. ovalis* (1.1 ± 0.3 g DW m⁻² and 7.4 ± 1.3 % cover) spanned 4.7 ± 0.7 km².

Stretching between Mangrove Point on the mainland and Big Woody Island, a large expanse of isolated patches of seagrass were mapped. The northern half (Meadow 28, Figure 32c) covered an area of 8.0 ± 1.1 km² and was comprised of light (2.0 ± 0.6 g DW m⁻²) *Zostera muelleri* growing in sandy substrate. Average percent cover was 7.1 ± 2.2 %. The southern half (Meadow 29) covered an area of 4.7 ± 0.7 km² and was comprised of light (0.7 ± 0.3 g DW m⁻²) *Halodule uninervis* growing in muddy substrate. Average percent cover was 14.4 ± 5.5 %.

Elsewhere, several smaller meadows were comprised of patches of light *Z. muelleri*, *H. uninervis* and *H. ovalis* (Meadows 30 to 39 and Meadows 52 to 54, Figure 32c). These meadows were found on mud substrate and covered a combined total area of 1.7 ± 0.9 km². At the southern tip of Little Woody Island, a small *Z. muelleri* dominated meadow (Meadow 33, Figure 32c) had the highest average biomass (3.3 ± 1.1 g DW m⁻²) and one of the highest mean percent cover of 13.4 ± 4.8 % in Great Sandy Strait.

Southern section

Meadows mapped along the mainland coast south of the Moonboom Islands were dominated by *H. uninervis* on muddy substrate, whereas meadows on the K'gari coast and the Eastern banks of Tin Can Bay were dominated by *Z. muelleri* on sandy substrate (Figure 32c).

Just south of the Moonboom islands on the mainland coast, patches of light (0.3 ± 0.1 g DW m⁻²) *H. ovalis*/*H. uninervis* were mapped along the shoreline. Mean percent cover was 3.1 ± 0.9 %. Just to the south, the Poona meadow (Meadow 11, Figure 32c) covered a total area of 8.12 ± 0.9 km² and was comprised of light (3.2 ± 0.6 g DW m⁻²) *Z. muelleri* with *H. ovalis*. Mean percent cover was 7.4 ± 1.3 %. A subtidal meadow (Meadow 53, Figure 32c) comprised of light *H. ovalis* with *H. decipiens* was mapped adjacent to the northern section of Meadow 11.

The Kauri Creek meadow (Meadow 13, Figure 32c) spanned an area of 6.9 ± 0.8 km² from the mangroves to the shallow subtidal zone. The meadow was comprised of light (0.4 ± 0.1 g DW m⁻²) *H. uninervis* with *H. ovalis*. Mean percent cover was 4.8 ± 0.9 %. Further south, the Tin Can Bay meadow (Meadow 12, Figure 32c) covered an area of 0.9 ± 0.2 km² and was comprised of light (0.4 ± 0.3 g DW m⁻²) *H. uninervis*. Mean percent cover was 4.2 ± 1.5 %.

On the K'gari coast, a light (0.3 ± 0.2 g DW m⁻²) *Z. muelleri* meadow (Meadow 47, Figure 32c) covered an area of 2.9 ± 0.9 km². Mean percent cover was 4.2 ± 1.5 %. South of Inskip Point, on the western banks of Tin Can Bay, several smaller meadows were mapped on the intertidal sandbars. They were all comprised of light *Z. muelleri*. The remaining meadows were comprised of just one or two isolated patches (Figure 32c).

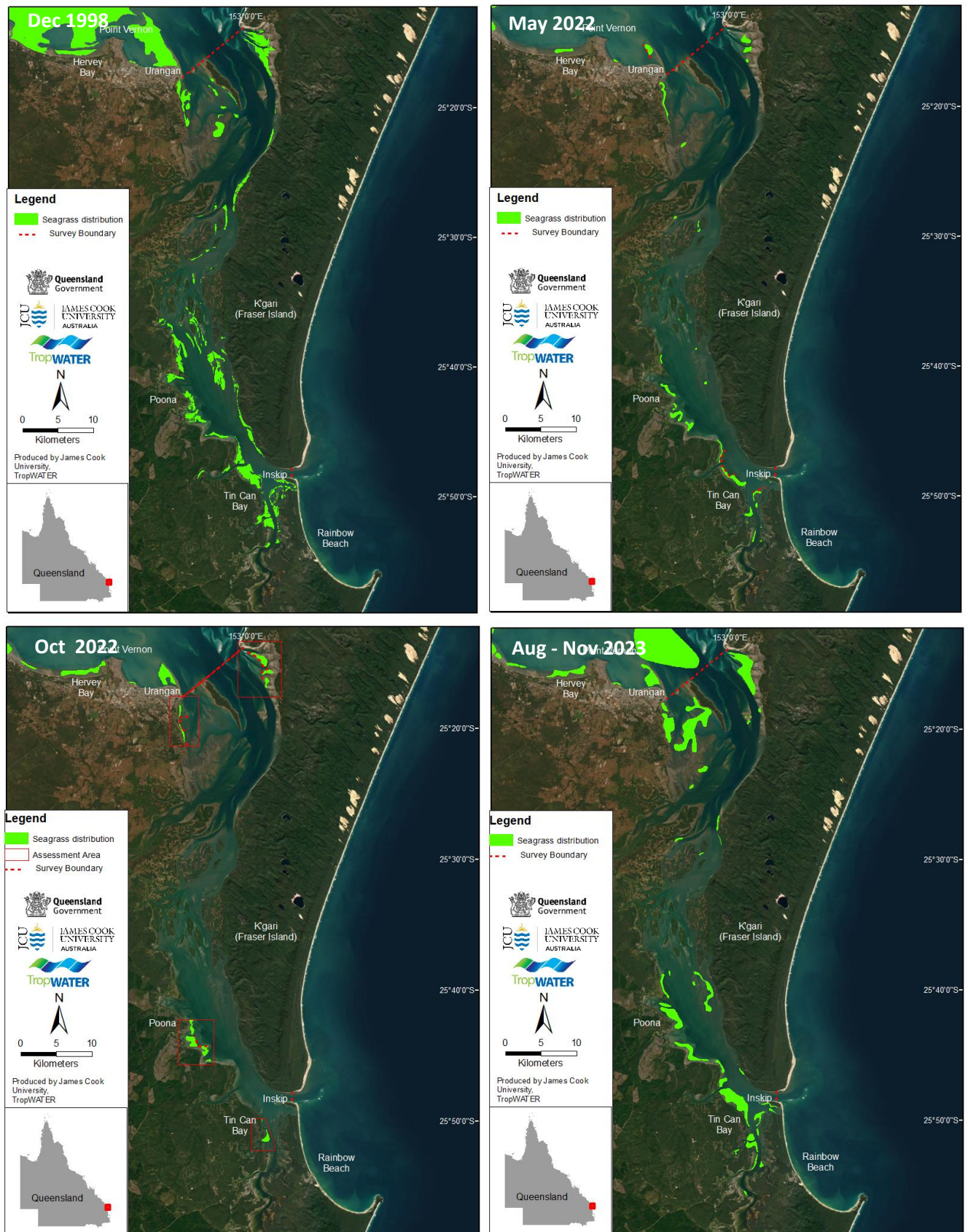


Figure 26. Total area of seagrass mapped in the Great Sandy Strait in December 1998, May 2022, October 2022 and August – November 2023. Data sources: McKenzie 2017, Bryant et al. 2023.

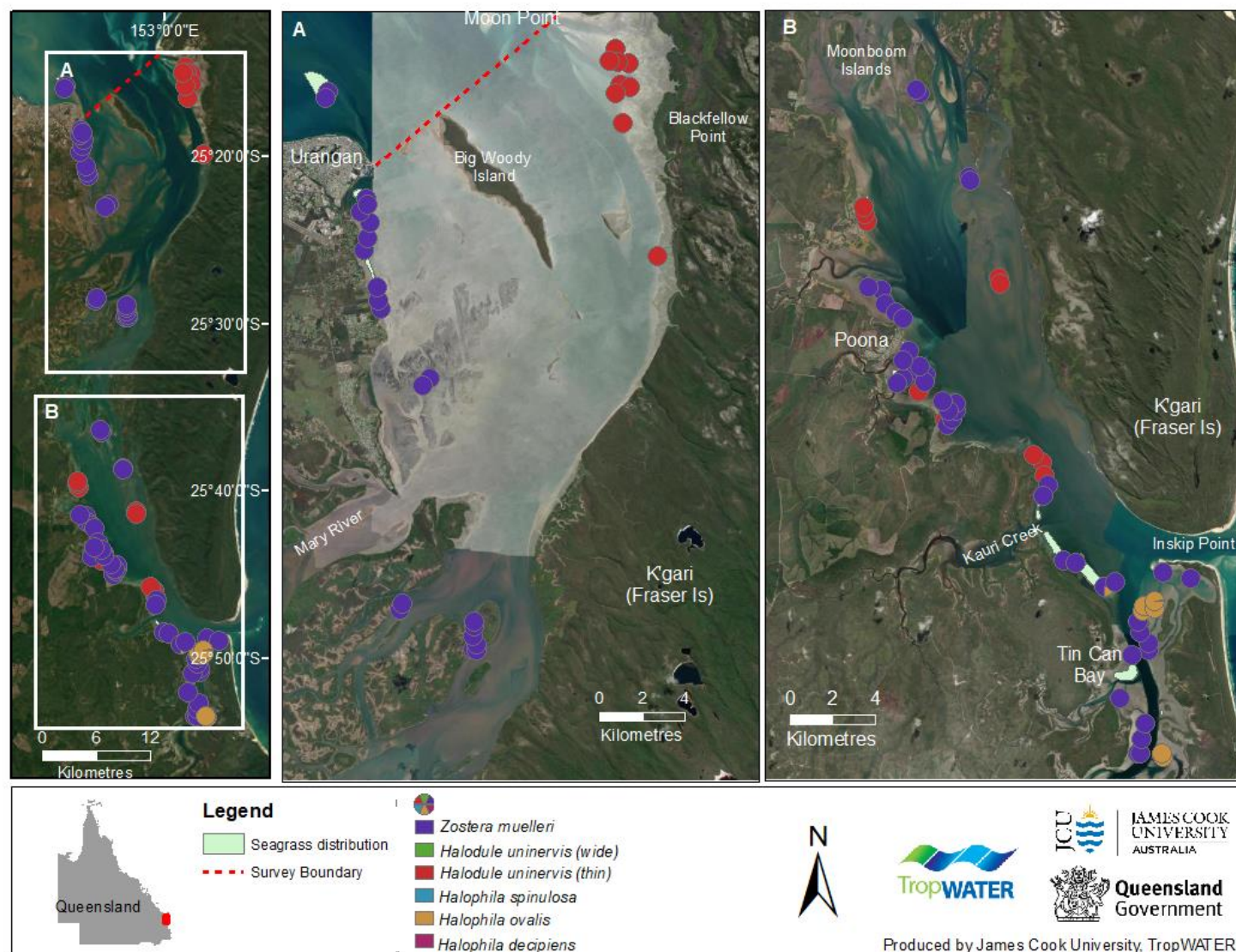


Figure 27a. Species composition of above ground seagrass biomass (g DW m⁻²) in May 2022. Data source: Bryant et al. 2023.

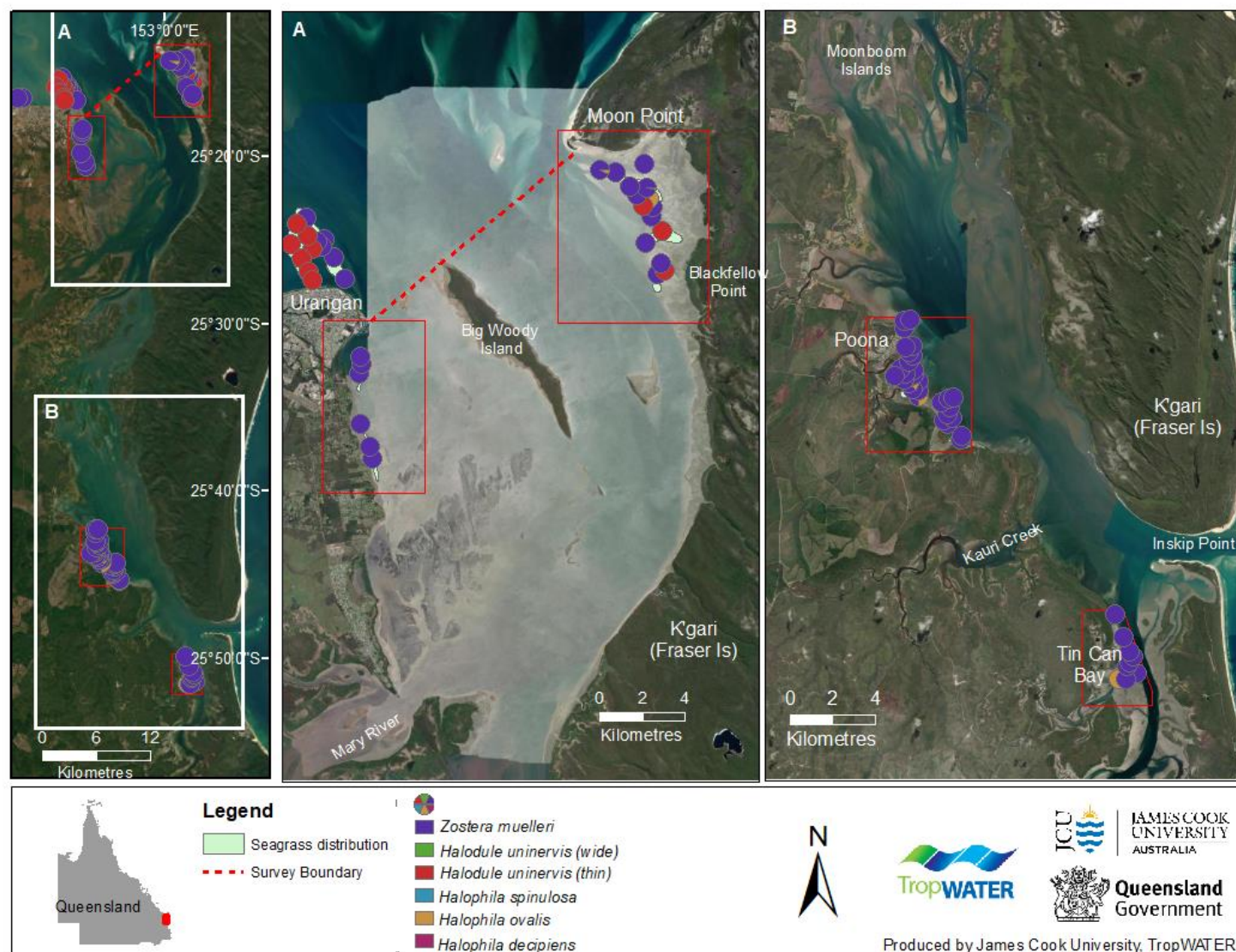


Figure 27b. Species composition of above ground seagrass biomass (g DW m⁻²) in October 2022. Data source: Bryant et al. 2023.

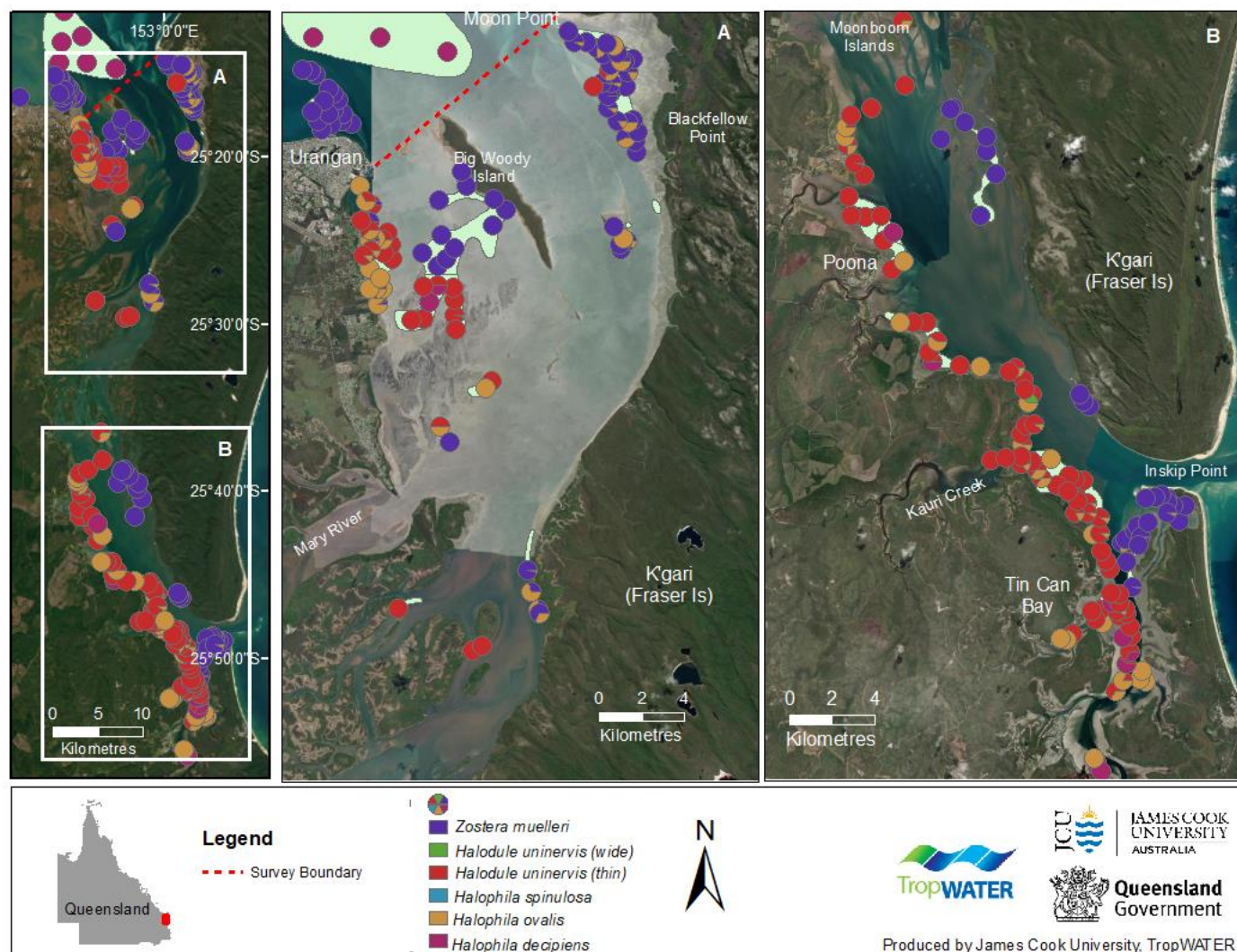


Figure 27c. Species composition of above ground seagrass biomass (g DW m⁻²) in August-November 2023.

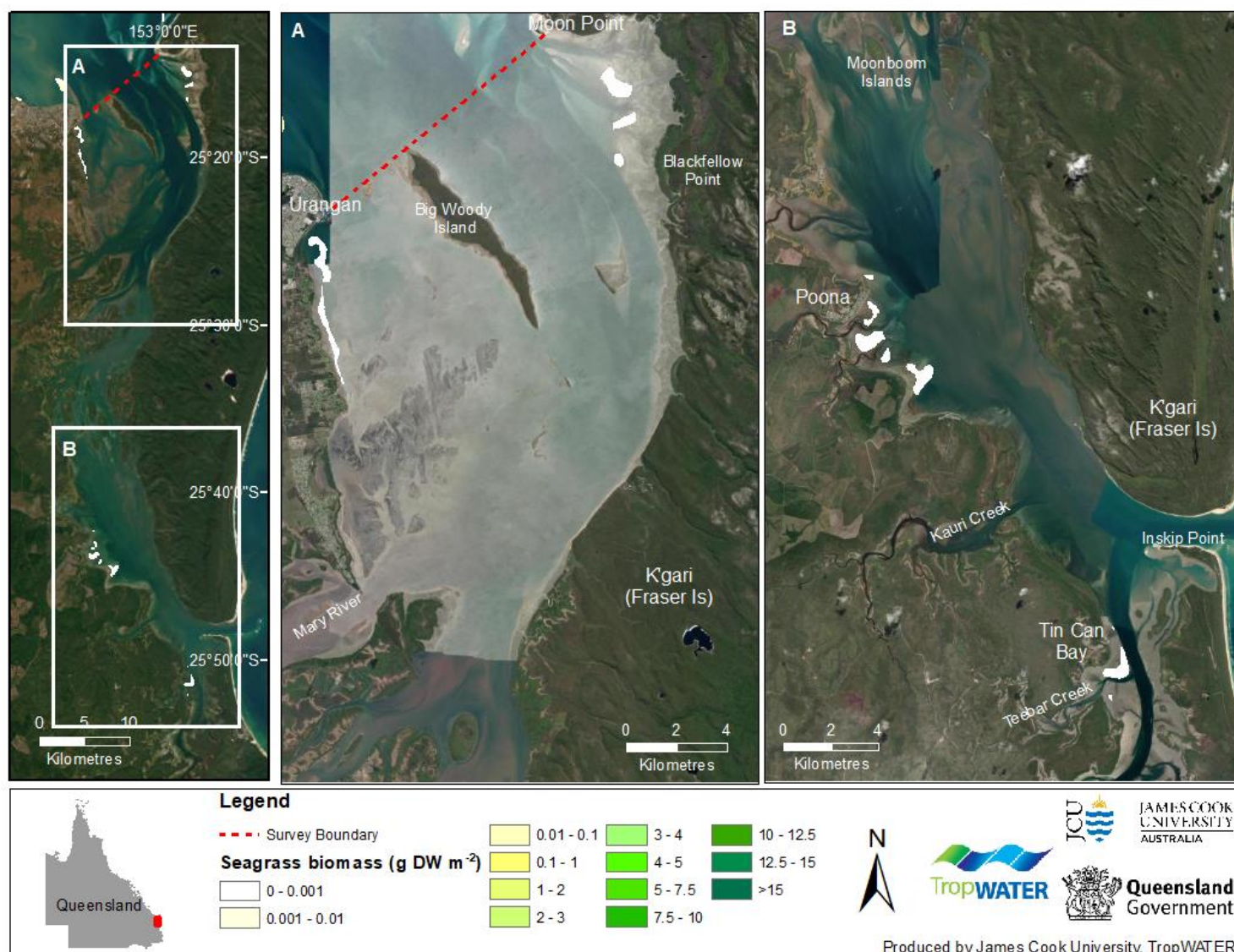


Figure 28a. Seagrass above ground seagrass biomass (g DW m⁻²) in Great Sandy Strait in May 2022. Data source: Bryant et al. 2023.

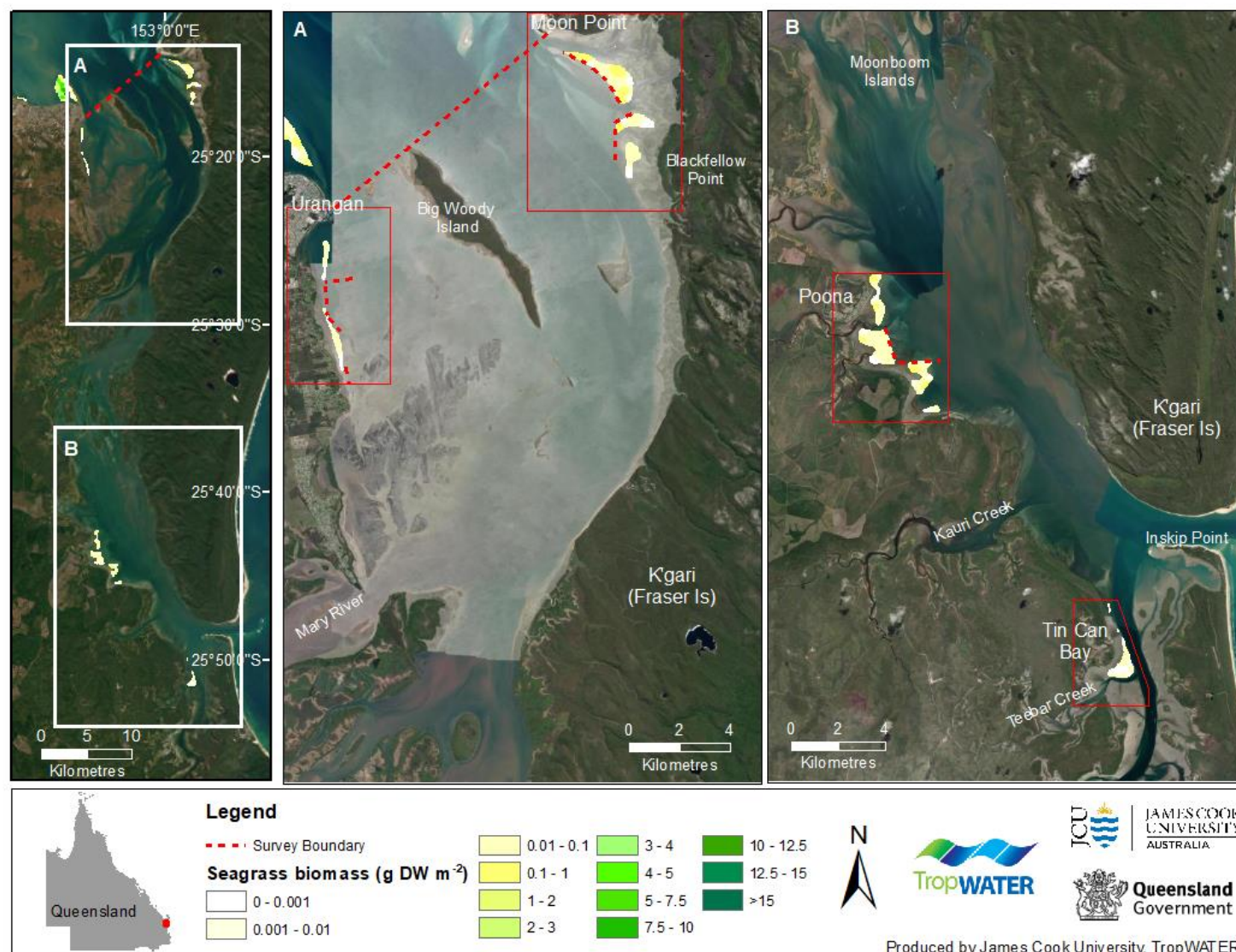


Figure 28b. Seagrass above ground seagrass biomass (g DW m⁻²) in Great Sandy Strait in October 2022. Data source: Bryant et al. 2023.

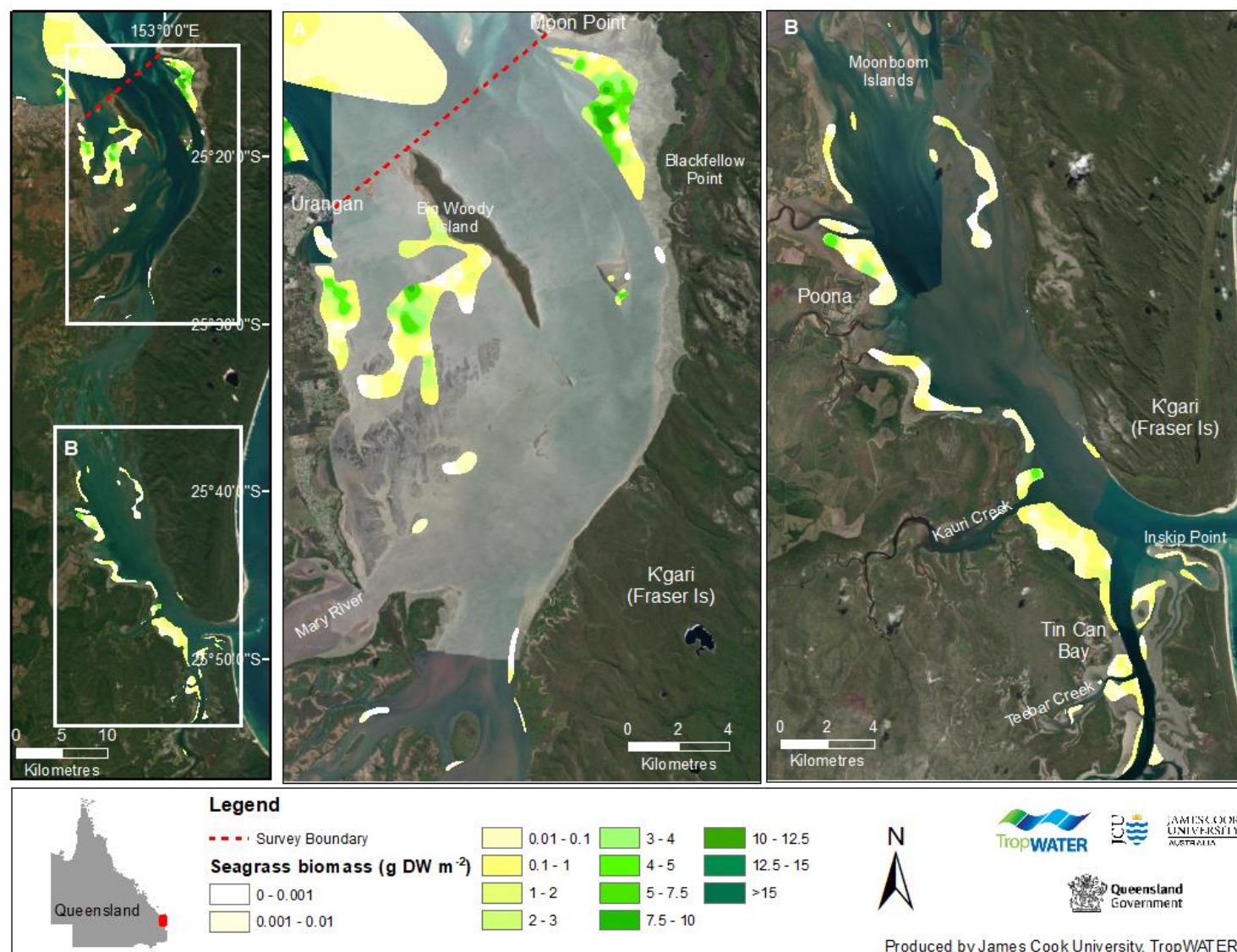


Figure 28c. Seagrass above ground seagrass biomass (g DW m⁻²) in Great Sandy Strait in August-November 2023.

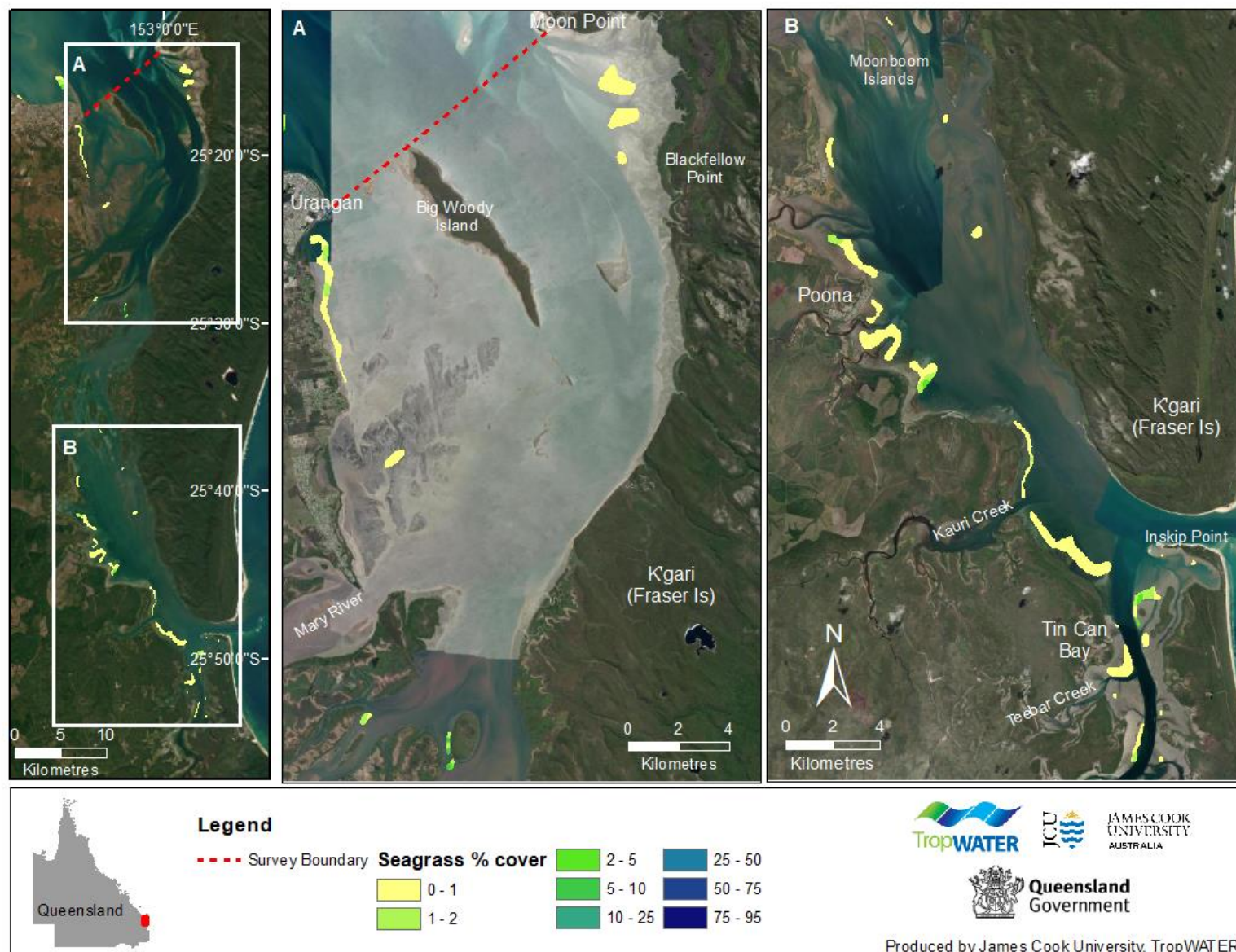


Figure 29a. Seagrass percent cover in Great Sandy Strait in May 2022. Data source: Bryant et al. 2023.

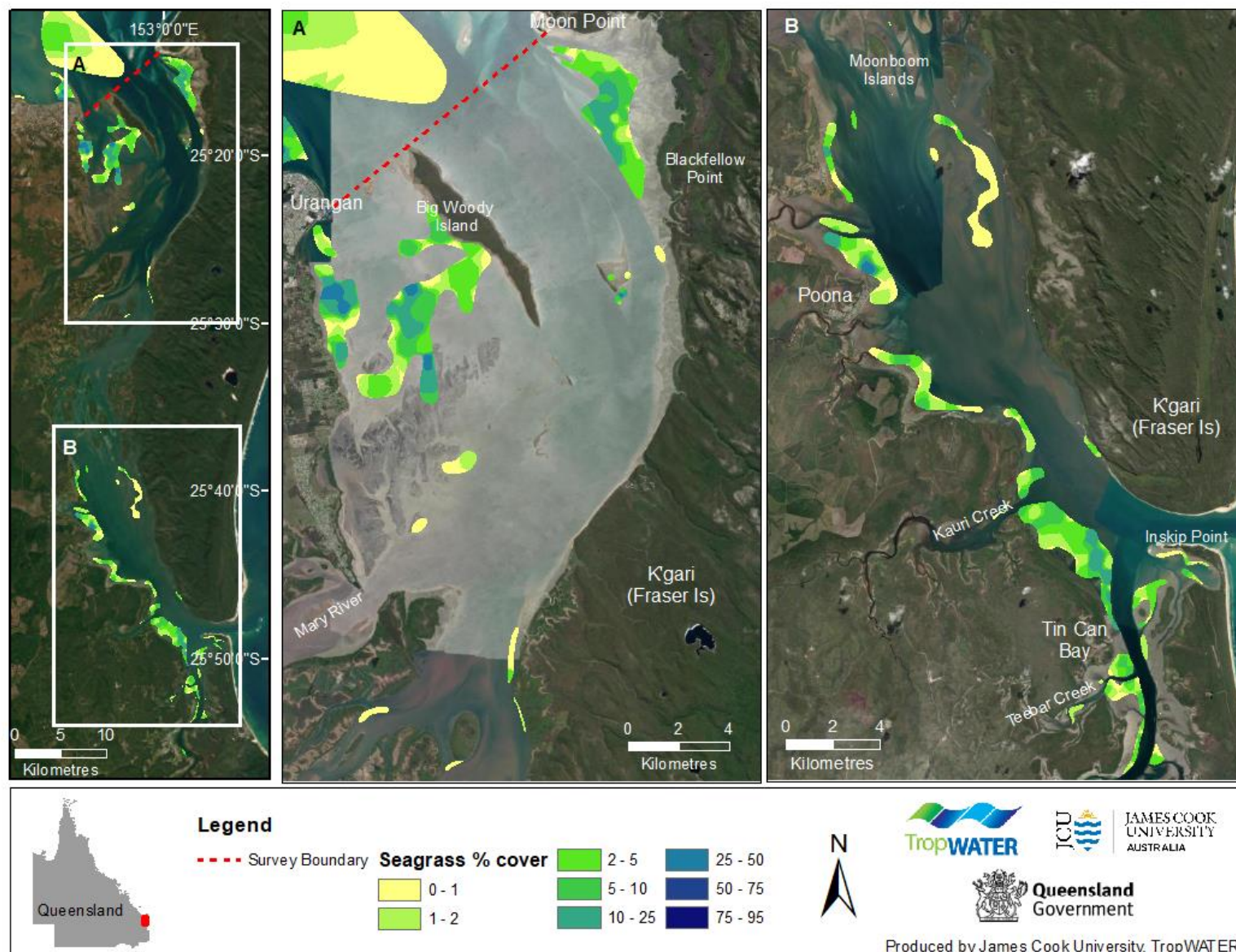


Figure 29b. Seagrass percent cover in Great Sandy Strait in October/November 2022. Data source: Bryant et al. 2023.

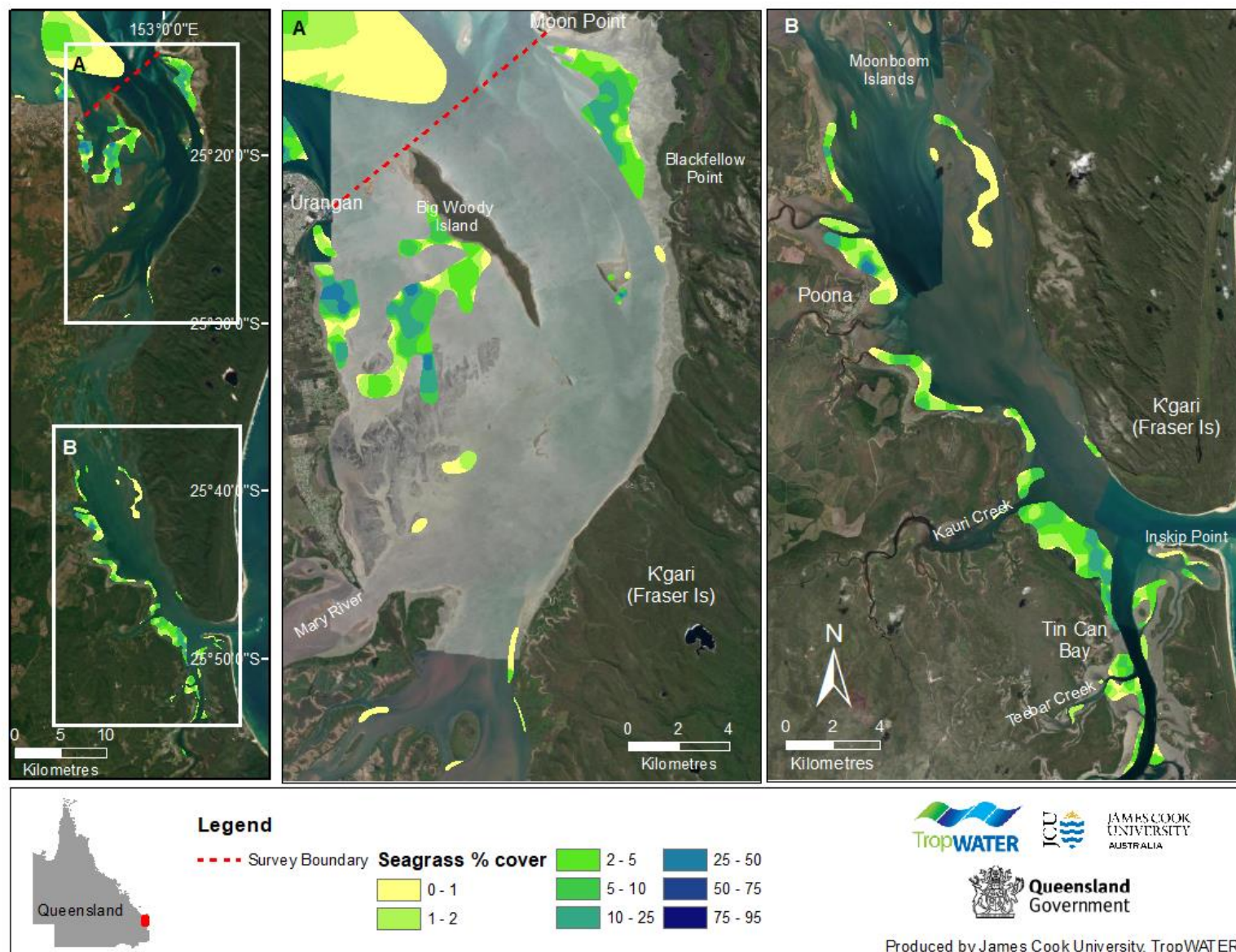


Figure 29c. Seagrass percent cover in Great Sandy Strait in August to November 2023.

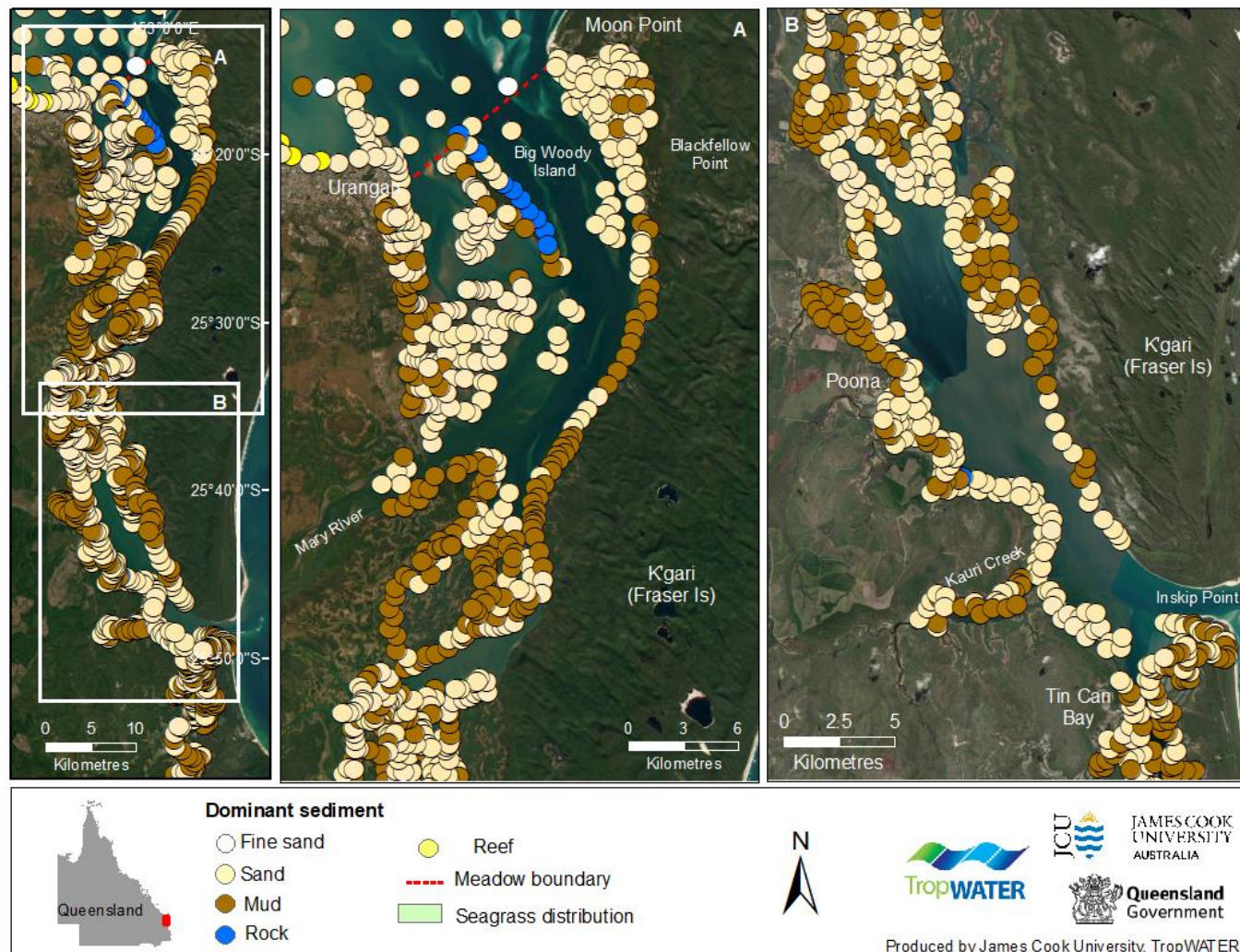


Figure 30a. Dominant sediment type at survey sites in Great Sandy Strait May 2022. Data source: Bryant et al. 2023.

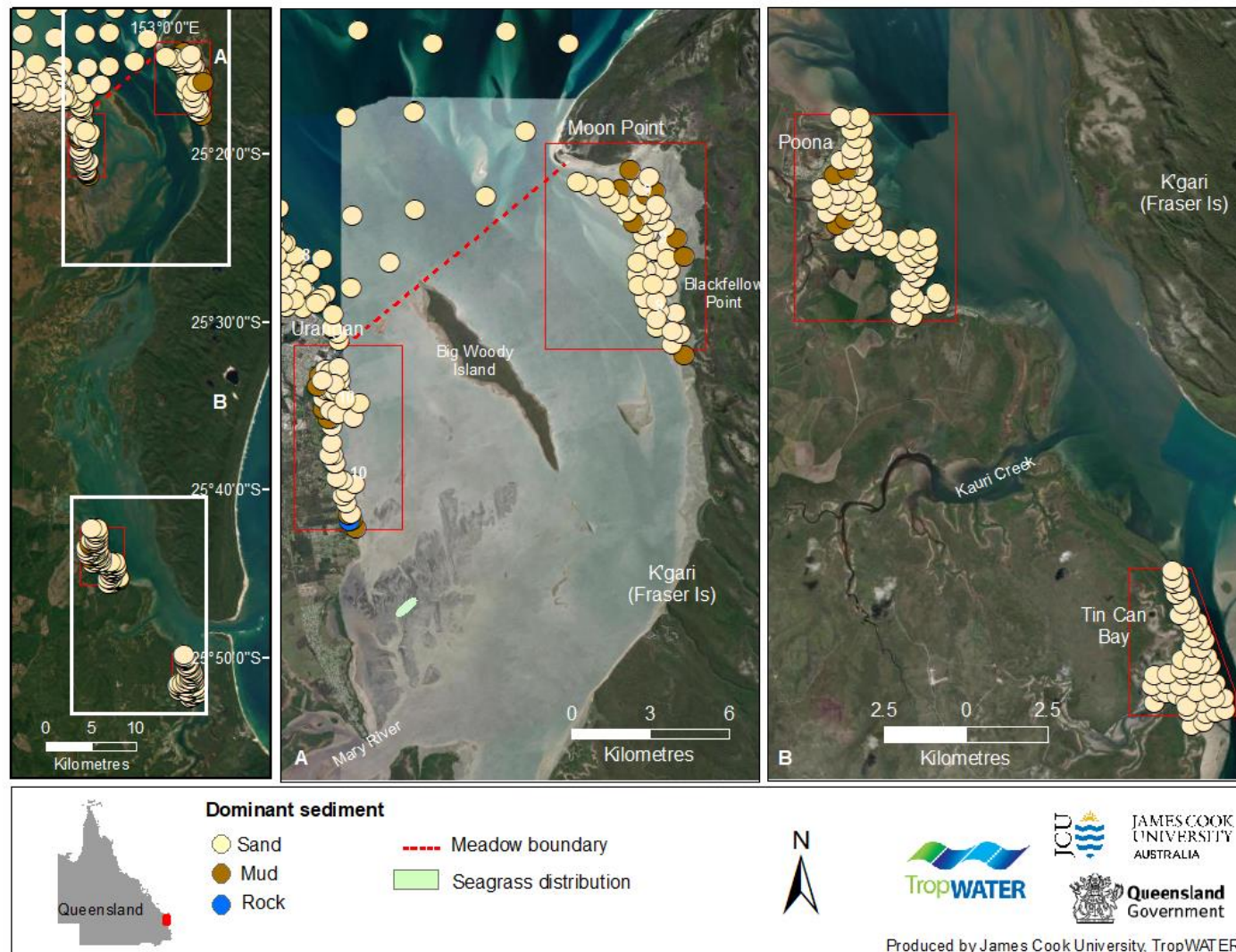


Figure 30b. Dominant sediment type at survey sites in Great Sandy Strait October 2022. Data source: Bryant et al. 2023.

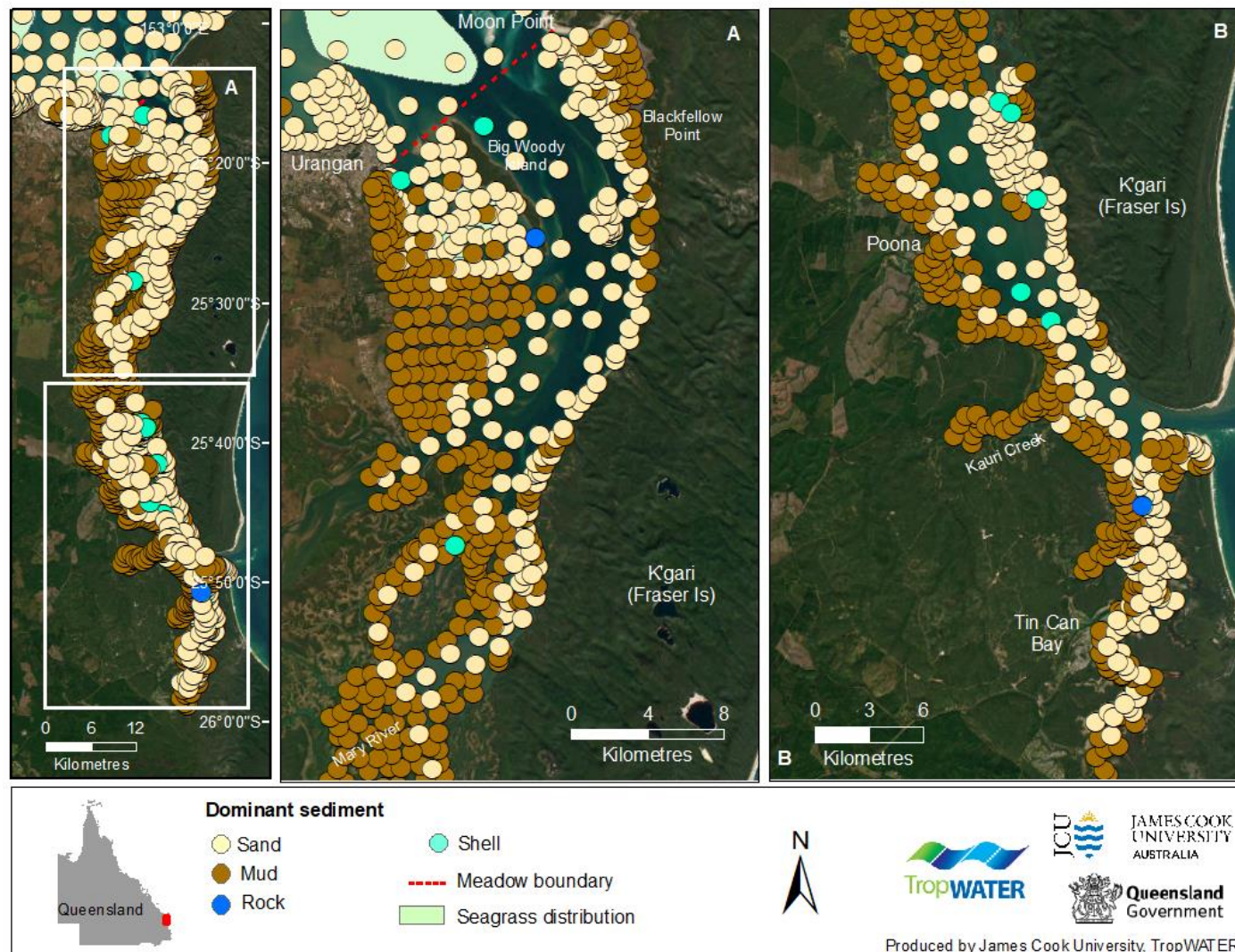


Figure 30c. Dominant sediment type at survey sites in Great Sandy Strait in August to November 2023.

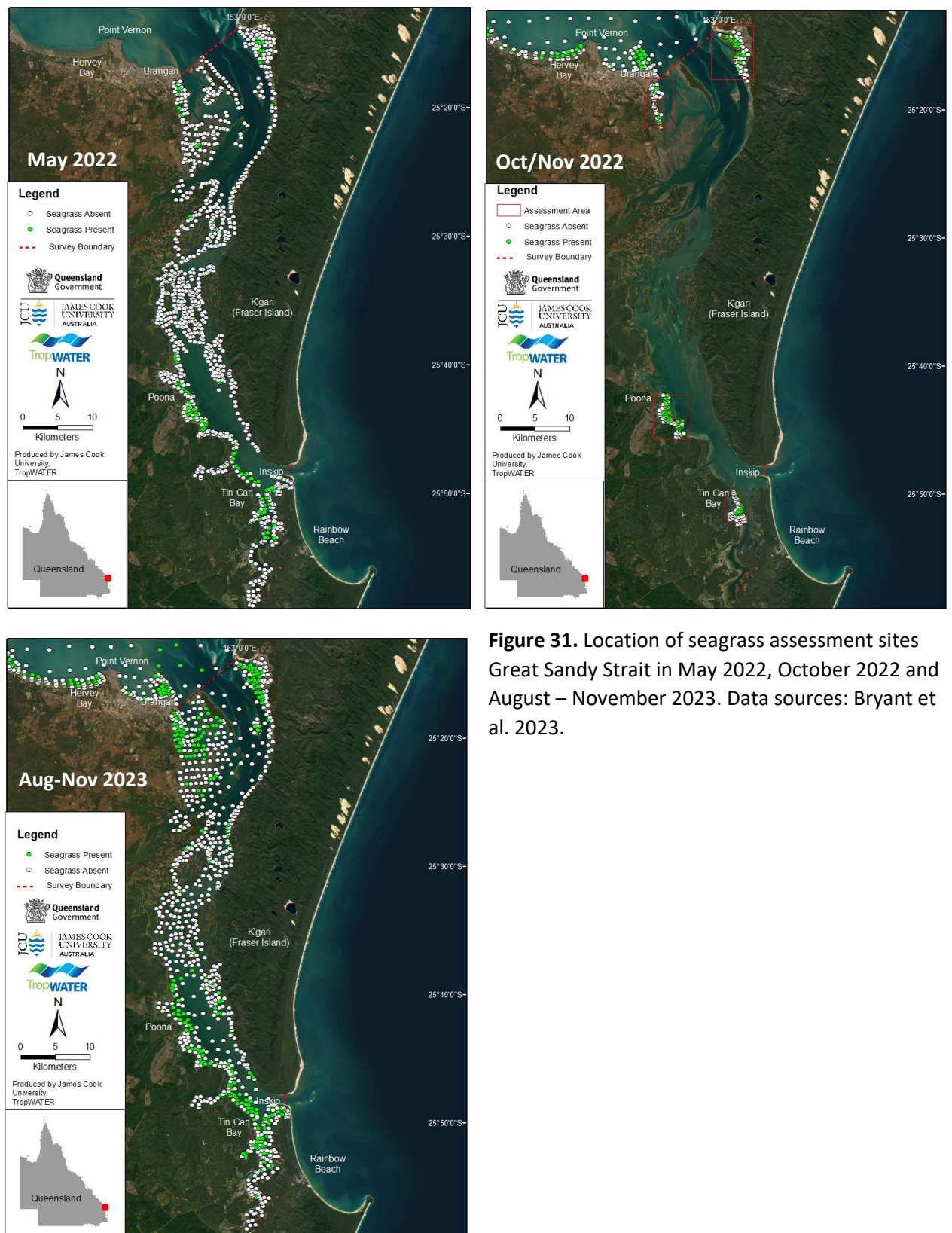


Figure 31. Location of seagrass assessment sites Great Sandy Strait in May 2022, October 2022 and August – November 2023. Data sources: Bryant et al. 2023.

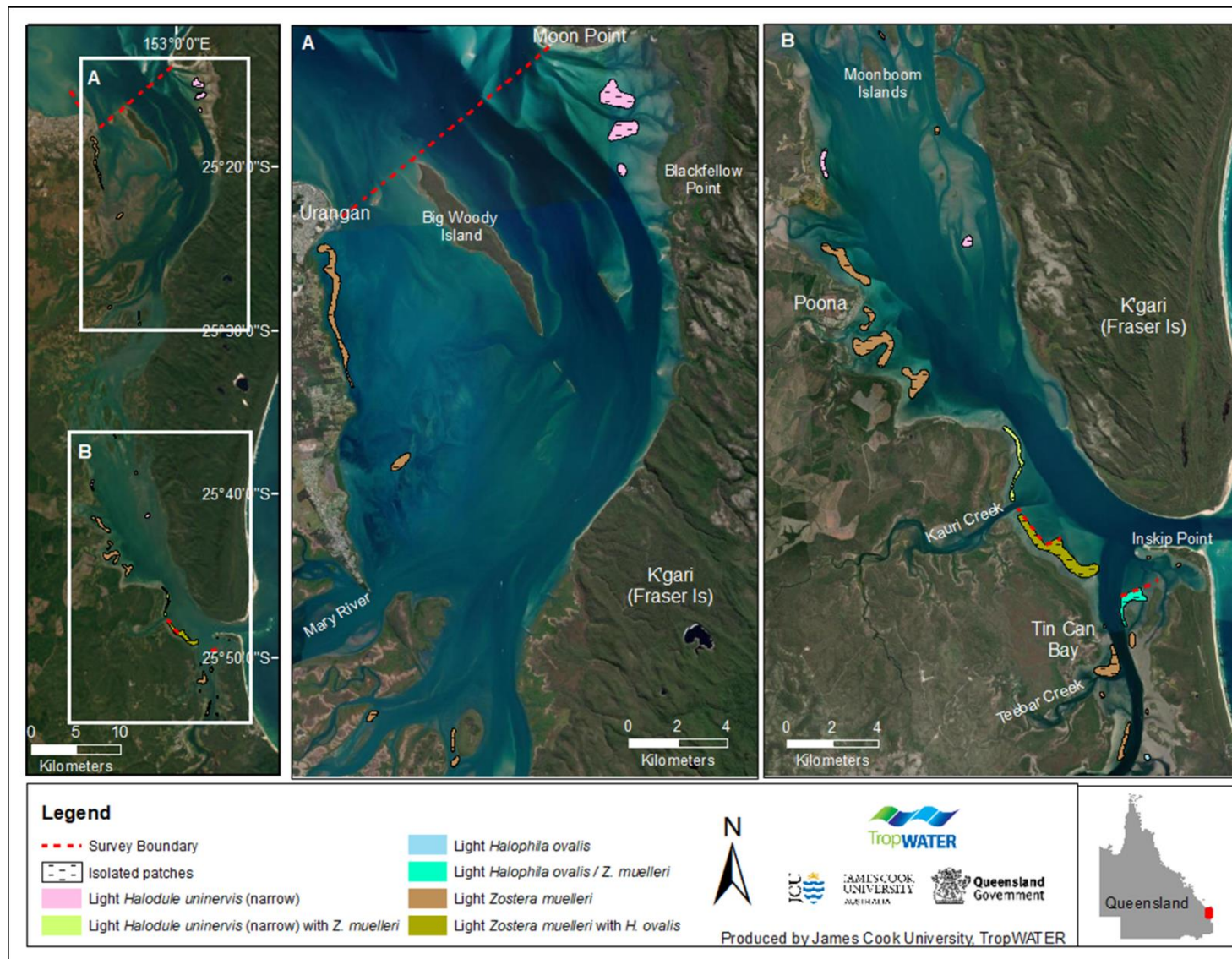


Figure 32a. Community type and landscape category of seagrass meadows mapped in Great Sandy Strait in May 2022 (Bryant et al. 2023).

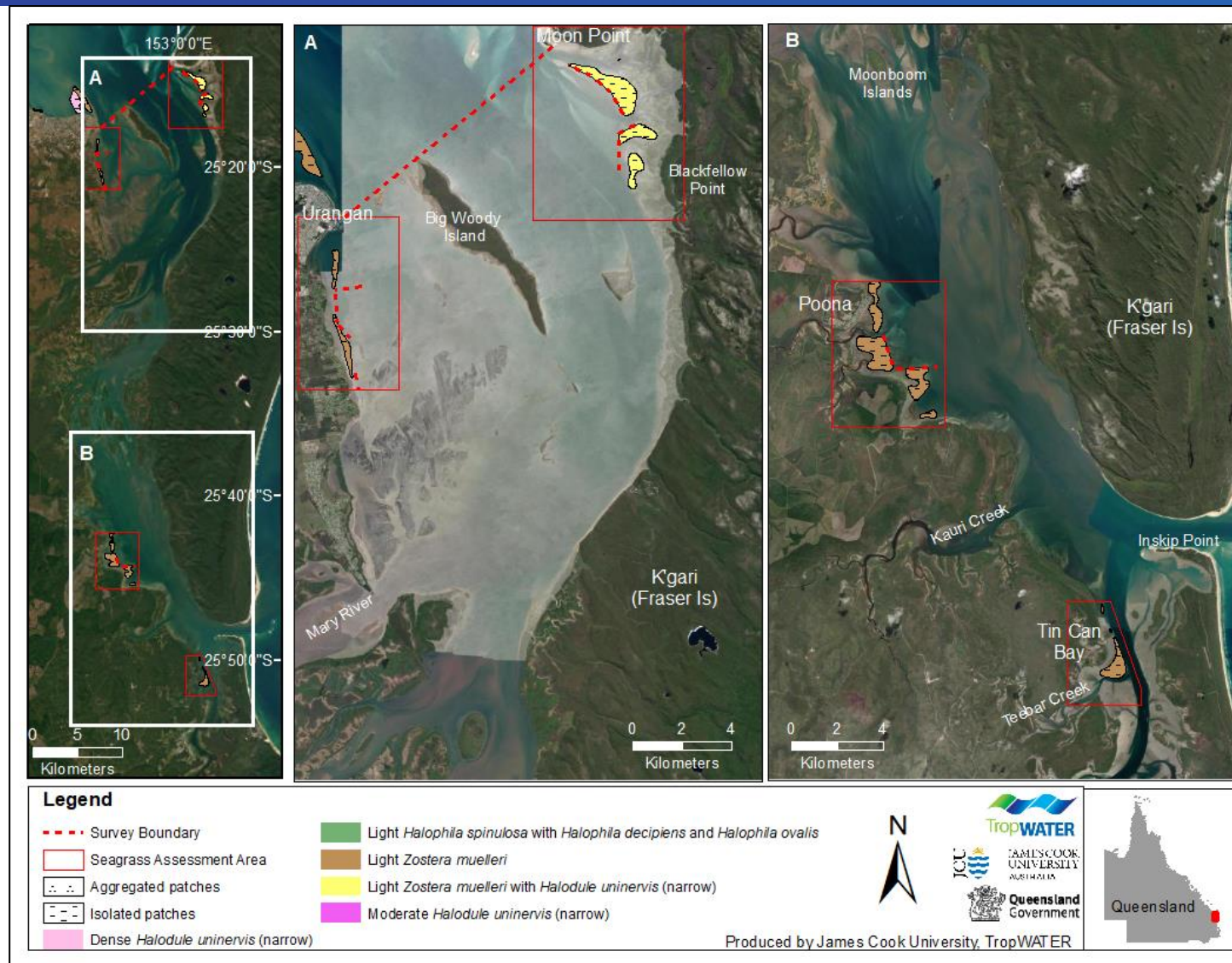


Figure 32b. Community type and landscape category of seagrass meadows mapped in Great Sandy Strait in October 2022 (Bryant et al. 2023)

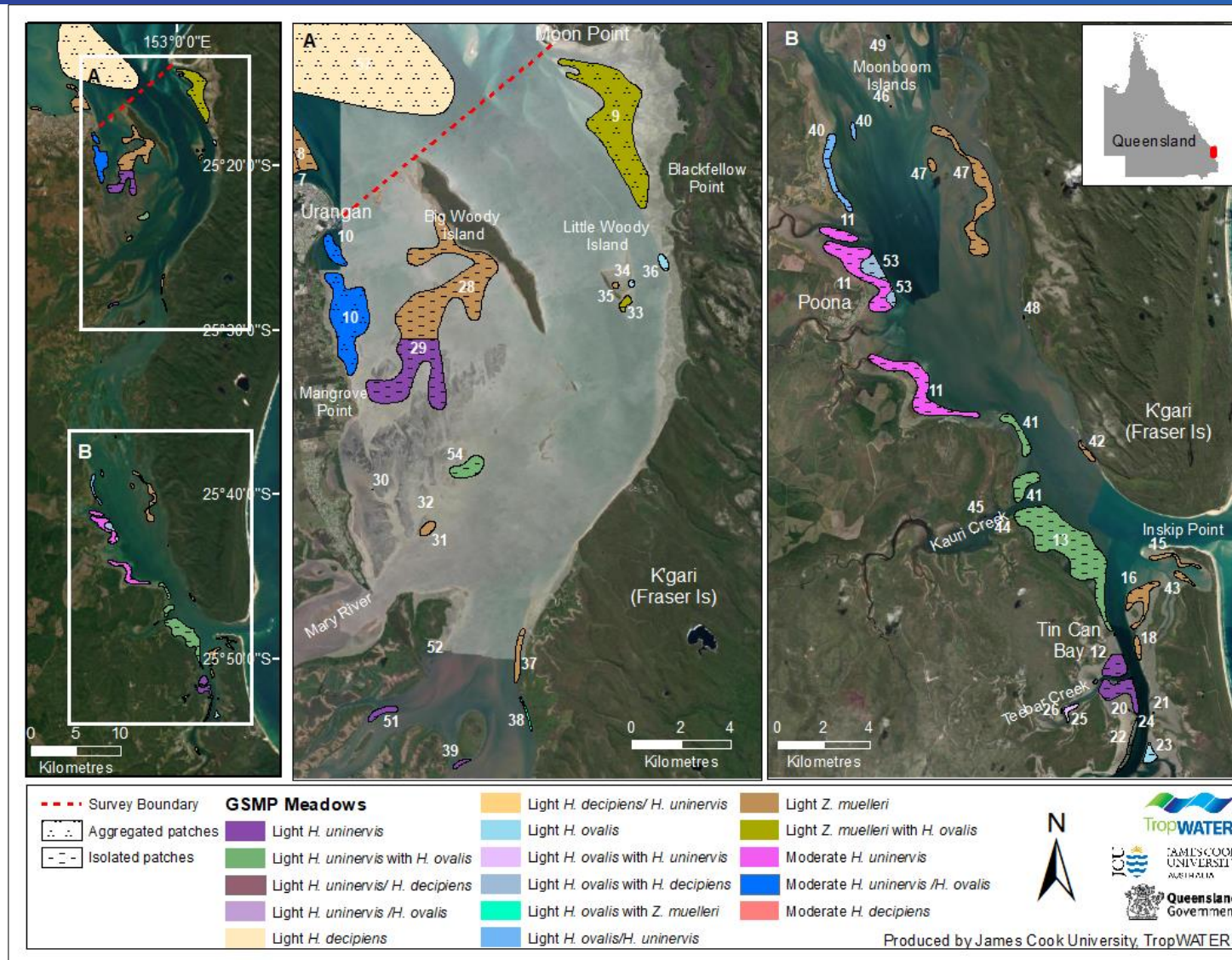


Figure 32c. Community type and landscape category of seagrass meadows mapped in Great Sandy Strait in August to November 2023.

Post-flood recovery

The total area of intertidal seagrass mapped from August to November 2023 ($53.04 \pm 11.41 \text{ km}^2$) had more than tripled since the first post-flood survey in May ($12.1 \pm 4.1 \text{ km}^2$) and was very similar to the total area of intertidal seagrass mapped in December 1998 ($52.9 \pm 17.25 \text{ km}^2$; McKenzie et al. 2000), although a wider distribution of seagrass is now present from Urangan to Woody Island and very little seagrass is present from the Mary River South to Moonboom Islands (Figure 26 above).

Average biomass across all intertidal sites within mapped seagrass meadows in the Great Sandy Strait in August to November 2023 ($0.9 \pm 0.1 \text{ g DW m}^{-2}$) had increased since the initial post-flood survey in May 2022 ($0.1 \pm 0.03 \text{ g DW m}^{-2}$) (Figure 33, Table 7) but remained low compared to the vast majority of intertidal meadows in December 1998.

Seagrass was only found at one shallow subtidal site at 2.7m dbMSL on the margin of an intertidal meadow. The depth distribution of all species was narrow compared to 1998 when seagrass extended into the shallow subtidal zone (Figure 34).

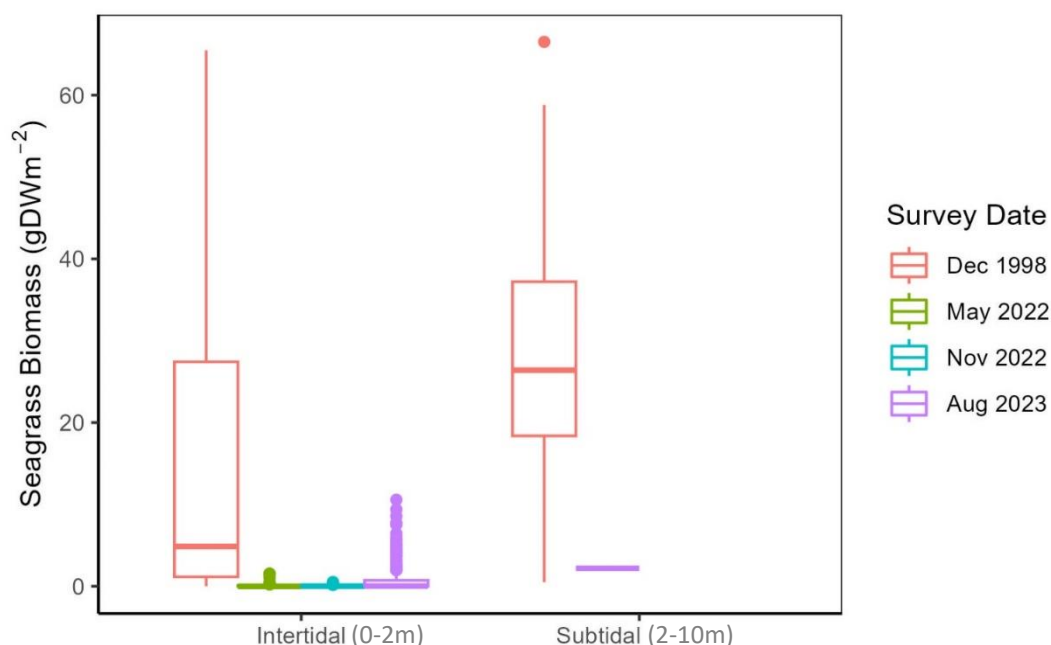


Figure 33. Seagrass biomass (gDWm^{-2}) at all sites within mapped seagrass meadows at two depth zones in Great Sandy Strait in May 2022, October/November 2022 and August 2023. Box plots show the minimum, maximum, median and 25th and 75th percentiles. Data sources: Bryant et al. 2023.

Table 7. Mean biomass of seagrass (gDWm⁻²) for all sites within mapped seagrass meadows at two depth zones in Great Sandy Strait in May 2022, October/November 2022 and August 2023. Data sources: Bryant et al. 2023.

Depth	SURVEY	Mean	SE	Max	Min	SD	CV	n
Intertidal (0-2m)	May 2022	0.10	0.03	1.55	0.00	0.27	2.73	111
	Oct/Nov 2022	0.06	0.01	0.53	0.00	0.09	1.55	86
	Aug 2023	0.90	0.11	10.57	0.00	1.82	2.01	256
Shallow subtidal (2-10m)	Aug 2023	2.20	NA	2.20	2.20	NA	NA	1

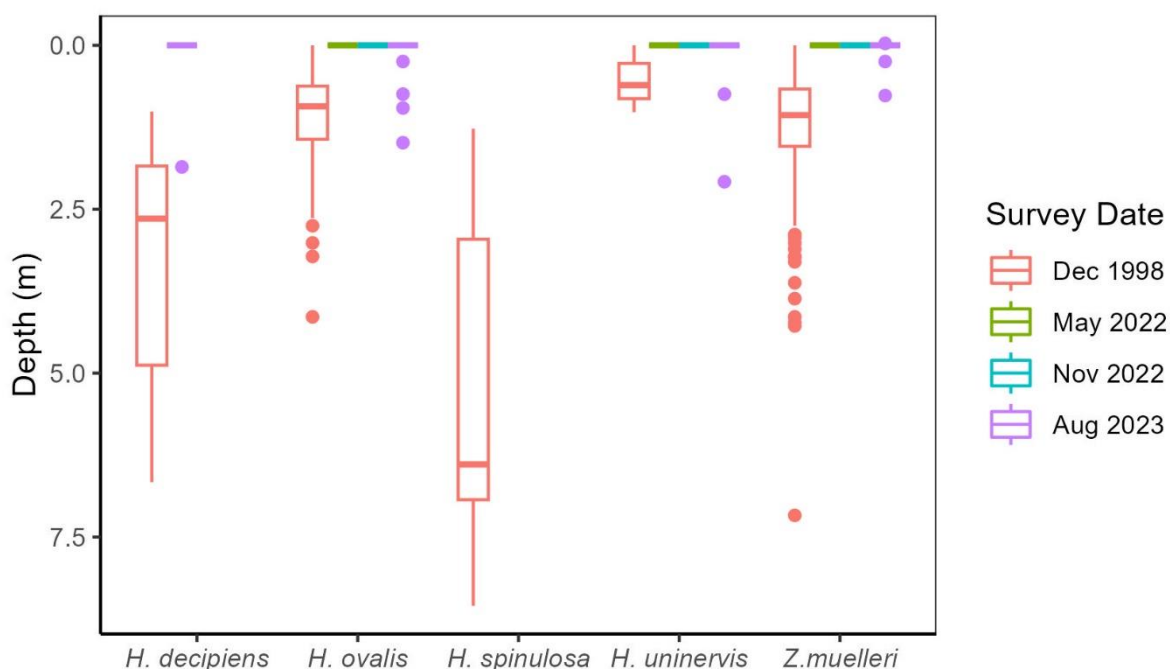


Figure 34. Depth distribution of species present in Great Sandy Strait during seagrass surveys in May 2022, October/November 2022 and August to November 2023. *C. serrulata* and *S. isoetifolium* not shown. Data sources: Bryant et al. 2023.

Based on the distribution of seagrass meadows in May 2022, four locations were selected to track seagrass recovery during peak seagrass growth in October 2022; Moon Point, Urangan, Poona and Tin Can Bay (Figure 32 b above). These locations encompassed a large portion of the seagrass remaining in the Great Sandy Strait following the flood event in the May 2022 survey and represented the main community types in the region.

Daytime low tides were not as low during the October survey (~ 0.7 m) as during May (~ 0.4 m). For this reason, the offshore portions of some meadows could not be assessed in October 2022. The results presented herein compare only the portion of meadows that were assessed in common during both the May and October surveys in 2022 and the August to November survey in 2023 (Table 8 and Figures 35 to 39).

Moon Point (Meadow 9)

The total area of seagrass mapped at the Moon Point meadow (4.9 ± 0.9 km²) had increased 63 % since October 2022 (3.0 ± 0.8 km²) and had almost tripled in size since May (1.3 ± 0.4 km²). The footprint of the meadow was similar to 1998. Isolated patches had become aggregated patches. Mean seagrass biomass (1.8 ± 0.5 g DW m⁻²) and mean percent cover (5.3 ± 1.2 %) had increased significantly since October 2022 survey (0.1 ± 0.03 g DW m⁻² and 0.9 ± 0.2 % cover) ($p = 0.0001$, $p < 0.0001$). The meadow remained a light *Z. muelleri* with *H. ovalis* community (Figure 35 and 36).

Urangan (Meadow 10)

South of Urangan, total seagrass area (2.1 ± 0.7 km²) more than doubled since October 2022 (0.8 ± 0.5 km²). Mean biomass (0.1 ± 0.06 g DW m⁻²) remained extremely low within the area mapped in October 2022 but was higher outside. Mean percent cover (3.5 ± 1.0 %) had increased significantly since the October 2022 survey (0.4 ± 0.1 %) ($p < 0.0001$). Aggregated patches of seagrass were *H. uninervis*, *Z. muelleri* and *H. ovalis* were present (Figure 35 and 37).

Poona (Meadow 11)

The total area of seagrass mapped in the Poona assessment area (3.2 ± 1.4 km²) was similar to the previous survey (3.4 ± 0.5 km²). There was a species shift from *Z. muelleri* to *H. uninervis*. Within the assessment area, mean biomass (0.03 ± 0.02 g DW m⁻²) and mean percent cover (2.1 ± 0.5 %) remained at a similar low level to October 2022 (Figure 35 and 38).

Tin Can Bay (Meadow 12)

In the Tin Can Bay assessment area, the total area of seagrass (0.9 ± 0.2 km²) was the same as mapped in October 2022 (0.9 ± 0.3 km²). Mean biomass (0.3 ± 0.02 g DW m⁻²) remained low but percent cover (5 ± 1 %) increased significantly since October 2022 (0.2 ± 0.07 %) ($p < 0.0001$). There was a species shift from *Z. muelleri* in October 2022 to a light cover of *H. uninervis* with *H. ovalis* (Figure 35 and 39).

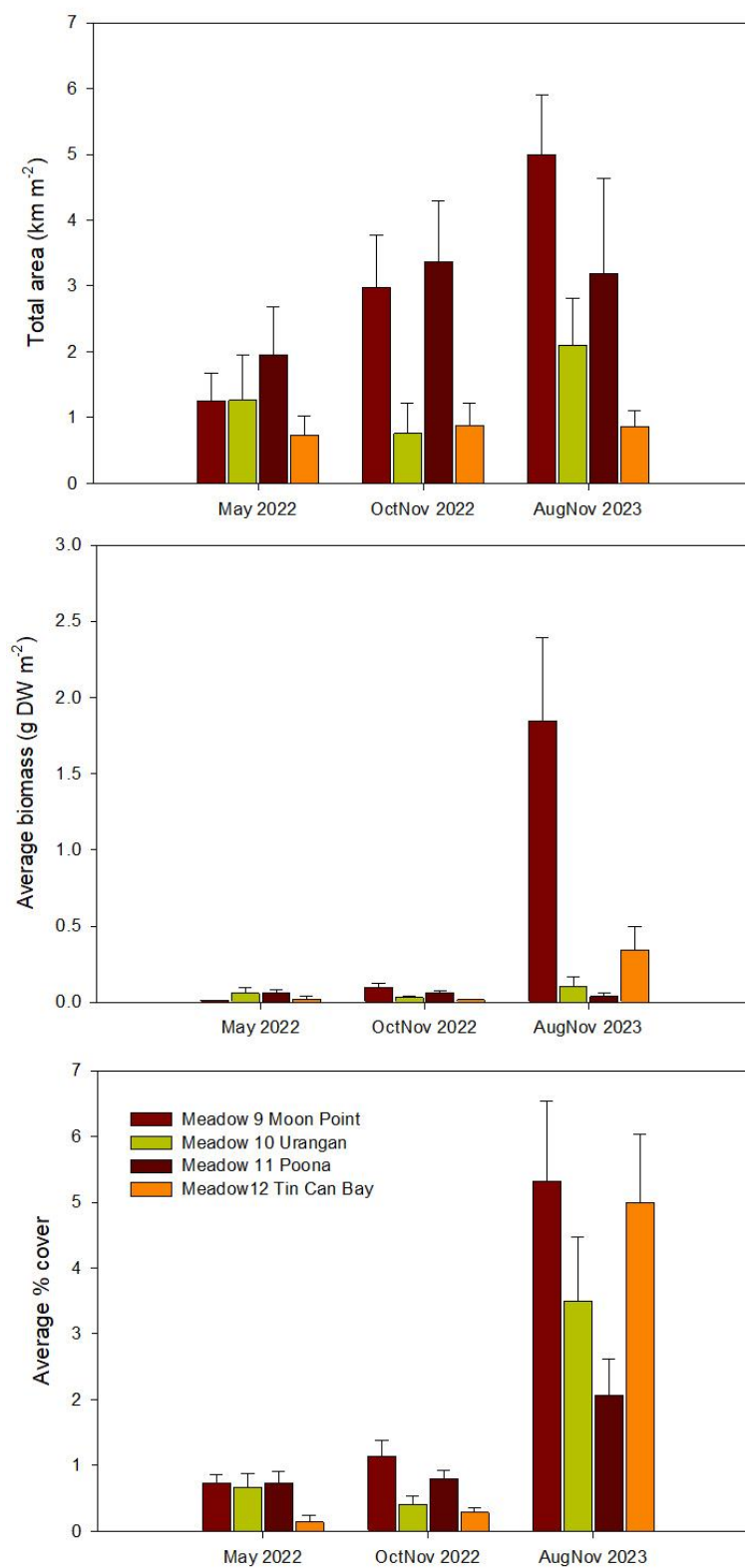


Figure 35. Total area (km²), mean seagrass biomass (g DW m⁻²), and mean % cover at meadows in the four seagrass assessment areas in May 2022, October 2022 and August – November 2023.

Table 8. Total area (km²), mean biomass (g DW m⁻²) and mean percent cover of seagrass at meadows mapped in the Great Sandy Strait in May and October/November 2022 and from August to November 2023. Daytime low tides were not as low during the October 2022 survey (~0.7 m) as during May 2022 (~0.4 m) or the most recent survey in 2023 and results compare only the portion of meadows that were assessed during all surveys.

Meadow	Total Area (km ²)			Mean Biomass (g DW m ⁻²)			Mean % Cover		
	May 2022	Oct/Nov 2022	Aug-Nov 2023	May 2022	Oct/Nov 2022	Aug-Nov 2023	May 2022	Oct/Nov 2022	Aug-Nov 2023
9	1.3 ± 0.4	3.0 ± 0.8	5.0 ± 0.9	0.01 ± 0.002	0.1 ± 0.03	1.8 ± 0.5	0.7 ± 0.1	0.9 ± 0.2	5.3 ± 1.2
10	1.3 ± 0.7	0.8 ± 0.5	2.1 ± 0.5	0.06 ± 0.03	0.03 ± 0.01	0.1 ± 0.06	0.7 ± 0.2	0.4 ± 0.1	3.5 ± 1.0
11	1.9 ± 0.7	3.4 ± 0.9	3.2 ± 1.4	0.06 ± 0.02	0.06 ± 0.01	0.04 ± 0.02	0.7 ± 0.2	0.7 ± 0.1	2.1 ± 0.5
12	0.7 ± 0.3	0.9 ± 0.3	0.9 ± 0.2	0.02 ± 0.02	0.02 ± 0.005	0.3 ± 0.2	0.1 ± 0.1	0.2 ± 0.07	5.0 ± 1.0

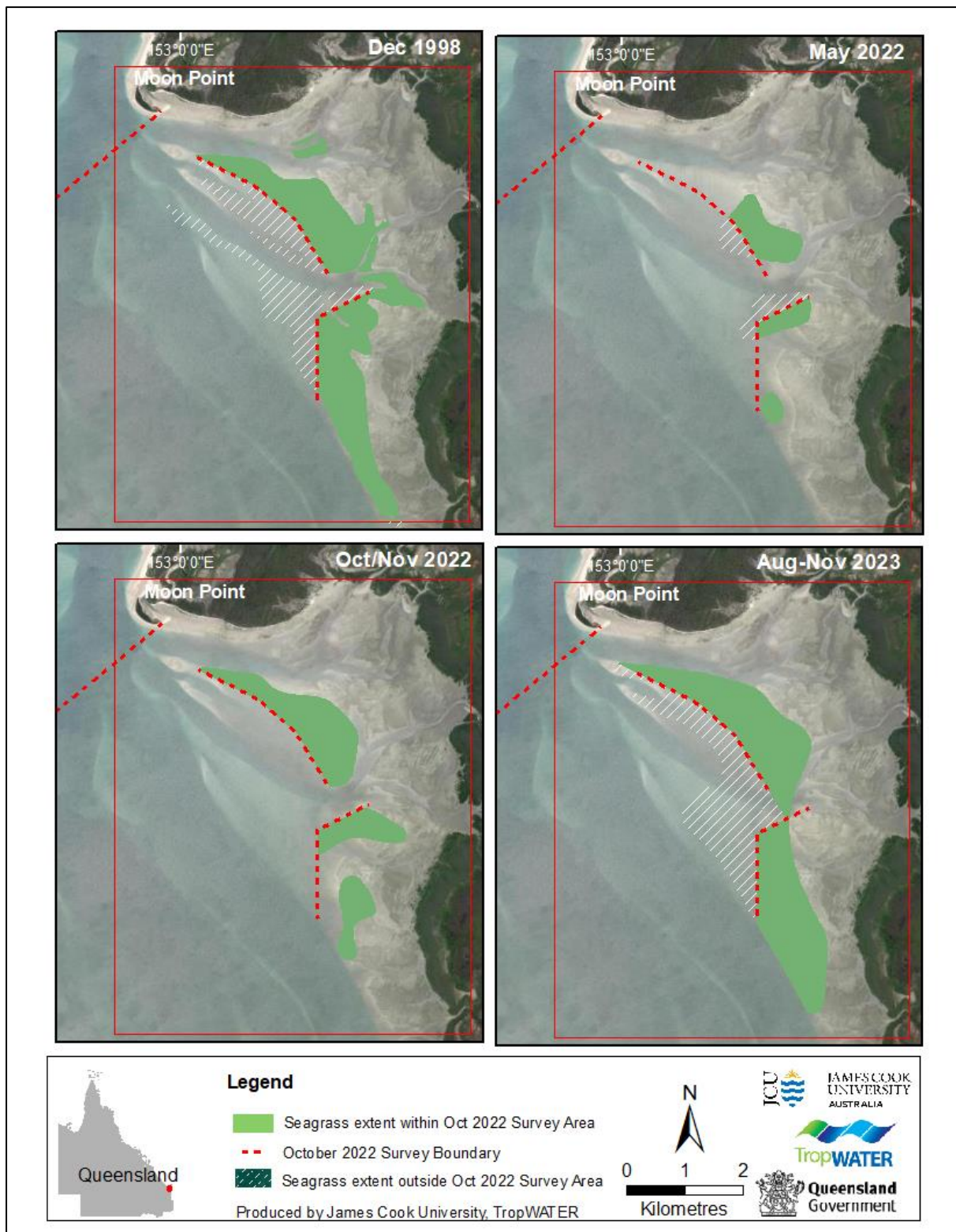


Figure 36. Seagrass extent at Moon Point in December 1998, May 2022, October/November 2022 and August-November 2023. Only intertidal areas that could be assessed during all surveys are compared (shown in green). Data sources: McKenzie 2017, Bryant et al. 2023.

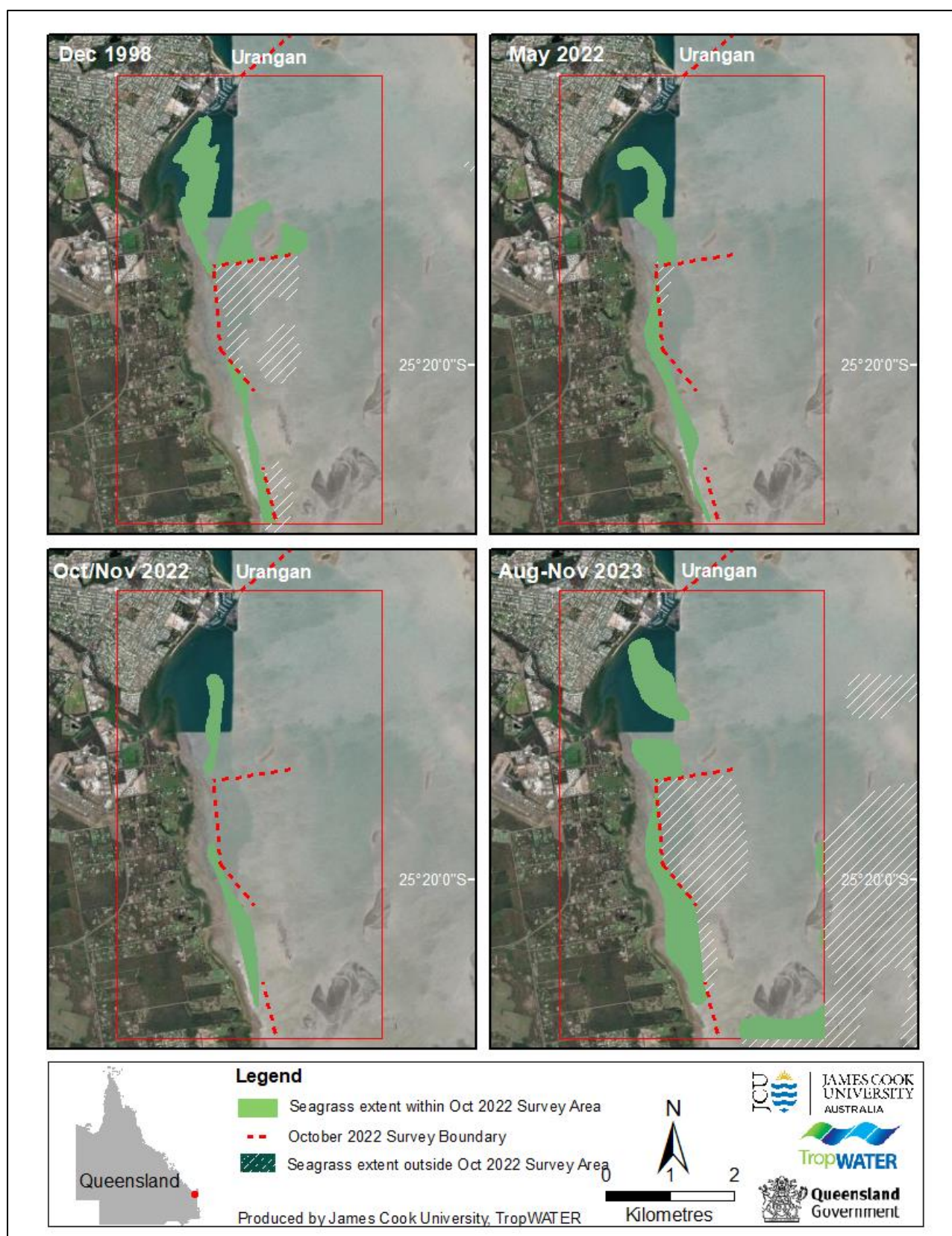


Figure 37. Seagrass extent at Urangan in December 1998, May 2022, October/November 2022, August-November 2023. Only intertidal areas that could be assessed during all surveys are compared (shown in green). Data sources: McKenzie 2017, Bryant et al. 2023.

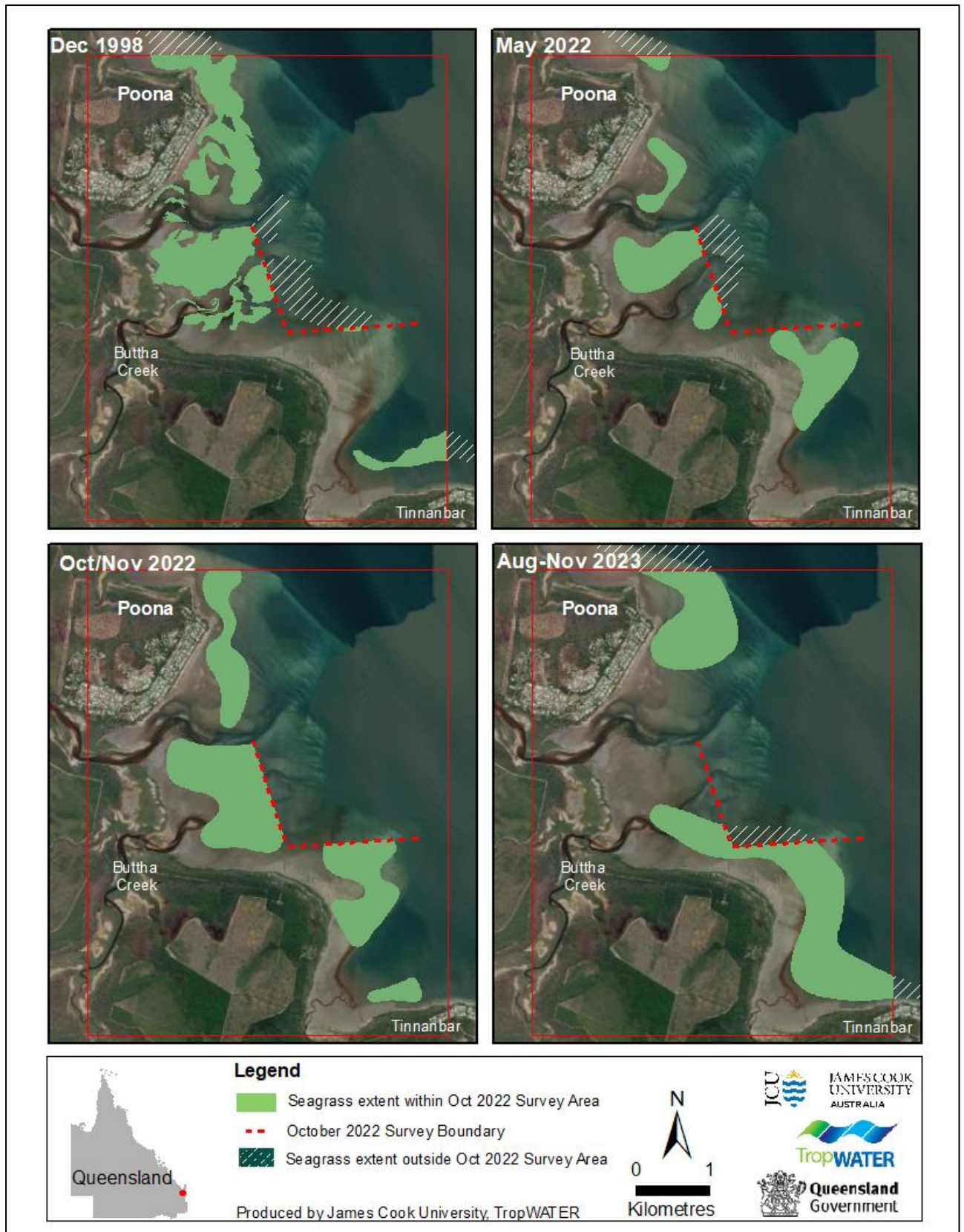


Figure 38. Seagrass extent at Poona in December 1998, May 2022, October/November 2022 and August-November 2023. Only intertidal areas that could be assessed during all surveys are compared (shown in green). Data sources: McKenzie 2017, Bryant et al. 2023.

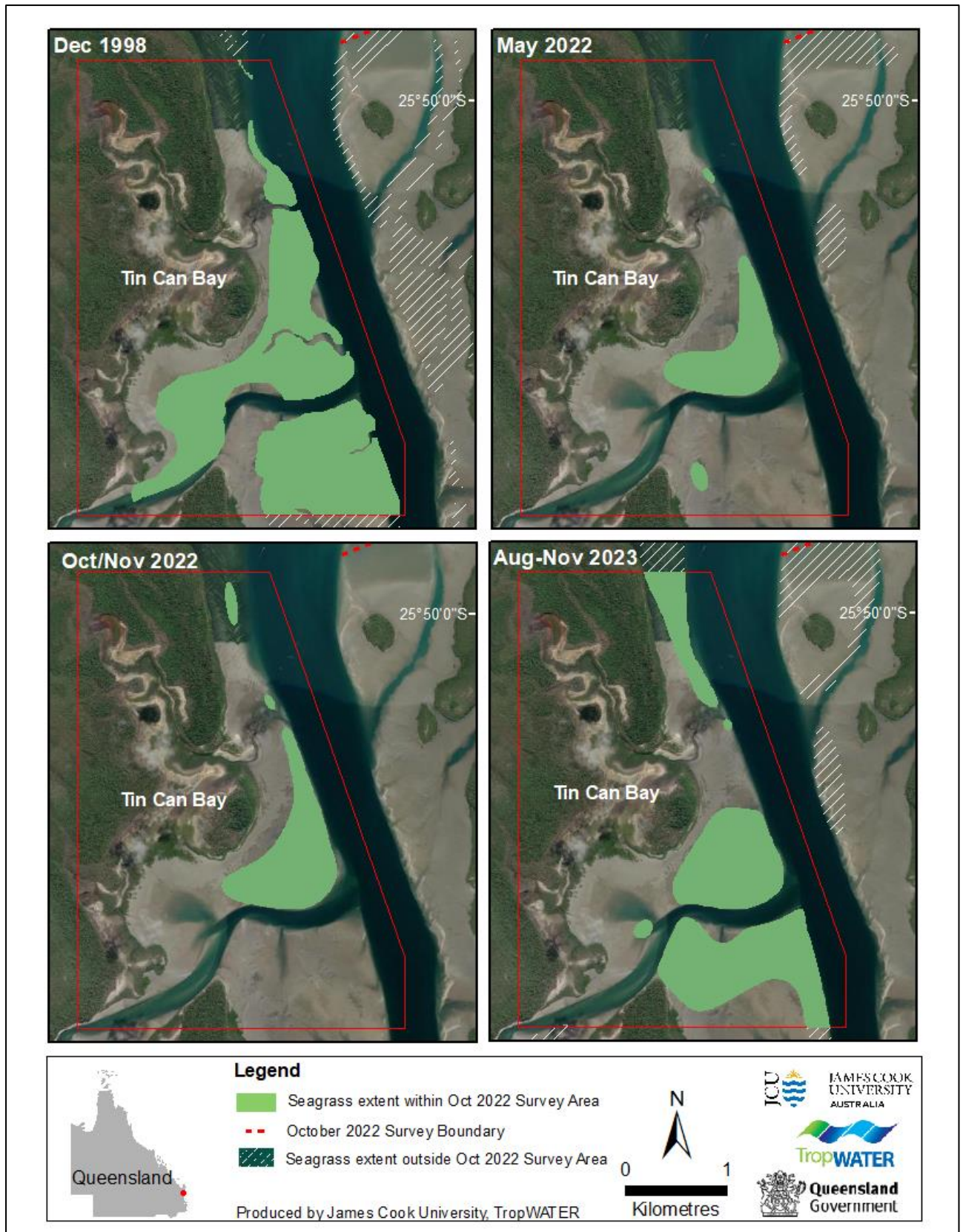


Figure 39. Seagrass extent at Tin Can Bay in December 1998, May 2022, October/November 2022 and August-November 2023. Only intertidal areas that could be assessed during all surveys are compared (shown in green). Data sources: McKenzie 2017, Bryant et al. 2023.

PAR and Temperature

Data collected at the original Toogoom site during 2023 showed that the 14 day rolling average total daily PAR was above the likely minimum light requirements for the growth of *Halophila* species ($2 \text{ mol m}^{-2} \text{ day}^{-1}$) from March through to mid-August but declined again from August to December, similar to 2022 (Figure 40). Average total daily PAR has remained below the growth requirements for *H. uninervis* and *Z. muelleri* for the duration of the monitoring program at this subtidal site (Figure 38).

Two additional benthic PAR and temperature monitoring stations were added to the monitoring program in June 2023, in deep-water offshore from Woodgate and Tobruk (Figure 5 above). The Woodgate monitoring site was established at the periphery of the deep-water meadow where *H. decipiens* had recolonised after flood related losses in 2022 (Bryant et al. 2023). Light levels in 2023 were low at Woodgate and below levels suitable for seagrass growth apart from a brief period in late August/early September where light reached minimum requirements for the growth of *Halophila* species (Figure 40).

The Tobruk monitoring site was established in deeper water near seagrass (*H. spinulosa*) biomass hot spots detected in November 2022 (Bryant et al. 2023). The rolling average total daily PAR at Tobruk was below minimum light requirements from June to late August but reached $2 \text{ mol m}^{-2} \text{ day}^{-1}$ (the likely minimum light requirements for *Halophila* species) from late August to October. The October/November 2023 survey showed both locations continue to support *Halophila* communities, although average biomass remains low compared to historical levels.

Maximum daily temperatures at the seagrass canopy at the shallow subtidal Toogoom station ranged from approximately 16°C to 30°C (Figure 40). Maximum temperature showed an increasing trend from mid-July to late January coinciding with what is the seagrass growing season in nearby Gladstone Harbour (Chartrand et al. 2016).

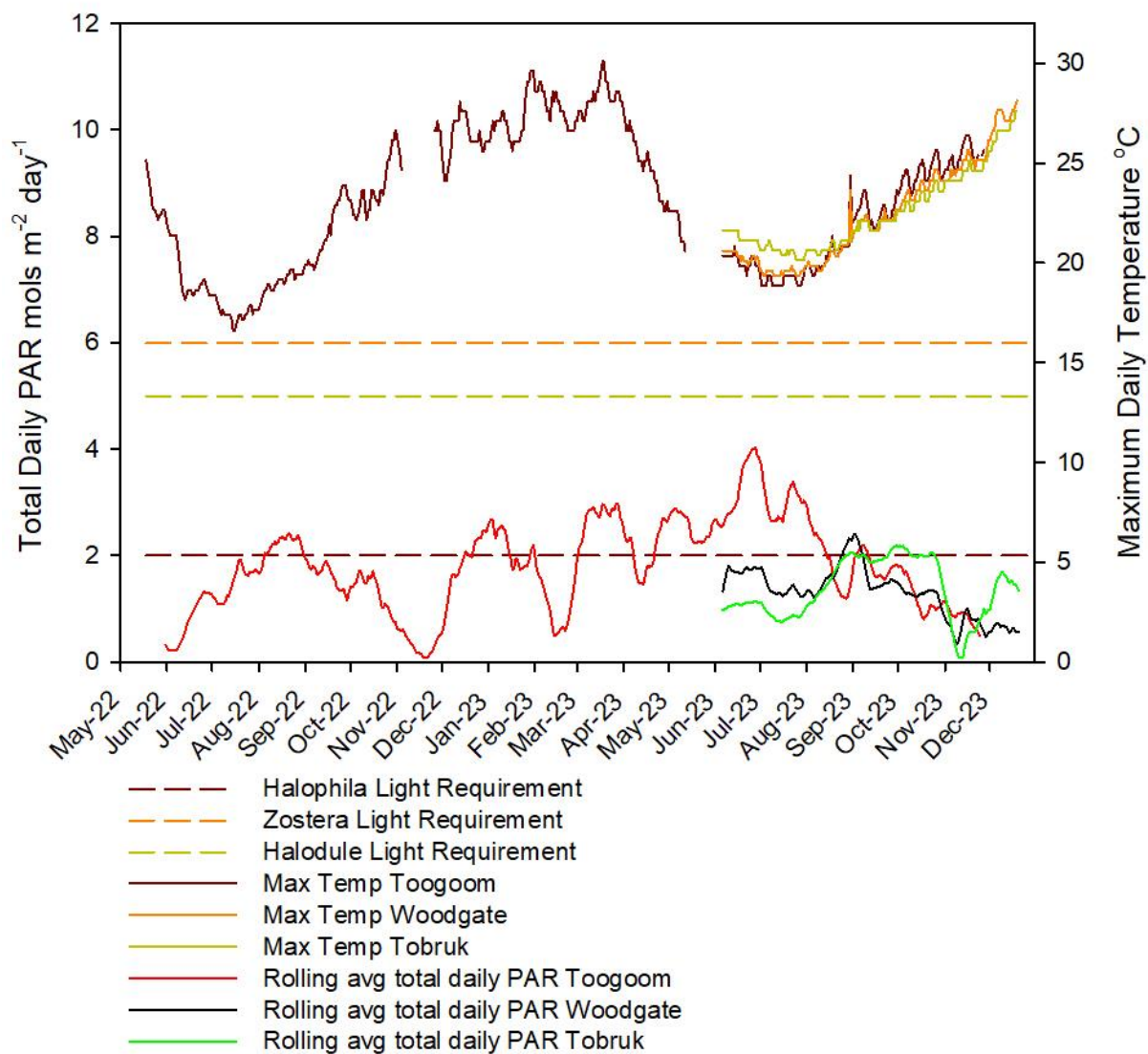


Figure 40. Total Daily PAR (mol m⁻² day⁻¹) and maximum daily temperature (°C) readings from light logging stations at Toogoom, Woodgate and Tobruk from May 2022 to December 2023. Light requirements (LR) for three different seagrass genera (*Halophila*, *Zostera*, *Halodule*) are also shown.

Megaherbivore exclusion experiment

Three months after establishing the experiments there was a significant effect of excluding megaherbivores with seagrass having a higher canopy height and seagrass biomass inside cages than the open-to-grazing control plots. However at the seven-month sampling point a major impact to all seagrasses at the site occurred in both treatments had declined substantially (see discussion for more detail)(Figure 41).

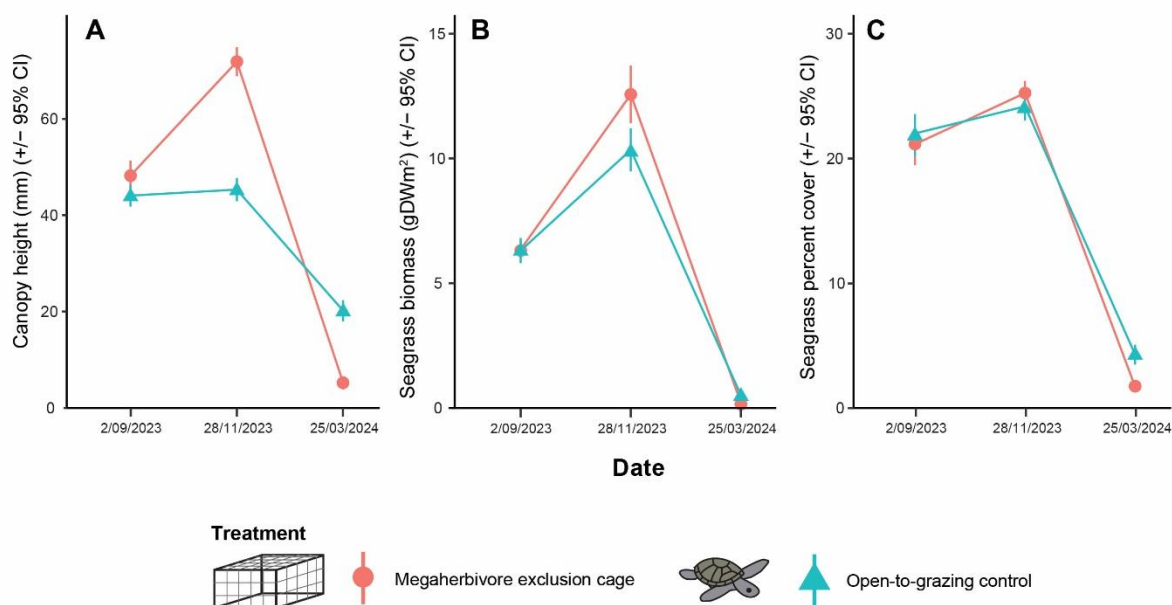


Figure 41. Seagrass canopy height (A), biomass (B) and percent cover (C) from September 2023 to March 2024.

Canopy height

Canopy height was influenced by the interaction between date and treatment ($F_2=654.85$ $p<0.05$), as well as date ($F_2=3253.6$, $p<0.001$) and treatment ($F_1=194.5$, $p<0.001$) individually. The Tukey post hoc test showed that treatments were significantly different at all time points ($p<0.001$), Figure 41A shows this difference in mean canopy height is less than 3 mm at the first time point, however in November canopy height in the cages is 26.6mm higher than in control plots. Within cages each time point differed significantly, whereas within controls the last time point was significantly lower than the first two (Tukey test $p<0.001$).

Biomass

There was an interactive effect of treatment and time on seagrass biomass ($F_2=3.35$ $p<0.05$) and a significant effect of time individually ($F_2=317.4$, $p<0.001$). Post hoc comparisons showed this difference was between treatments in the November sampling (Tukey test $p<0.05$) where there was a higher biomass of seagrass within cages than control plots (Figure 41B). Within the control and cage treatments there was a significant difference between each time point (Tukey test $p<0.001$), seagrass biomass increased in both cages and control plots from September to November, then declined in both treatments in March 2024.

Percent cover

There was a significant effect of date ($F_2=514.4$, $p<0.001$) and treatment ($F_1=18.6$, $p<0.001$) on seagrass percent cover individually, as well as an interactive effect of date and treatment ($F_2=3.36$, $p<0.05$). Post hoc analysis showed that the only time point with a statistically significant difference (Tukey test $p<0.05$) between treatments was in March 2024 where control plots had a higher percentage cover than controls (Figure 41C). Within both controls and cage plots over time the percentage cover in March 2024 was significantly lower than both time points in 2023 (Tukey test $P<0.001$).

Seed bank assessment

A small number of seeds or seed casing fragments (pericarp pieces) of either *Z. muelleri* or *H. uninervis* were found in most of the sampling blocks that were surveyed in October / November 2023 (Figure 42). Poona had the most *H. uninervis* seeds with a density of 6.4 ± 2.4 seeds m^{-2} (Figure 42 and 43; Table 9). Tin can Bay also had a very small amount of *H. uninervis* seeds (0.8 ± 0.8 seeds m^{-2}), while the other 3 blocks had no *H. uninervis* seeds (Table 9). Burrum Heads was the only block that had *Z. muelleri* seeds (0.8 ± 0.8 m^{-2}), however pericarps (outer casings of seeds) of this species were found in Moon Point, Poona and Tin can Bay, evidence that seeds were present and perhaps had germinated recently (Figure 42 and 44). Point Vernon was the only block that did not have any seeds or pericarps present during sampling in October and November 2023. Pericarps (outer casings of seeds) were found throughout the sampling blocks with the highest density found in Poona with 25.6 ± 8.9 m^2 of *H. uninervis* and in Tin Can Bay with 25.6 ± 5.8 m^2 of *Z. muelleri*. A very small quantity of *H. ovalis* pericarps was found in the Burrum Heads and Poona sampling blocks (0.8 ± 3.6 m^2). The seeds of this species are very small and usually found in the smaller sediment fractions, however in this instance the pericarps were found in the samples and therefore included. In the Burrum Heads block a sample contained a spathe of *Z. muelleri*, a fruiting/seeding fragment, no other fruiting or flowering seagrass fragments were noted.

Table 9. Seed bank density of survey blocks in Hervey Bay and Great Sandy Straits in October / November 2023.

Block	<i>Halodule uninervis</i> Mean Total seeds m^{-2}	<i>Halodule uninervis</i> Mean Total pericarps m^{-2}	<i>Zostera muelleri</i> Mean Total seeds m^{-2}	<i>Zostera muelleri</i> Mean Total pericarps m^{-2}	<i>Halophila ovalis</i> Mean Total seeds m^{-2}	<i>Halophila ovalis</i> Mean Total pericarps m^{-2}
Burrum Heads	0	9.6 ± 6	0.8 ± 0.8	4 ± 2.8	0	0.8 ± 0.8
Point Vernon	0	0	0	0	0	0
Moon Point	0	7.2 ± 2.7	0	21.6 ± 10.3	0	0
Poona	6.4 ± 2.4	25.6 ± 8.9	0	15.2 ± 7.3	0	0.8 ± 0.8
Tin Can Bay	0.8 ± 0.8	21.6 ± 5.8	0	25.6 ± 9.5	0	0

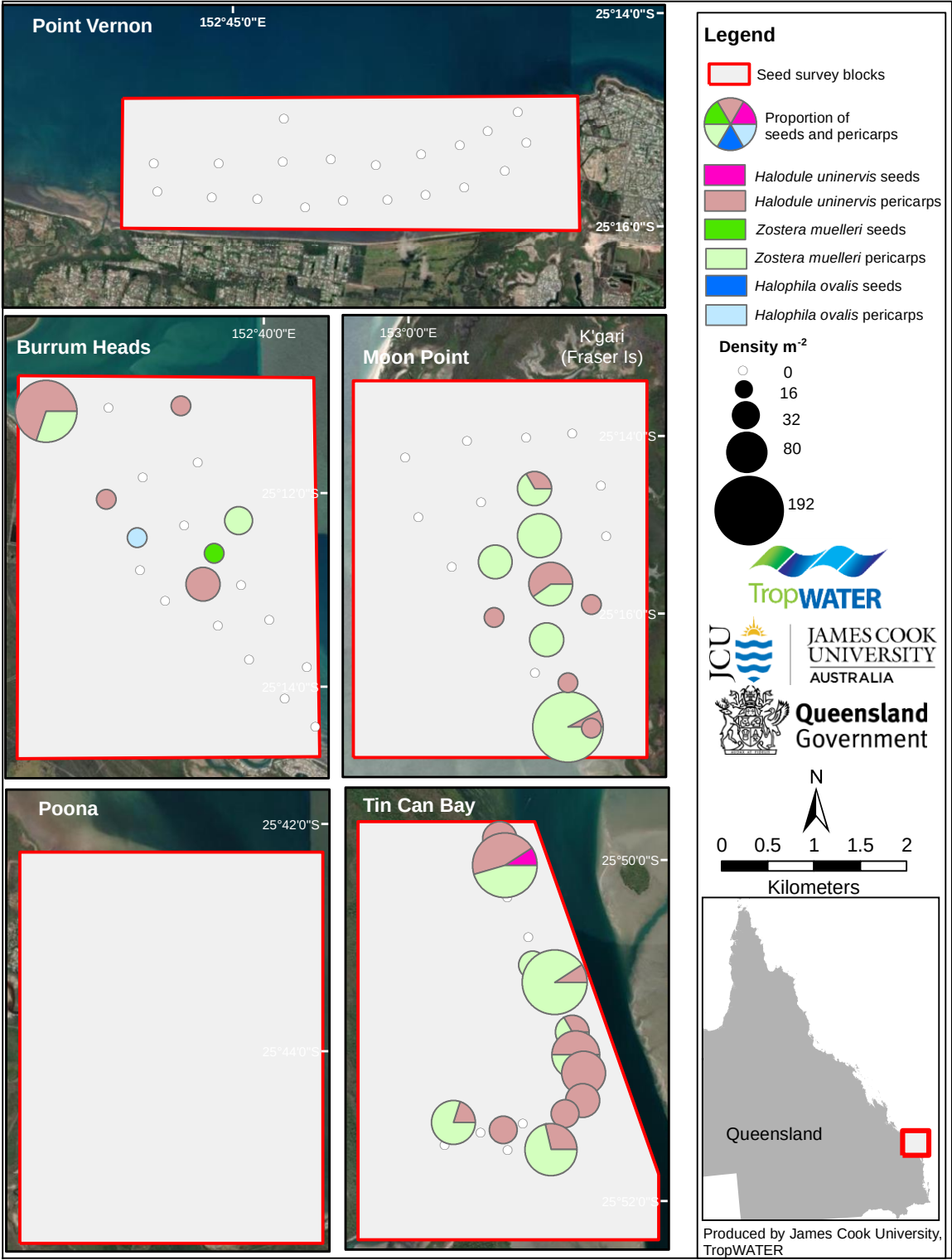


Figure 42. Seed and pericarp density in October /November 2023.

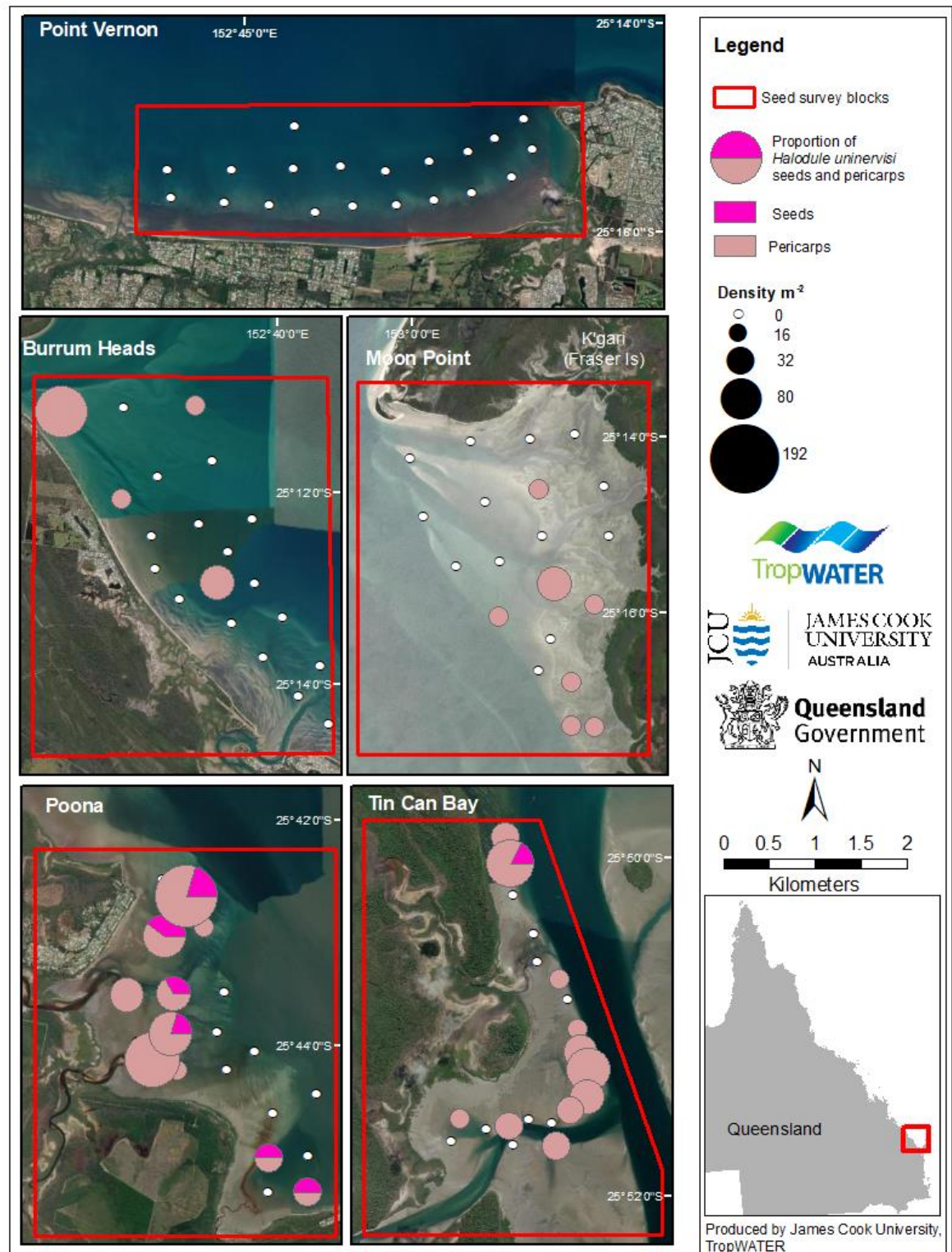


Figure 43. Density of *H. uninervis* seeds and pericarps in October/ November 2023.

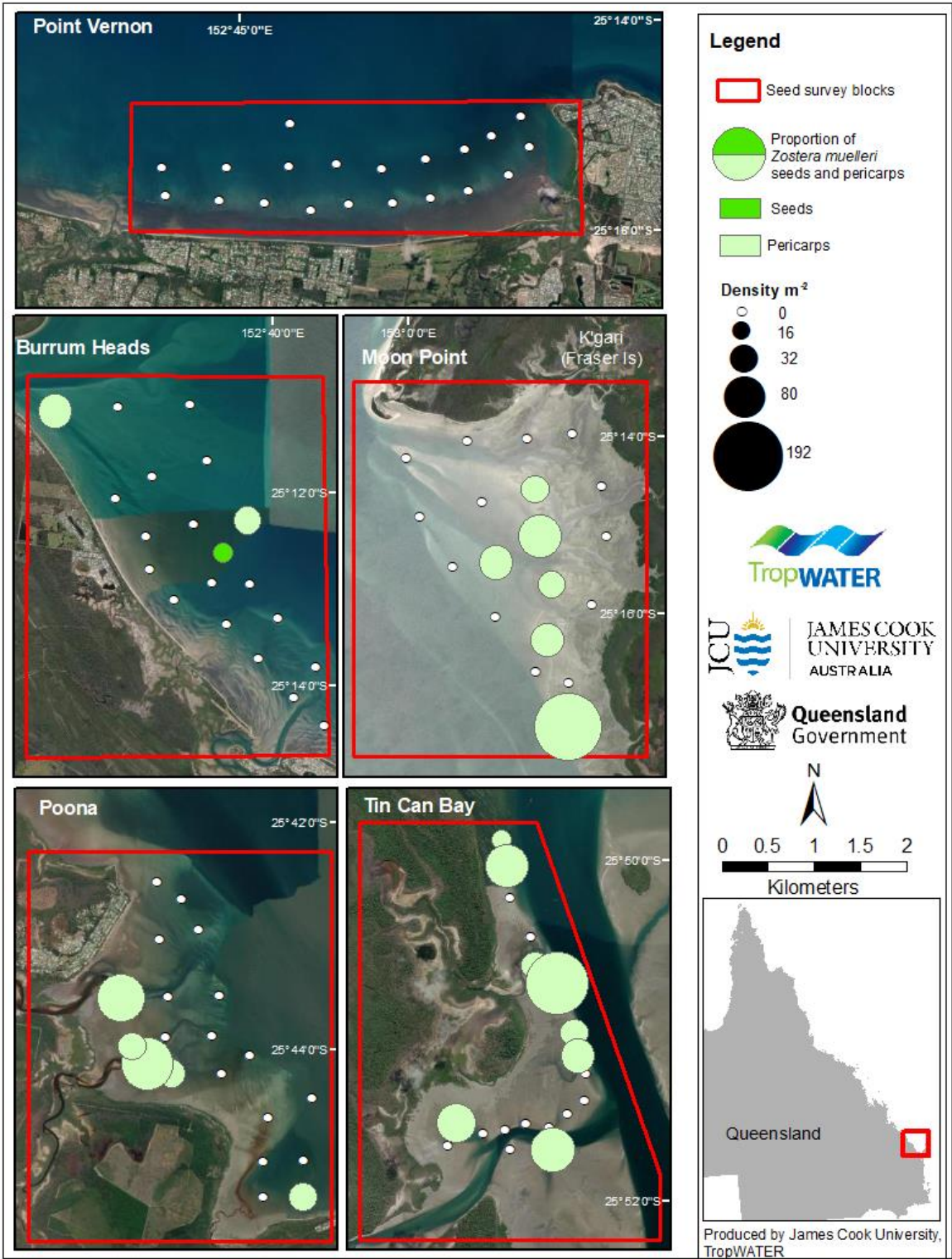


Figure 44. Density of *Z. muelleri* seeds and pericarps in October/ November 2023.

DISCUSSION

Seagrass surveys conducted in the Great Sandy Marine Park (GSMP) at roughly 3 months, 9 months and 18 months following large scale flood events in 2022 have highlighted the level of flood impact and insights into recovery of the seagrass communities in the region. Despite the lack of broad-scale seagrass mapping efforts for the region in the two decades prior to the flood, it is clear that there were severe impacts to seagrasses and associated dugongs and green turtles. In May 2022 there were less than 22% of previously mapped seagrasses remaining in the Great Sandy Strait and 32% in Hervey Bay, and for coastal areas where seagrasses were present cover was generally less than 1% (Bryant et al. 2023). Fortunately, there has been substantial seagrass recovery since then with results of the August-November 2023 seagrass monitoring surveys showing large increases in the spatial footprint of seagrasses across all areas of the GSMP. While still well below historical levels for biomass and cover, the spatial footprint of intertidal meadows was similar to historical levels in the Great Sandy Strait, however the distribution had changed with a larger footprint in the northern section of the Great Sandy Strait and very little seagrass in the area between Turkey Island and the Moonboom Islands. Substantial spatial recovery had also occurred in Hervey Bay. Many areas of seagrass had also increased in biomass although for the majority of intertidal meadows this remained well below historically recorded values. There was also evidence of a seed bank returning to meadows in the region with low numbers of *Zostera muelleri* and *Halodule uninervis* seeds found throughout the GSMP and evidence of recent seed germination. While these fell short of providing a fully functional and abundant seed bank, they were a positive sign of ongoing recovery. Experiments assessing the impacts of dugong and turtle feeding on seagrass growth and recovery revealed that herbivory had an influence on seagrass structure but by the time of the study, in late 2023, this was unlikely to be a significant impediment to ongoing seagrass recovery in the region.

These are all promising results for ongoing recovery of seagrasses in the GSMP but it should be stressed that seagrasses remained in a vulnerable state at the time of the survey. Levels of resilience will remain low until such a time as seagrasses can fully re-establish back to their previous biomass, and seed banks and reproduction are fully restored. Until that time seagrasses are highly vulnerable to future impacts including more flood events or anthropogenic impacts. A key to understanding their ongoing viability, recovery, function and management approaches is to ensure a strategic monitoring approach is in place that avoids the issues encountered at the start of this program where a lack of larger spatial scale seagrass assessment were a major impediment. The 2 years of post-flood seagrass assessments presented here and in York et al. (2022) and Bryant et al. (2023) and further reviewed in Rasheed et al (2023) provide a sound basis for such a program.

The turbid flood plumes from the Mary River persisted throughout the Great Sandy Strait and along the western and southern coastal regions of Hervey Bay reducing water quality through January, February and March 2022 (Lewis et al 2022). Poor water quality is one of the most common causes for seagrass declines as it reduces available light for photosynthesis that enables seagrass to grow and survive (Ralph et al. 2007). It is likely that the lack of light due to the persistent turbid plumes was the principal cause of seagrass declines (Rasheed et al. 2023) but a range of other water quality issues associated with flooding such as herbicide and nutrient inputs and smothering by fine sediments could also have had an influence on seagrasses post the 2022 flood (Rasheed et al. 2023).

PAR monitoring data in Hervey Bay indicates that light levels were above the likely minimum light requirements for *Halophila* species for at least part of the growing season in 2023 at all locations where PAR was monitored and has likely contributed to the further recovery of *Halophila* communities in the region. Light was well below growth requirements for other species (*H. uninervis* and *Z. muelleri*)

in subtidal waters which is likely impeding the recovery of these communities into these areas. The ongoing monitoring of PAR and temperature including the addition of intertidal monitoring sites (e.g. Moon Point and Tin Can Bay) instigated through a range of DES programs throughout the region will be beneficial in understanding the capacity for further seagrass recovery in the region.

Despite the observed recovery during 2022 and 2023, it is clear that seagrass communities, particularly intertidal meadows consisting of *Z. muelleri*, *H. uninervis* and *H. ovalis*, remain well below the abundance that they have been reported in past surveys in 1973, 1998 and 2002 (Dredge et al. 1997; Lee Long et al. 1993; McKenzie et al. 2017, McKenzie et al. 2000; McKenzie and Campbell 2003; Sheppard et al. 2007). These communities that are generally found along intertidal sand and mud flats through the Great Sandy Strait and the south-west corner of Hervey Bay between Urangan and Burrum Heads play an important role in ecosystem functioning and the delivery of services (Scott et al. 2018). This includes the provision of nursery habitat for juvenile fish and prawns (Dredge et al. 1977; Hyland 1993), foraging grounds for dugong and turtle (Preen et al. 1995; Shepherd et al 2007; Hazel and Gyuris 2006) and blue carbon sequestration (Samper-Real et al. 2016) when the seagrasses are abundant.

Deep-water meadows also play similar and very important ecological roles such as offering fisheries habitat (Hayes et al. 2020), sequestering carbon (York et al. 2018) and offering a refuge for dugong and turtles to migrate to for a source of food (Preen and Marsh 1995; Rasheed et al 2023). The deep-water seagrasses in the middle of Hervey Bay appear to have been better able to recover from the impacts of the flood plume than intertidal communities. The post-flood May 2022 distribution and mean seagrass percent cover is comparable to that of the post-flood monitoring undertaken in 1992 (Preen et al. 1995) following a similar series of sequential events (two floods and a cyclone). By the November 2022 survey, however the deep-water seagrasses were already showing good signs of recovery with considerable expansion of the meadow and an increase in abundance measured as above ground biomass and percentage cover of the seabed, and this recovery continued in 2023.

The loss of seagrass area and abundance in the GSMP after the 2022 flood has caused great concern for marine managers and the general public due to the loss of a food source for two dependent and vulnerable species, the dugong and the green turtle. As with the aftermath of previous large flooding events in Hervey Bay, the dugong and green turtle populations have been severely affected. Catastrophic seagrass losses in Hervey Bay in 1992 following flooding saw the dugong population plummet and the proportion of calves in the population declined from 22 to 2% and 6 – 8 months after the event a hundred dugong carcasses were recovered emaciated due to starvation (Preen and Marsh 1995). In the most recent dugong aerial survey conducted in November 2022 over Hervey Bay and the Great Sandy Strait, no dugongs were sighted in the historically significant habitat of the Great Sandy Strait between the town of Hervey Bay and the bottom of the strait (Cleguer et al 2023; Rasheed et al 2023). It is important to note that the timing of the aerial survey coincided with the second seagrass survey in November 2022, revealing that the majority of dugongs were located in the middle of Hervey Bay where seagrass was most abundant (Rasheed et al 2023). Dugong have been observed in the past to migrate large distances in search of food (Preen and Marsh 1995, Sheppard et al. 2006).

Green turtle strandings along the Queensland coast are also closely linked to large flood events with a lag of 7 – 12 months post-event (Flint et al. 2017). In 2022 the Great Sandy region saw the largest number of reported green turtle strandings in recent history and much greater than the previous flood and cyclone impacts in the region in 2011-12 (Figure 45). Part of the increase in stranding numbers could be the result of increased volunteer support and therefore reporting of strandings. Ongoing strandings could possibly remain high over the next few years until the population of green turtles

stabilises at lower numbers due to mortality or migration, or the seagrass resource continues to recover and allows the turtle population to recover.

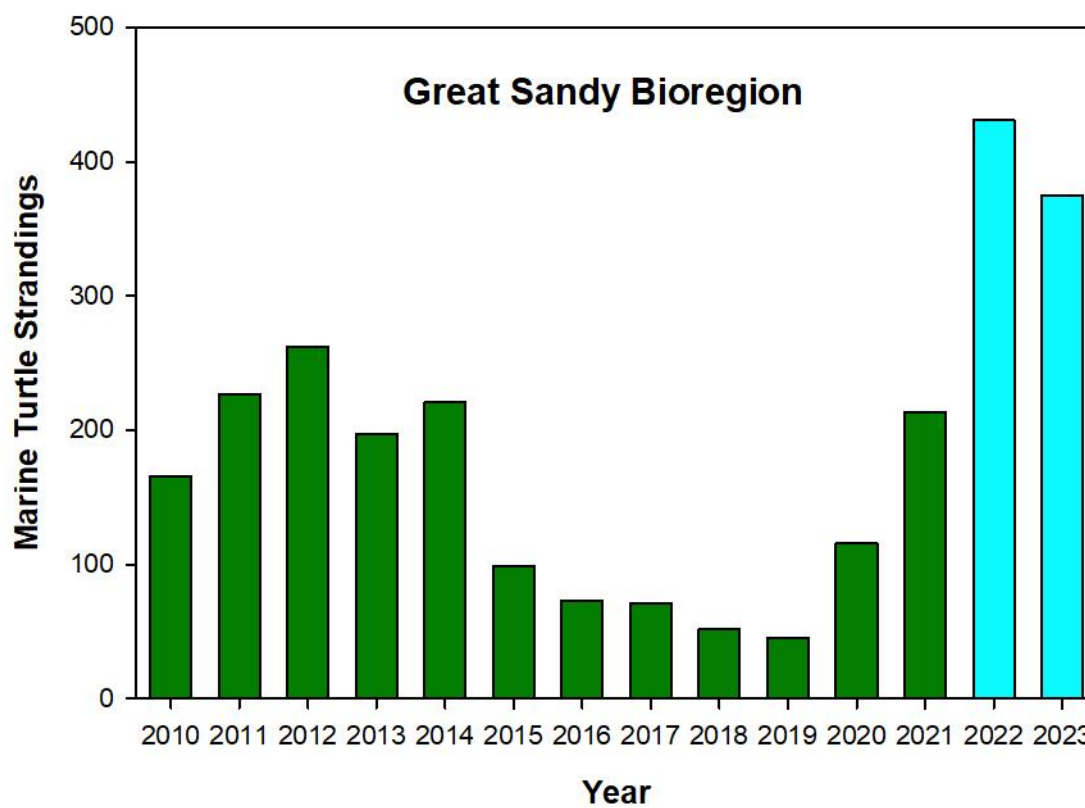


Figure 45. Historical stranding data of sea turtles for the Great Sandy Marine Park region from 2010 to 2023.

The recovery of the shallow inshore meadows may have been further delayed by hungry dugong and green turtles concentrating their foraging on some of the limited food resources remaining in the bay in the months following the flood related loss. Dugong feeding trails were observed in the very sparse intertidal meadows in Tin Can Bay during the most recent seagrass surveys and turtles were prevalent at intertidal meadows in the northern section of the Great Sandy Strait. Grazing by megaherbivores can have significant impacts on seagrass meadow structure and even cause meadow collapse (Scott et al. 2018).

Initial results from the megaherbivore exclusion study at the Moon Point meadow at K'gari showed an impact of megaherbivore grazing on seagrass. However, after seven months there was a site effect of the experiment and seagrass cover was reduced across the majority of the site regardless of treatment. While the cause is unclear its possible it could have been due to scouring from currents flowing past the equipment at the site, due to sand movement or the disturbance caused by the experimental set up or even potentially attracting herbivorous fish to shelter within the cages. These results indicate that herbivory does structure the seagrasses here, however the site effects make it difficult to understand more about these patterns. Given the recovery of seagrass in the Moon Point meadow and more broadly throughout the survey area, it is likely that at the time the experiment was established in late 2023 herbivory was not driving further seagrass declines or significantly impacting on seagrass recovery. It is possible that grazing by dugongs and turtles could have been delaying the seagrass recovery in the period immediately following the flood event in 2022 as the distribution of

seagrasses was greatly reduced and large numbers of green turtles remained at these remnant meadows (Rasheed 2023). Under these circumstances complete meadow collapse due to grazing pressure is possible, and has been observed as a result of green turtle overgrazing in a number of locations around the world when things are pushed out of balance (Christianen et al., 2014; Fourqurean et al., 2019; Gangal et al., 2021). Fortunately the recovery of deep-water and shallow seagrasses by November 2023, likely offered sufficient seagrass resources for returning dugong and turtles and a likely more balanced seagrass-herbivore dynamic (Scott et al 2018).

Recovery of seagrass in the Great Sandy Marine Park is likely to continue to be two-paced with the colonising species in the deeper waters of Hervey Bay returning more rapidly than the more opportunistic and persistent intertidal species along the shallower coastal zone. This is evident from the most recent November 2023 survey with the greatest expansion and increase in abundance occurring in the deep-water meadow, similar to what has been observed previously after flooding in the past in Hervey Bay (Preen et al. 1995) and also further to the north in the Great Barrier Reef (Rasheed et al. 2014). The deep-water seagrass meadows in the region consist of colonisers from the *Halophila* genus that can recover quickly if remnant patches provide reproductive propagules, or if a viable seed bank is present in marine sediments and germinate when growing conditions become more favourable (Kilminster et al. 2015). However, recovery of deep-water seagrass from previous large disturbance events in Hervey Bay and similar seagrass communities at Abbot Point has required several years of favourable growing conditions before seagrass returned to anywhere near their pre-disturbance levels (Preen et al. 2015; Rasheed et al. 2014). Monitoring these deep-water species over the next few years will be critical to understand the longer term recovery implications from the flood losses.

Recovery of intertidal and shallow subtidal meadows of more-persistent species (e.g., *Zostera muelleri* and *Halodule uninervis*) can take longer due to their slower growth and recruitment processes (Rasheed 1999, Kilminster et al. 2015). The recovery of shallower subtidal and intertidal seagrasses following large-scale disturbances from floods and cyclones in Hervey Bay in 1992 and at Abbot Point in 2010-11 was slower than the deep-water communities (Preen et al. 1995, Rasheed et al. 2014). However, abundant and continuous seagrass had returned to intertidal and subtidal meadows near Burrum Heads by 2004, following the 1999 flood events (Sheppard et al. 2007). Also, recovery of intertidal *Zostera muelleri* meadows in the Great Sandy Strait in 1999 was complete in only three years (Campbell and McKenzie 2004). Recovery for these types of meadows is particularly slow where all the adult plants have been completely or near-completely lost and return of seagrass is dependent on seed germination from an existing seed bank or dispersal from other areas (Rasheed 1999, 2004).

The detection of seagrass seeds in the sediments of meadows within the GSMP was another good sign of the progression of seagrass recovery. The beginnings of developing seed banks were positive but overall numbers of seagrass seeds of *H. uninervis* and *Z. muelleri* seeds found in Hervey Bay are low ($0.8 - 6.4 \text{ m}^{-2}$) compared to studies in other areas of Queensland. The Marine Monitoring Program long term monitoring program in Hervey Bay found that the total seedbank was around 100 seeds m^{-2} at Burrum Heads over the past three years (McKenzie et al. 2023). A similar subtropical region to the south in Moreton Bay have reported a seed bank density of $177 \pm 28.4 \text{ seeds m}^{-2}$ of *Z. muelleri* (Conacher et al. 1994). Seed bank density studies in Gladstone Harbour report a range of *Z. muelleri* seeds from $57 - 1300 \text{ seeds m}^{-2}$ (Reason et al. 2017). While further north in Townsville where more than $5000 \pm 0.06 \text{ seeds m}^{-2}$ of *H. uninervis* were found in the seedbank (Inglis 2000). Similar block scale studies in a tropical region in Cairns Harbour have found *H. uninervis* seeds in the range of 3.2 to 141.1 m^{-2} and *Z. muelleri* seeds in the range of 3.8 to 27.9 m^{-2} over the past 4 years (Reason et al. 2023).

The low number of seeds may be because many of the seeds produced had already germinated prior to sampling and the newly recruited seedlings are likely contributing to the expansion of the meadows and increasing their biomass. There was some evidence of this with broken pieces of seed casing outer skin, or pericarps, being found commonly in the samples. Alternatively, low seed numbers may indicate a lack of a successful flowering/fruiting season and recruitment of new seeds from the previous growing season. A depression in flowering and fruiting in the year or two following disturbances may be fairly common for many seagrass meadows. With no comparable scale studies on seagrass seedbank in the Hervey Bay and Great Sandy Strait region it is difficult to be certain of the cause or the likely trajectory of seed bank development over the coming seasons. The current very low numbers of seeds in the sediment mean it is unlikely that there is a fully functioning persistent seedbank able to convey a substantial level of resistance for a further large scale seagrass loss at the time of the survey. Ongoing monitoring of these areas will be crucial in understanding how these important habitats are recovering naturally and if, when and where potential seagrass rehabilitation interventions are likely to be required in the future.

Conclusions and Recommendations

The August to November 2023 surveys of seagrass in Hervey Bay and the Great Sandy Strait showed further promising signs of recovery since the initial post-flood survey in May and the follow up survey in October/November 2022. Most of the increase in seagrass distribution was again at the large deep-water in the middle of the bay, however there was also substantial expansion of intertidal seagrass meadows in the Great Sandy Strait and along the western shore of Hervey Bay. There were small increases in seagrass abundance at the coastal subtidal meadows and at some intertidal areas, however abundance still remained low compared to historical levels. This is likely to have ongoing implications for the species that depend on them including dugongs and green turtles. We expect to see further recovery in Hervey Bay and the Great Sandy Strait in 2024 as long as favourable climate conditions persist. The extent and pace of ongoing recovery is unknown and previous seagrass losses in the region have taken at least three years to recover. It is critical that continued monitoring occurs to be able to manage seagrasses and their reliant fauna including dugongs and green turtles.

The network of benthic light (PAR) logging stations is starting to reveal key information on the growing conditions for local seagrasses, and found that within subtidal waters in the bay light conditions were suitable for *Halophila* seagrass communities but insufficient for the higher light requiring species during 2023. These higher light requiring species were largely restricted to intertidal banks and new PAR monitoring stations installed during 2023 will be beneficial in understanding the light dynamics and seagrass changes there in the future.

The results of this work provide an excellent basis for establishing strategic longer-term monitoring of linked seagrass, water quality and dugong and turtle monitoring programs for the GSMP in 2024 and beyond. The next few years will be critical for seagrasses to reach former high levels of function and resilience.

The full extent of flood related losses in 2022 was difficult to ascertain as there had not been large spatial scale assessments of seagrasses in Hervey Bay for more than 20 years prior to the May 2022 post-flood survey. Given the significance of seagrass to the region and the impacts of recent floods we recommend the following be considered:

- Develop a long-term monitoring approach that incorporates some larger spatial assessments of deep-water and shallow subtidal seagrasses as well as intertidal meadows in Hervey Bay and the Great Sandy Strait on a regular (at least annual) basis (see below).

- Consider repeating assessments of seagrass seed-banks prior to the 2024 growing season to build on our understanding of seed bank dynamics in the region and their contribution to the recovery and resilience of seagrass resources.
- Continue to support the expanded network of PAR and temperature monitoring sites including at intertidal meadows in Hervey Bay and Great Sandy Strait (We note that additional monitoring stations have recently been installed or are planned in the near future) in order to support the assessment of drivers of seagrass changes and their interpretation.

Long Term Monitoring Strategy

Given the current state of seagrasses and their regional importance, a strategy incorporating regular (at least annual) monitoring of a subset of meadows/monitoring blocks is recommended. The suggested long term monitoring strategy aims to assess inter-annual changes in seagrass distribution, abundance and species composition at key seagrass meadows in Hervey Bay and the Great Sandy Strait at a scale that matches the management questions around post-flood impact and recovery and state of the seagrass resource for management of dugongs and turtles within the GSMP. In order to allow detailed comparisons, we suggest methods should follow those employed during the 2022 and 2023 surveys (detailed above) applied over smaller “Seagrass Assessment Areas” for the annual monitoring, complimented by whole of GSMP seagrass mapping every 5 years (Figure 46). Figure 46 details the suggested spatial blocks for annual assessment that encompasses key seagrass meadows/ areas in Hervey Bay and the Great Sandy Strait at a scale that can adequately represent broader GSMP wide changes in seagrass. The approach of annual assessments of representative areas would ideally take place between September and November during the peak seagrass growing season, in order to assess seagrasses at their maximum distribution and abundance.

In the event of another significant flood event, incident response monitoring could be undertaken within the seagrass assessment areas at appropriate intervals (e.g. three months and six to nine months following the event) to monitor impacts to seagrass distribution and abundance and track recovery between regular annual monitoring surveys.

In addition to the annual assessments of representative seagrass areas we suggest coordinating Hervey Bay and GSS wide full-resurveying of all seagrasses every 5 years to update the entire distribution and time these to coincide with aerial surveys of dugongs and turtles that are conducted on a 5 yearly basis.

This approach of monitoring subsets of the total seagrass area annually with periodic assessments (every 3-5 years) has been employed elsewhere across Queensland including in the northern part of the Burnett Mary region around Rodds Bay and Gladstone where it is used to develop the seagrass scores for the Gladstone Healthy Harbour Partnership reporting (Carter et al 2023) with similar assessments contributing to the seagrass and environmental reporting of the other regional report cards for healthy waterways in the GBR .

In each of the deep subtidal assessment areas in Hervey Bay (we suggest four), at least sixteen sites (4 x 4 rows) would be assessed by boat with an underwater digital camera mounted on a drop frame. The smaller subtidal meadows (e.g. Meadow 2 at Burrum Heads) would be monitored by a boat running transects from the low tide mark to the edge of the seagrass meadow. Intertidal Seagrass Assessment Areas would be monitored by helicopter during the lowest daytime tides between September and November following the same methodology as employed during the 2022 and 2023

surveys and would complement the current Marine Monitoring Program conducted twice yearly at transect sites at Burrum Heads and Urangan by Seagrass-Watch.

Figure 46 details the location of suggested Seagrass Assessment Areas. We suggest four subtidal monitoring blocks in addition to the six coastal monitoring meadow blocks.

The suggested Seagrass Assessment Areas have been selected to incorporate:

- a) Areas of remaining seagrass with the highest total area and/or abundance - based on 2022 and 2023 surveys;
- b) Meadows with historically high seagrass distribution and/or abundance – based on 1998 and 2002 surveys;
- c) Meadows located both inside and outside of the 2022 flood plume;
- d) Meadows located at a range of depths (intertidal, shallow subtidal and deep-water);
- e) The range of seagrass species communities present in the region;
- f) Areas relevant to management including Marine Parks zoning and the Great Sandy Strait Ramsar wetland;
- g) Meadows with historical data on seagrass distribution and abundance; and
- h) Meadows in proximity to light logging stations.

The suggested monitoring strategy could be conducted relatively inexpensively as a partnership with the majority of field data collection able to be collected by local partners from GSMP staff and or community and traditional owner rangers and an additional 5 hours of helicopter survey time each year. The data collection and seagrass scoring methodology would be consistent with approaches for other nearby regional seagrass report cards including in the Gladstone Healthy Harbour Partnership (Carter et al 2023) and the other regional partnerships for waterway health along the Great Barrier Reef Catchments.

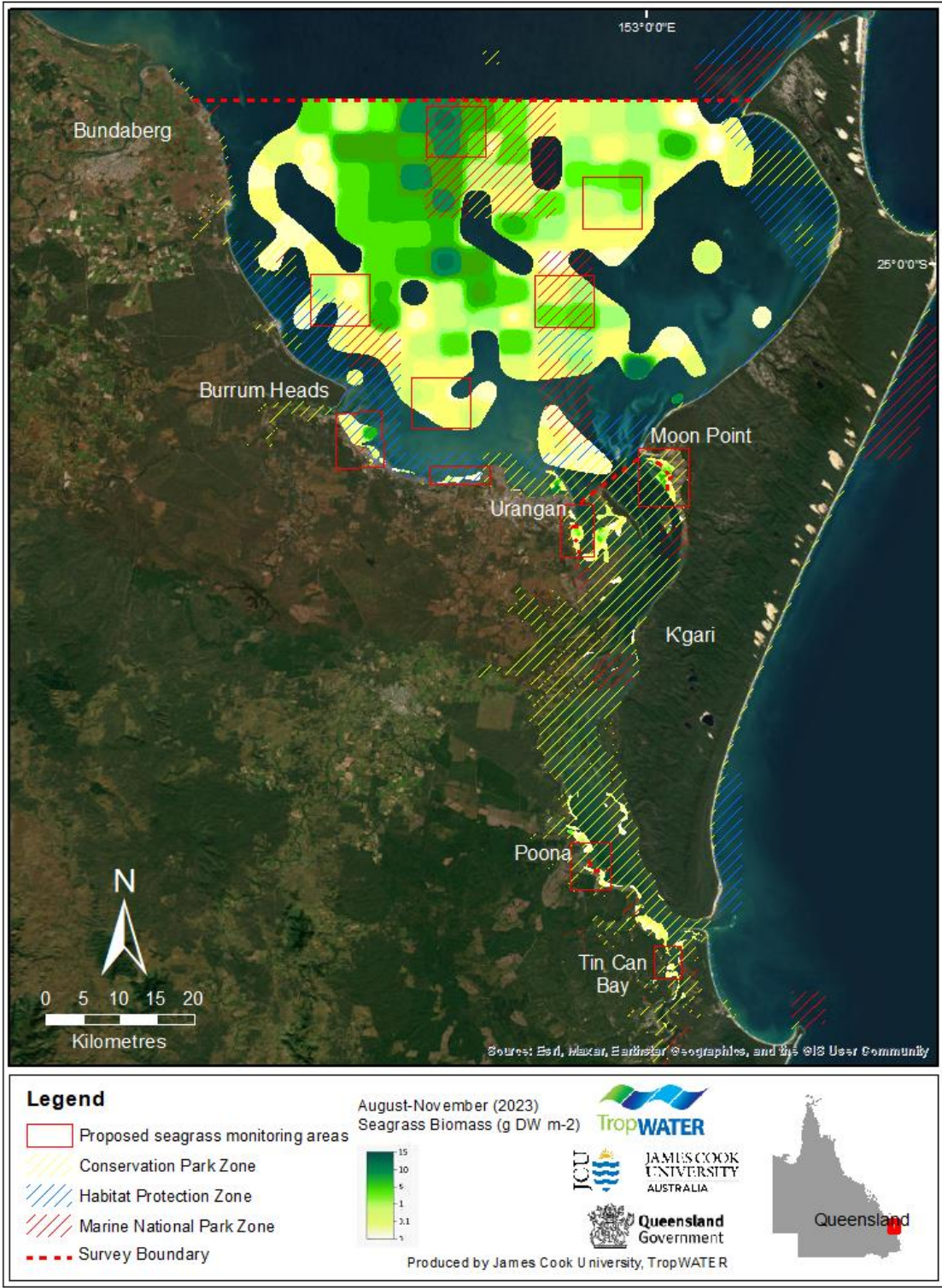


Figure 46. Suggested locations for Long Term Monitoring Seagrass Assessment Areas.

APPENDICES

Appendix 1. Coastal benthic survey data sheet

COASTAL BENTHIC SURVEY

Recorder:

Vessel:

Date:

Site #: Location:
 Time: hrs Depth: m Observer:
 Sed/Substrate: % Consolidated
 Beach / Coffee Rk (Cons)

☐ Helicopter ☐ Camera ☐ Grab ☐ Diver
☐ Dugong ☐ Turtle ☐ Dolphin ☐ DFT

ALGAE Total % cover:

Algal category	% of total algae	% Consolidated
Erect macros		
Erect calcareous		
Filamentous		
Turf Mat		
Encrusting		

COMMENTS:

SEAGRASS Total % cover:

Rank	Species / % composition	% Cover

Epiphyte Cover: None L M H

☐ Exclude from Biomass

BENTHOS

Benthic category	% of total cover
Open Substrate	
Hard Coral	
Soft Coral	
Sponges	
Other BMI	

Site #: Location:
 Time: hrs Depth: m Observer:
 Sed/Substrate: % Consolidated
 Beach / Coffee Rk (Cons)

☐ Helicopter ☐ Camera ☐ Grab ☐ Diver
☐ Dugong ☐ Turtle ☐ Dolphin ☐ DFT

ALGAE Total % cover:

Algal category	% of total algae	% Consolidated
Erect macros		
Erect calcareous		
Filamentous		
Turf Mat		
Encrusting		

COMMENTS:

SEAGRASS Total % cover:

Rank	Species / % composition	% Cover

Epiphyte Cover: None L M H

☐ Exclude from Biomass

BENTHOS

Benthic category	% of total cover
Open Substrate	
Hard Coral	
Soft Coral	
Sponges	
Other BMI	

Site #: Location:
 Time: hrs Depth: m Observer:
 Sed/Substrate: % Consolidated
 Beach / Coffee Rk (Cons)

☐ Helicopter ☐ Camera ☐ Grab ☐ Diver
☐ Dugong ☐ Turtle ☐ Dolphin ☐ DFT

ALGAE Total % cover:

Algal category	% of total algae	% Consolidated
Erect macros		
Erect calcareous		
Filamentous		
Turf Mat		
Encrusting		

COMMENTS:

SEAGRASS Total % cover:

Rank	Species / % composition	% Cover

Epiphyte Cover: None L M H

☐ Exclude from Biomass

BENTHOS

Benthic category	% of total cover
Open Substrate	
Hard Coral	
Soft Coral	
Sponges	
Other BMI	

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