2022 Dugong Aerial Survey: Mission Beach to Moreton Bay

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Distribution and abundance of dugongs along the urban coast of the Great Barrier Reef, Hervey Bay and Moreton Bay in 2022

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Acknowledgments

Our JCU-TropWATER team extends its deepest respect and recognition to all Traditional Owners of the Great Barrier Reef, Hervey Bay-Great Sandy Strait, and Moreton Bay regions as First Nations Peoples holding the hopes, dreams, traditions, and cultures of the Reef.

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EXECUTIVE SUMMARY

Project objectives

- Dugongs are of significant biodiversity value as the only extant species in the Family Dugongidae and one of only four species in the Order Sirenia, all of which are listed as vulnerable to extinction by the IUCN.
- Australia has international responsibilities for dugong conservation, particularly in the Great Barrier Reef (GBR) region, where the dugong feeding grounds are listed as one of the World Heritage values of the region.
- Dugongs have been monitored along the Queensland coast since the 1980s using a series of standardised aerial surveys. These surveys have provided long-term information on the distribution and abundance of dugongs, which has informed management and are a requirement of the Reef 2050 Long-Term Sustainability Plan (Reef 2050 Plan). The surveys have been loosely coordinated across jurisdictions and largely conducted at the same time of year at approximately five-year intervals. The areas adjacent to the Great Barrier Reef have been included to account for temporary migrations of dugongs across jurisdictional boundaries.
- This report presents the result of an aerial survey for dugongs and large juvenile and adult marine turtles[1] that was conducted in November-December 2022 in the coastal waters of Queensland from Mission Beach to the Queensland-New South Wales border. The survey is the latest in the time series of surveys conducted by James Cook University-TropWATER researchers since the 1980s.
- The objectives of our study were to:
    1. continue the time series of surveys for dugongs and large marine turtles.[1]
    2. to use the latest programming, modelling, and statistical advances to enhance our dugong distribution and abundance analysis.
    3. engage with First Nations people across the surveyed area to: (1) raise awareness about dugong and sea turtle ecology and conservation issues, (2) seek interest from the communities in becoming involved in dugong survey work at different spatial scales, particularly aerial imagery surveys.
    4. discuss new avenues for reducing uncertainty in the results for the surveys and the potential of new research tools for dugong monitoring in the future
    5. provide advice to relevant management partners (GBRMPA, DCCEEW, and the Queensland Government) and Traditional Owners about the implications of the findings for the conservation, management, and monitoring of dugongs and large marine turtles[1] in the southern GBR, Hervey Bay-GSS and Moreton Bay.

Methods

- We surveyed the urban coast of the GBR between Mission Beach and Bundaberg (November 2022), as well as the Hervey Bay– Great Sandy Strait (November-December 2022) and Moreton Bay regions (December 2022).
- The survey design was based on the aerial surveys conducted by researchers at James Cook University since the 1980s as optimised during the RIMReP process.

[1] The results for large turtles will be in a separate report

- The aerial survey methodology followed the strip transect aerial survey technique used in earlier surveys along the Queensland coast.
- Imagery experiments were undertaken as part of this survey but will be synthesised in a separate report.
- Dugong abundance was estimated using the Hagihara method.
- N-mixture Bayesian models were used to assess trends in the dugong population across the three surveyed regions between 2005 and 2022. Temporal variation in the proportion of dugong calves was explored using all available historical survey data.
- A kernel density smoothing method used to develop spatially explicit models of dugong density and distribution.

Key findings

- The 2022 aerial survey confirmed the long-term importance of the following sub-populations of dugongs in the survey region: Hinchinbrook, Townsville region, Shoalwater Bay, Hervey Bay and Moreton Bay.
- The trends in the time series of aerial surveys for the urban coast of the GBR, Hervey Bay and Moreton Bay, all suggest long-term declines in dugong abundance in all three survey regions. Nonetheless this conclusion is more robust for the urban coast of the GBR than for Hervey Bay or Moreton Bay for the following reasons:
  a) Results from the 2022 survey increased the longevity of the trend of long-term decline in the dugong population off the urban coast. The estimated decline was approximately -2.3% per year between 2005 and 2022 compared with -4% per year from 2005 to 2016. The probability of long-term decline of the dugong population continued to be very high [0.97 based on survey data from 2005 to 2016 and 0.94- 2005 to 2022].
  b) Hervey Bay exhibited the most pronounced estimated population decline among the three regions covered in the 2022 survey, resulting in an estimated decline of approximately -5.7% per year between 2005 and 2022 with a probability of decline of 0.995, which is substantial evidence of a declining population. This updated result differs slightly from the previous analyses, which suggested a slight increase from 2005 to 2016 of +0.28% and a probability of decline of 0.47 (i.e., <50%). Taken together, we interpret the results to be the consequence of two large flood events in early 2022, which caused extensive loss of seagrass. We also suggest that the apparent long-term trend may be confounded by temporary emigration in addition to mortality as happened in the 1990s. Nonetheless, the fact that evidence of substantial temporary emigration from Hervey Bay was not detected elsewhere in the survey region is very concerning; and
  c) Moreton Bay had the shallowest estimated trend in population size from 2005-2022: -1.2% per year. The probability of decline was 0.72, which means that a conclusion of population decline is more warranted than a population increase, but that this conviction should be held weakly. A zero-trend cannot be dismissed, especially because the results from 2005 to 2016 suggested an increase of 1.63% per year with a probability of decline of only 0.28 .
- The proportion of calves is a 2-3 year lagged measure of population health and varies with the status of the seagrass on which dugongs depend for food. The percentage was 6.7% along the urban coast of the GBR, 9% in Hervey Bay, and 5.5% in Moreton Bay. All these results are within the range recorded for previous surveys but the results for the urban GBR and Moreton Bay are at the low end of their ranges, presumably reflecting the recent wet years. The result

for Hervey Bay is surprising and suggests that mothers with calves may have remained in that Bay after the flood.

- The study highlights the considerable inter-annual variation and uncertainty of the statistical analyses, whereby few of the inferential outputs achieved conventional levels of "statistical significance” (i.e., low statistical power). We make recommendations to improve statistical power of subsequent surveys.

Advice for policy makers

- The findings from the 2022 survey add to the evidence highlighting the significant impact of climate and weather on the abundance, distribution, and reproductive capacity of dugongs. This impact is primarily attributed to the influence of climatic drivers on seagrass habitats, which are essential ecosystems for dugongs.
- The results highlights the need to reduce non-climate impacts on dugongs and their seagrass habitats by improving water quality, decreasing the risk of incidental capture of dugong in gillnets throughout the east cost of Queensland as recently agreed by the Commonwealth and Queensland Ministers and working with Traditional Owners to manage their dugong populations.
- Hervey Bay seems particularly prone to extensive seagrass loss after extreme flood events, which emphasises the need to reduce non-climate impacts on dugongs and their seagrass habitats in this region as well as the southern section of the GBR.
- The Townsville area also needs particular attention given the proximity of the seagrass meadows, in which dugongs depend to coastal development including port development. A baseline on the spatial-temporal dynamics of habitats use by dugongs in the region is required to help detect any deviation from the ‘norm’ due to added stressors.
- To better understand the response of dugongs to extensive seagrass loss after extreme weather events, consideration should be given to conducting annual local scale dugong surveys, for several years after major flood events in conjunction with seagrass surveys. To this end it would be important to conduct repeat dugong aerial surveys of Hervey Bay region in coordination with the seagrass monitoring, to monitor the response of dugongs to changes in the seagrass habitats in the region.

Advice for Traditional Owners in the survey area

- The status of the dugong in coastal areas of sea countries surveyed in 2022 is very concerning. Therefore, we suggest that discussions should be initiated with TOs around Indigenous management of dugong, including evaluating the role recreational boat traffic, capture in fishing nets, and hunting pressure may play in localised dugong declines.
- Efforts should be increased to foster partnerships with researchers in the design and implementation of local scale research relevant to the management of dugongs and seagrasses in sea country.

1 INTRODUCTION

Significance of the dugong and sea turtles in the Great Barrier Reef and neighbour regions

In Australia, the dugong (*Dugong dugon*) is a *Matter of National Environmental Significance* because it is listed as a listed migratory and marine species under the Environment Protection and Biodiversity Conservation Act. The dugong is also listed as Vulnerable under the Nature Conservation Act 1992 (Qld) and at a global scale (Marsh and Sobtzick, 2019).

Australia is a signatory to several international agreements that define its obligations to protect dugongs including the Convention on Migratory Species and its *Memorandum of Understanding on the Conservation and Management of Dugongs and their Habitats throughout their Range* (Dugong MOU). Signatories to the Dugong MOU agree to cooperate to restore or maintain a favourable dugong conservation status. The dugong is also explicitly mentioned as an attribute of the *Outstanding Universal Value* of the Great Barrier Reef World Heritage Area (hereafter GBRWHA, Criterion X) in the Statement of Outstanding Universal value, because the GBRWHA provides feeding habitat for the species.

As the only surviving member of the family Dugongidae (Marsh et al. 2011), the dugong is a species of high biodiversity value. Anecdotal evidence suggests that dugong numbers have decreased throughout most of their range (Marsh and Sobtzick, 2019), which is the basis for their global listing. Significant populations persist in Australian waters, which are now believed to support most of the world's dugongs. The dugong is of high cultural value to the Traditional Custodians of the GBRWHA. Hence the status of the dugong is reported in the Great Barrier Reef Outlook Reports (e.g., GBRMPA 2019) and State Party Reports on the state of conservation for Australia's Great Barrier Reef e.g., DCCEW 2022) and in the national State of Environment Report (Trebilco et al. 2021).

Aerial surveys of dugongs on the eastern coast of Queensland

Since the late 1980s, it has been established practice to monitor the GBRWHA for dugongs, every five years using trained human observers in light aircraft (henceforth observer surveys) with empirically derived corrections for detection bias (see Cleguer and Marsh 2023 for an inventory). The surveys have been carried out in two stages in separate years for logistical reasons: (1) the urban coast of the GBR (from Bundaberg (24.8°S) to Cooktown (15.5°S) including a Central Section (from Cooktown to Midge Point 20.3°S) and a Southern Section (hereafter 'sGBR', from Midge Point to Bundaberg, see Figure 1); (2) the Northern GBR from Cooktown to the northern boundary of the GBRWHA (10.5°S) (Figure 1). These sections as are based on GBRMP zoning, rather than biological reasons. However, the aerial surveys of the urban coast of the GBR have historically included the Hervey Bay-Great Sandy Strait region (hereafter 'Hervey Bay') and Moreton Bay because of the documented dugong movements between the GBR and these habitats in South-East Queensland (Cope et al. 2015; Zeh et al. 2016). The survey design has not considered McGowan et al. (2023) identified a deep genetic break in the dugong population on the eastern coast of Queensland in the vicinity of Midge Point (-20.6°S) and satellite-tracked dugongs have not been observed moving across this break.

The efficacy of the 5-yearly survey schedule was confirmed by prospective power analysis as part of the RIMREP process (Marsh et al. 2019). This schedule is also consistent with the statutory five-year reporting period required by the Great Barrier Reef Marine Park Act 1975 for the Great Barrier Reef Outlook Report.

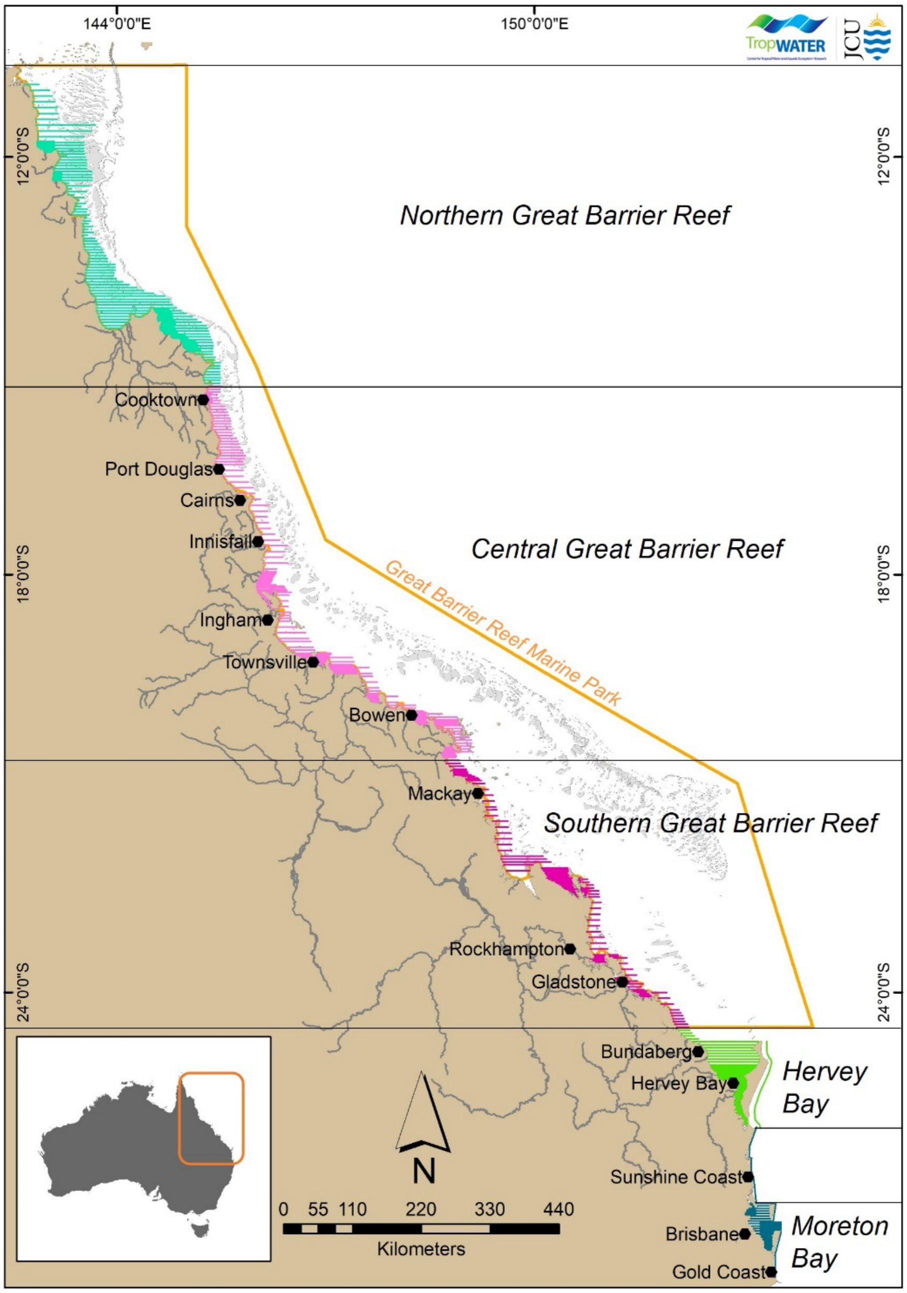

Figure 1. The eastern coast of Queensland with names of aeras covered during the time-series of dugong aerial surveys.

An observer survey of the urban coast of the GBR was last conducted in 2016 (Sobtzick et al. 2017) and is now one year overdue according to established practice. The most recent estimate of this dugong population is 3400 ±se 650 animals (Trebilco et al. 2021), including the region between Hinchinbrook Island and Cooktown, which was surveyed in 2018 (Marsh et al. 2020) because it was unable to be surveyed in 2016 due to adverse weather.

The urban coast the GBR dugong population is distributed at relatively low density along much of this coast with higher densities in the Hinchinbrook Island area, Townsville area and Shoalwater Bay. In its section on dugongs, the Australian State of Environment Report (SoE) 2021 states that the condition of the dugong along the urban coast of the GBR is “poor” and its trend is “deteriorating” (Trebilco et al. 2021). Confidence in this assessment is rated as “adequate” and is based on the time series of aerial surveys conducted this century and Bayesian modelling by Dr Robert Rankin (Marsh et al. 2019, Rankin and Marsh unpublished). In contrast the SoE report notes that the nGBR dugong population, between -18°S and -10°S and last surveyed in 2018-2019, is stable or slightly increasing, comprising 7000 +SE 600 animals, and that its condition is ‘very good’ based on Marsh et al. (2020). The next survey of the northern section of the GBR is due in 2023.

In the Hervey Bay region, two significant flood events occurred in January and February-March 2022. These events led to the highest recorded river flows in the Mary River in over 110 years, resulting in the persistence of flood plumes along the western shoreline of Hervey Bay and throughout Great Sandy Strait (GSS) (Lewis et al. 2022). These floods raised concerns regarding the status of seagrass communities in the region, as well as the dugong and green turtle populations that rely on seagrass as a primary food source, especially as two floods and cyclone in 1992-1993 have had serious impacts on both seagrass and dugong numbers and fecundity (Preen et al. 1995; Preen and Marsh, 1995). To address these concerns, the post-flood distribution of seagrass in Hervey Bay and Great Sandy Strait was mapped in May 2022 (York et al. 2022), followed by another assessment in October/November 2022 to monitor the region's recovery (Bryant et al. 2023). Our report presents the findings from the aerial survey of Hervey Bay conducted at the same time as the November 2022 seagrass survey.

Engagement with Australia’s First Nations People

Dugongs and sea turtles are central to Australian Indigenous people’s cultural identity and traditional values; and critical to the cultural, natural, socio-economic values of Traditional Use of Marine Resources Agreements (TUMRAs) and Indigenous Protected Areas (IPAs). Over the 30+ years of dugong surveys conducted across the Queensland coast, H. Marsh’s JCU research group have actively engaged with Traditional Owners to raise awareness around dugongs and sea turtles’ conservation issues. An example of output from this engagement process is reflected in the latest report of the nGBR in which Marsh et al. (2020) recommended that the major priority for dugong management in the nGBR continue to be supporting the implementation of community-based management by Traditional Owners (e.g., by completing Traditional Use Marine Resource Agreements (TUMRAs)).

It has proved challenging to involve Indigenous peoples in large-scale observer aerial surveys dugongs for logistical and cultural reasons. The use of drones in wildlife surveys as the potential to alleviate at least some of these issues and increase the chances for Indigenous peoples to become more involved in wildlife survey programs. This is especially true for local scale surveys using small off-the-shelf drones because this approach is very user-friendly (e.g., Cleguer et al. 2021). Off-the-shelf, small drones, which are relatively cheap and easy to use, are increasingly deployed by ranger groups, citizen scientists and communities across Australia (Perry et al. 2023). As part of this study and throughout out engagement process, we explored the interest from Traditional Owners and Indigenous ranger groups about using these novel survey approaches in their sea country across the eastern coast of Queensland.

Given all the above, the objectives of our study were to:

1. continue the time series of surveys for dugongs (and large marine turtles)
2. use the latest programming, modelling, and statistical advances to enhance our dugong distribution and abundance analysis
3. engage with First Nations People across the surveyed area to: (1) raise awareness about dugong and sea turtle ecology and conservation issues, (2) seek interest from the community to become involved in dugong survey work, particularly aerial imagery surveys
4. provide advice to relevant management partners (GBRMPA, DCCEEW, and the Queensland Government) about the implications of the findings for the future monitoring as well as conservation and management of dugongs in the urban coast of the GBR, Hervey Bay and Moreton Bay.[2]

2 METHODS

2.1 STUDY LOCATION

Our initial intent was to survey the inshore waters of the urban coast of the GBR including the relevant regions of the Central and Southern sections of the GBRMP (Figure 2) plus Hervey Bay and Moreton Bay.

In contrast to the two survey aircrafts used in some previous observer surveys, we chose to use only one team and aircraft for the 2022 survey to ensure good management of the imagery experimental work in this survey. The slow start of the survey from Townsville due to marginal weather led the team omitting the northern sections of the central GBR (Mission Beach to Cooktown), knowing that funding was secured to cover this area the following year. As a result, the 2022 survey area was from Mission Beach (17° 52' 10" S) to the southern section of Moreton Bay (27° 42' 32" S) (see Figures 1 and 2).

2.2 SURVEY DESIGN

There have been some changes in the design of dugong aerial surveys over the past 35 years, largely driven by adaptive monitoring and advances in technology as well as changes in the logistical and financial constraints. As part of the RIMReP process, Marsh et al. (2019) analysed the design and results from dugong surveys conducted within the GBRWHA to optimise the survey design for the Great

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[2] The 2022-2023 aerial surveys and imagery experiments conducted across the GBRWHA were funded by the Great Barrier Reef Foundation – Reef Trust Partnership, whereas the surveys and imagery acquisition conducted in Hervey Bay and Moreton Bay in 2022 were funded by Department of Climate Change, Energy, the Environment and Water.

Analysis of the observer surveys for turtles and the experimental work on imagery surveys is ongoing and will be reported in separate documents.

Barrier Reef surveys of dugongs (as well as large juvenile and adult turtles). The optimised survey design for Moreton Bay and Hervey Bay did not differ from the established design.

The optimised design of the southern and northern GBR surveys resulted in a reduction in required flight time compared to the original survey design, thus decreasing the number of survey days and overall cost for the two regions. For this project, we followed advice from Marsh et al. (2019) and used the optimised design to conduct the surveys (Figures 2 and 3).

The survey team included:

- A pilot with hundreds of hours experience in flying with the survey aircraft (P68C). A backup pilot was also available if required.
- An experienced survey leader (lead author).
- Three experienced marine mammal observers, including one highly experienced dugong aerial survey observer.
- One inexperienced marine mammal observer.
- One team driver to transfer equipment between airports.

All participants were provided with thorough theoretical and practical training. The practical component of the training involved practice surveys in Cleveland Bay. The complete survey team underwent Helicopter Underwater Escape training to ensure adherence to safety measures.

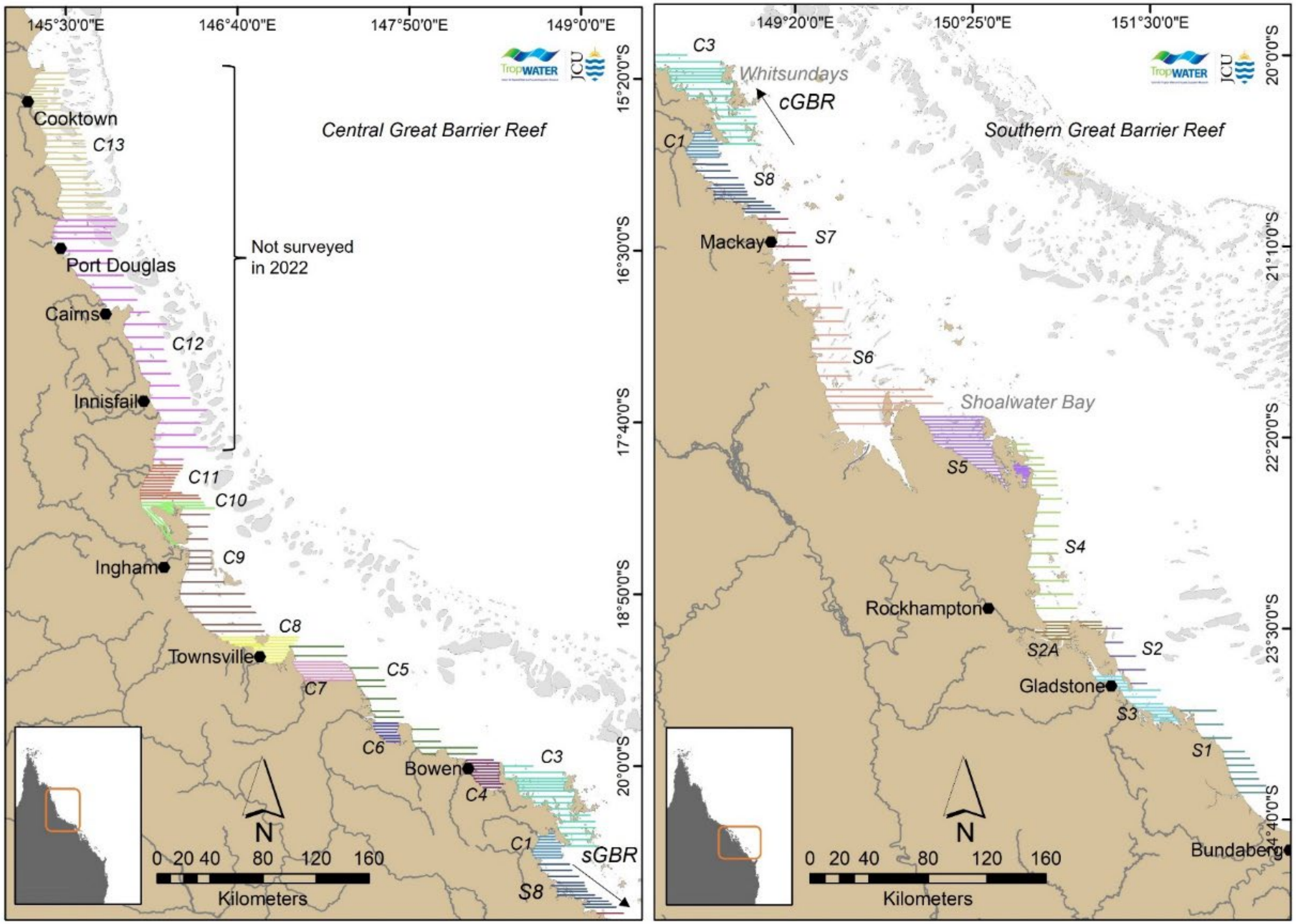


Figure 2. Maps of the 2022 survey transects and blocks in the central and southern sections of the Great Barrier Reef. The survey of blocks C12 and C13 was not attempted for reasons explained in section 3.1.

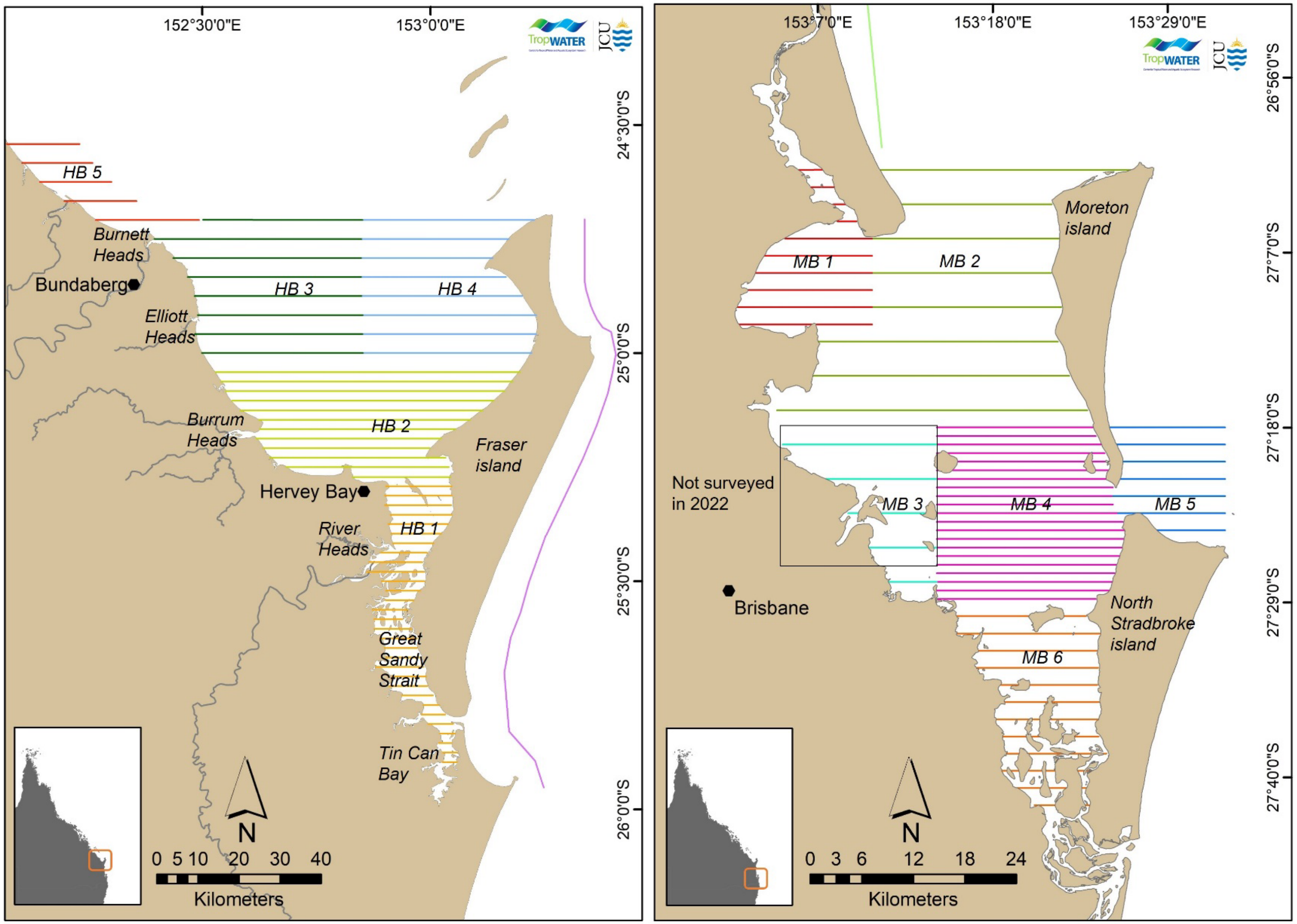


Figure 3. Maps of the 2022 survey transects and blocks in the Hervey Bay and Moreton Bay regions. Four out of the five transects in block MB3 were not surveyed for reasons explained in section 3.1.

2.3 SURVEY METHODOLOGY

The aerial survey methodology followed the strip transect aerial survey technique detailed in Marsh and Sinclair (1989) and used in subsequent surveys along the Queensland coast (See Cleguer and Marsh 2023 for an inventory of all surveys conducted in Queensland and their associated methodologies).

Strip transect sampling uses the same fundamental principles as distance sampling, with the additional assumption that the detectability of the target animals is constant across the designated survey strip. Observers record all observed sightings occurring within a strip of predefined width on either side of the transect line. This method has been extensively applied to dugong surveys (see Pollock et al. 2006) and (Hagihara et al. 2014, 2018). The method is particularly suitable for dugongs and large marine turtles as a result of their relatively brief and cryptic surfacing behaviour, which prevents reliable recording of distance of individuals from the transect line from a passing aircraft.

A 6-seat, high-wing, twin-engine Partenavia 68C was flown along predetermined transects as close as possible to a ground speed of 100 knots (Figure 4). To comply with the requirements of the Civil Aviation Safety Authority and to calibrate observer and imagery experiment work, the survey was conducted at a height of 600 feet (183 m) above sea level rather than 500 feet (152 m) flown in surveys conducted between 2011 and 2016 and 450 feet (137 m) prior to 2011. Marsh and Sinclair (1989) experimentally showed that there was no significant difference in observed dugong density between survey regimes conducted at 137m and 274m, so we anticipate that the effect of this change should not have been significant, especially as the transect width remained constant.

Transects 200 m wide on the water surface on each side of the aircraft were demarcated using fiberglass rods attached to artificial wing struts on the aircraft (Figure 4). Distance categories (50, 100, and 150 m) within the strip were marked by colour bands on the artificial wing struts. Two trained tandem teams of observers on each side of the aircraft scanned their respective transects and recorded their sightings onto separate tracks of an audio recorder (Zoom H4n, Zoom Corporation). The two members of each tandem team operated independently and could neither see nor hear each other when on transect. The location of the sightings in the distance categories within the survey strip enabled the survey team to decide if simultaneous sightings by tandem team members were of the same group of animals when reviewing the recordings. The sightings of the tandem observers were also used to calculate survey specific corrections for perception bias (i.e., for animals visible in the survey transect but missed by observers) for each side of the aircraft as outlined below (Marsh and Sinclair 1989, Pollock et al. 2006).

The surveys were conducted in passing mode with dugongs (and large marine turtles) as the focal species (i.e., In situations where animals other than dugongs and sea turtles were present within the observers' field of view simultaneously with dugongs and/or sea turtles, priority was assigned to the collection of information on the former). For each animal sighting, observers recorded the type of animal (e.g., dugong or sea turtle), total number of animals seen, position in the transect (e.g., low, or medium), and a composite index of environmental conditions (see Appendix 1). In addition, the number of calves was recorded for each dugong sighting as an index of population health (Marsh et al. 2019; Marsh 2022). Calves were defined as being less than 2/3 of the size of the accompanying cow and swimming near her. When groups of dugongs were too large to accurately count in passing mode (generally more than 10 animals), the aircraft abandoned the transect and went into circling mode to obtain a total count of the group before resuming the transect.

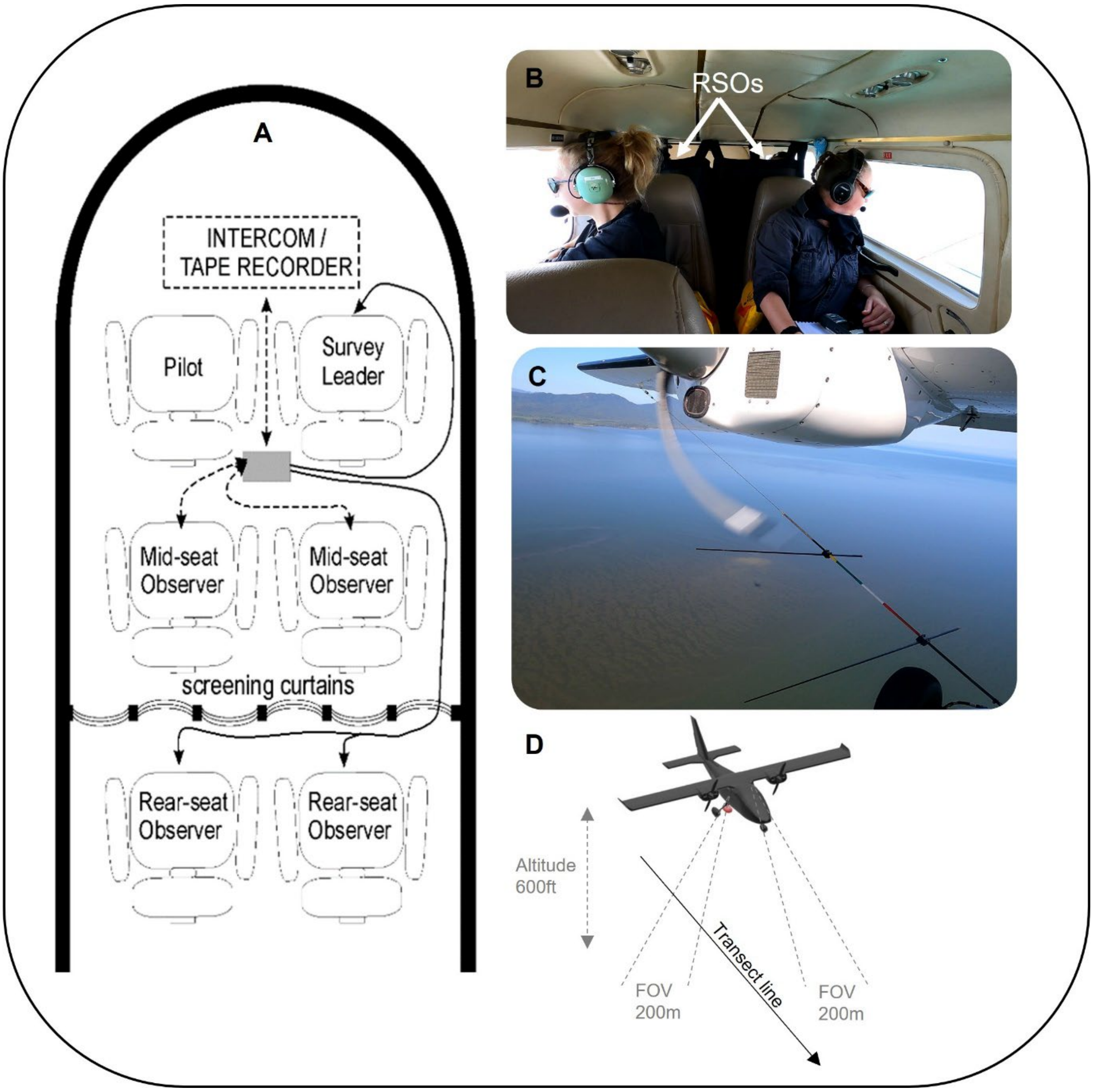


Figure 4. (A) survey aircraft setup, (b) view of the mid-seat observers, separated with the rear-seat observers (RSOs) using a black curtain, (c) view of the transect markers from the inside of the aircraft, (D) schematic representation of survey line, field of view (FOV) and altitude.

The survey leader collected data on environmental conditions at the beginning of each flight (cloud cover, cloud height, wind speed and direction, and air visibility, see Appendix 1) and each transect (e.g., transect direction). Every few minutes during each transect, and whenever conditions changed, the survey leader recorded sea state (assessed by the survey leader), water visibility, and glare (assessed by the mid-seat observers). An example of the spatial distribution of recordings of water visibility is provided in Figure 5.

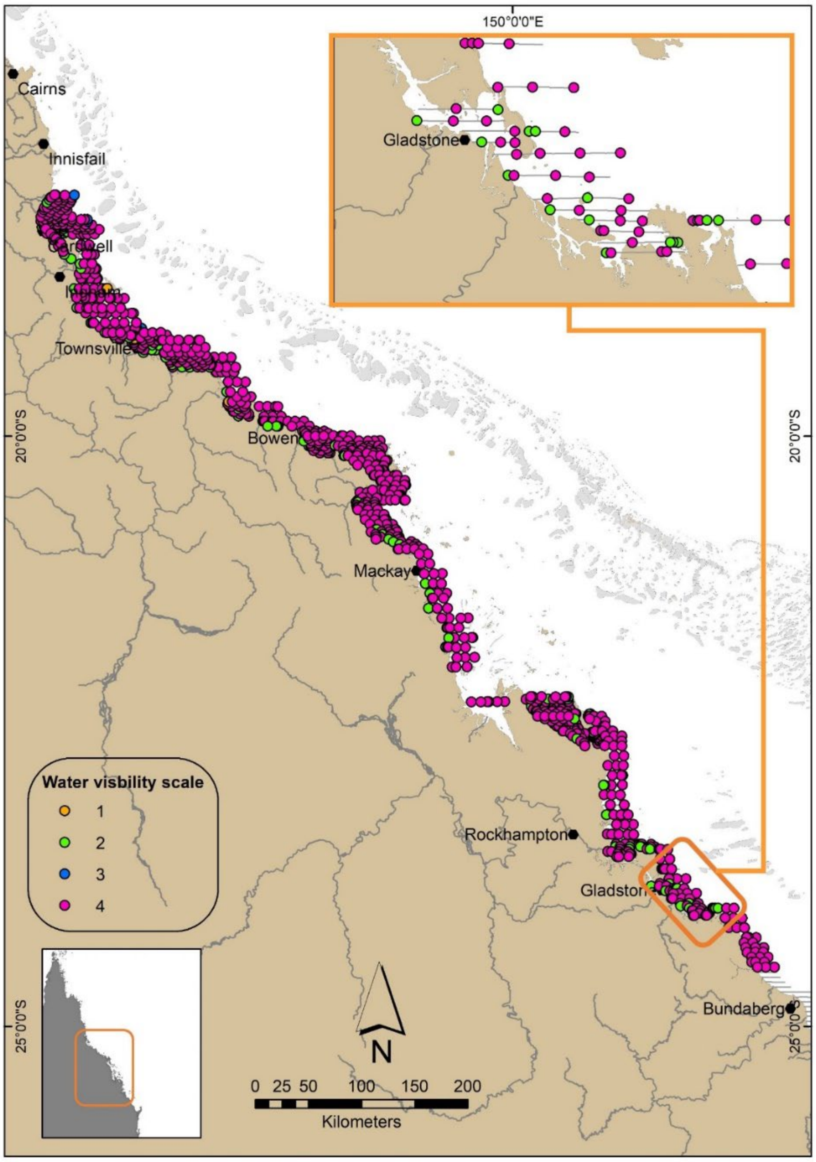


Figure 5. Maps showing the distribution of environmental data records (here water visibility) along transect lines. The insert shows a zoomed-in example of records made in the Gladstone area.

2.4 POPULATION AND DENSITY ESTIMATES

2.4.1 DUGONG POPULATION ESTIMATES

We used the method developed by Hagihara et al. (2014, 2018), henceforth the Hagihara method, to estimate dugong relative abundance and density. The method attempts to correct for availability bias (animals not available to observers because of environmental conditions and animal diving behaviour) and perception bias (animals visible in the survey transect but missed by observers due to imperfect detection). We followed recommendations from Marsh et al. (2019) who considered that the way the Hagihara method corrects for availability bias to be superior to previous methods (Marsh and Sinclair 1989; Pollock et al. 2006) for correcting availability bias because it makes fewer assumptions. Using the Hagihara method also aligns with recommendations from Cleguer and Marsh (2023) to increase effort to standardise survey and data analysis approaches across surveyed areas of the dugong Australian range. The additional data required to implement the Hagihara method has been collected since 2005 in the urban coast of the GBR, Hervey Bay and Moreton Bay; hence the results from 2005 (refer to Marsh and Lawler 2007), 2011 (refer to Sobtzick et al. 2012) and 2016 (refer to Sobtzick et al. 2017) are included in this report for comparative purposes. Access to the data collected in those years can be request on the JCU Dugong database webpage.

To estimate the perception bias, a mark-recapture model was used to calculate the proportion of the 'available' dugongs that are counted during each survey (Marsh and Sinclair 1989; Pollock et al. 2006). Each primary observer sighted (marked) a group of dugongs that may or may not have been seen (recaptured) by the corresponding secondary observer, and thus each dugong sighting was categorised as being recorded by one or both observers. These categories were then fitted into a mark recapture framework to calculate the probability of a dugong group being seen (captured) by a tandem team. Pollock et al. (2006) describe how to fit generalised Lincoln-Petersen models to determine perception probability (conditional on dugongs being available) and whether this varied according to observer, experience (primary or secondary observers), or side (port or starboard) using program MARK (White and Burnham, 1999). The perception probabilities used for each observer were provided by the model that best fits the data according to Akaike's Information Criterion (AIC), which corrects for small sample bias. Following the Hagihara method, the standard error for the population estimate for each block were simulated using the program Python using 5000 iterations. The analyses assumed that there was no directional movement of animals between each day of survey across the surveyed area.

Automation of the dugong aerial survey data analysis

Past aerial survey data have been processed and analysed using a range of tools, linking back to Excel spreadsheets, with many steps done manually, and by different people, all increasing the risks of human errors. To minimise such errors and their propagation through the analysis process, we created scripts in R (R Core Team 2020, version 4.2.3) that automatically perform the different steps, while keeping the previous workflow as much as possible to allow for easier troubleshooting and comparisons with previous years.

We used R as the preferred programming language as it is open-source, widely used within the discipline, and it has the many packages available that allow for automatically calling other programs required in the previous workflow. The scripts bundle we created follows the workflow used in previous survey analyses, which used an external software (program MARK, written in FORTRAN) and an external script written in Python. The new R scripts allow users to use raw data with the fewest manual changes as an input and manually enter a minimal number of variables specific to each survey. The scripts then automatically perform all the required analyses to create the same key outputs as produced by the former method, and additional material directly formatted for interpretation and publishing.

The key outputs of the scripts bundle include an estimation of dugong abundance (Hagihara method) for every block surveyed that meet the criteria for estimation, with the associated standard error. A shapefile of dugong sightings and a Master File of all data recorded including conditions and sightings (corrected and georeferenced) is also produced. Auxiliary outputs produced include tables used routinely for survey reports, etc.

With clean and correct input data, the outputs can now be produced and checked within days by a single user, compared with several weeks of manual labour by several collaborators. A separate report with details on the scripts, as well as a handbook for users was also produced at a later stage.

Extraction of water depth data

To perform the analysis using the Hagihara method, an accurate estimation of the observed water depth at the time and location of each dugong sighting is required. Extracting the observed water depth previously involved the following:

1) Converting geographic coordinates to UTM.
2) Using 1), identifying the nearest weather stations (reference and secondary where applicable) which contained tide gauges.
3) For each station identified in 2), manually search online for the Mean Sea Level (MSL) referred to the Lowest Astronomical Tide (LAT), and the time difference to the reference station for any secondary station (data was extracted manually from pdf documents), and
4) For each station and dugong sighting, manually extracting tide Height above LAT.
5) From these values, calculating the tidal height of the nearest station (in m), at the time of each dugong sighting, above LAT using the excel spreadsheet formula.
6) Calculating the bathymetry at the location of each dugong sighting from the GPS locations of each sighting and a map of the bathymetry covering the Great Barrier Reef available at the time, using a separate GIS software. The Digital Elevation Model (DEM) used in the past typically had a grid pixel size of ~100m.
7) The observed (corrected) water depth at the time and location of each dugong sighting was then calculated as the bathymetry + tidal height of the nearest station – Mean Sea Level.

Our new, more accurate, method uses location and time at each sighting as an input, to automatically to extract:

1) at the location of each dugong sighting, Mean Sea Level (MSL) from the High-resolution depth model for the Great Barrier Reef at 30m resolution (Beaman, 2017) using R.
2) at the location and time of each dugong sighting, Sea Surface Elevation (SSE) from the Ereef GBR1 raw model output using Matlab (The MathWorks Inc. 2021, version 2021a).

The observed (corrected) water depth at the time and location of each dugong sighting is then calculated as the sum of the MSL and SSE extracted for that sighting.

The Matlab script will be translated into R at a later stage, so this step is fully integrated within the bundle of scripts.

2.4.2 BAYESIAN APPROACH TO INVESTIGATE DUGONG POPULATION TRENDS

An analysis of population trends was performed using a hierarchical Bayesian N-Mixture model to estimate changes in adjusted-counts over time. The method integrated various sources of statistical uncertainty and variation, such as stochastically imputing undetected dugongs due to the availability biases and capture-recapture uncertainties described above.

The N-Mixture method was developed and studied by Rankin and Marsh (2020), who concluded that it had higher statistical "power" (i.e., reliability in detecting trend) and lower estimation-bias than earlier estimators which estimated dugong population trends from adjusted counts (e.g., Horvitz-Thompson estimator).

The present study continued with these models, using data from 2005 to 2022 to estimate population trends as well as the statistical probability that different regions were in decline. Specifically, the study aimed to:

(1) estimate dugong population densities in the urban coast of the GBR, Hervey Bay and Moreton Bay;

(2) estimate the annual percent change in dugong population density, as well as a retrospective probability of a decline; and

(3) the probability that the dugong density in the year 2022 was greater than the population density in previous survey years.

At the core of the N-Mixure trend-analysis was a Negative Binomial distribution to model counts of dugongs $N_{t,s}$ at transect *s* in year *t, and how they* changed across years and different regions.

The primary focus of estimation was the regression coefficients $\beta_0 + \beta_{t,l}$ which sum to the (log) density of dugongs in year t at location *l* (where *l* can be the urban coast of the GBR, Moreton Bay or Hervey Bay, depending on the transect). We used the posterior samples of $\boldsymbol{\beta}$ to make conclusions about the dugongs' population densities and trends over time.

The Negative Binomial regression equation is as follows:

$$\begin{aligned} p(N_{t,s}|\lambda_{t,l},\theta) &= \mathrm{NB}(N;\mathbb{E}[N_{t,s}],\theta) \\ \mathbb{E}[N_{t,s}] &= \lambda_{t,l}A_s \\ \log(\lambda_{t,l}) &= \beta_0 + \beta_{t,l} \end{aligned} \quad (1)$$

where *NB* is the Negative Binomial count distribution with overdispersion parameter θ; $\mathbb{E}[N_{t,s}]$ is the expected (or average) number of dugongs in year *t* at transect *s.* Line 2 states that the expected number of dugongs at (*s,t*) is equal to the density of dugongs ($\lambda_{t,l}$) in year *t* at location *l* (conditional on transect *s* being in location *l*) multiplied by transect length A_s, which is a fixed measurement per transect, also known as an 'offset'. Line 3 states that the log-density of dugongs is a linear model of intercept β_0 and marginal density $\beta_{t,l}$ for year *t* at location *l*. Notice that all *S* transects in location *l* have the same expected density.

Use of priors

To complete regression Equation (1) and sample from the posterior distributions of the regression coefficients ($\boldsymbol{\beta}$), we used independent Normal priors on the Negative Binomial regression coefficients, using the same prior-parameters for all priors, including the intercept β_0 and the per-year/per-location marginal densities $\beta_{t,l}$ for $t \in \{2005, 2011, 2016, 2022\}$ and $l \in \{\mathrm{HB}, \mathrm{MB}, \mathrm{SGBR}\}$. We used a uniform prior on the overdispersion parameter. Additional technical details on the use of priors can be found in Appendix 2.

Inference

We used Markov Chain Monte Carlo (MCMC) analysis to sample from the posteriors of model parameters. Although the regression coefficients $\boldsymbol{\beta}$ and densities $\boldsymbol{\lambda}$ where the primary focus of estimation, we calculated other quantities to help understand the magnitude and confidence of population trends, including:

a) the log-linear trend of dugong populations at each location over 17 years, as the annualised percent change, including 95%CIs, (i.e., the population trend);

b) the posterior probability of a decline at each location;

c) the posterior probability that dugong densities in year 2022 are higher than densities in prior years (2005, 2011, and 2016), and

d) indices of excess variation and uncertainty, at sub-region levels, such as survey 'blocks'.

The above statistics helped us to understand the *magnitude* and *significance* of dugong population declines. For instance, the magnitude of the trend may be large or small, whereas the probability of decline quantified how *certain* we are of a decline, regardless of its magnitude. The index of excess variation can help prioritise regions of the survey-area that deserve additional survey effort.

The workflow and technical details on trend estimation, probability of decline comparison of 2022 dugong densities to previous survey years, excess variation calculations were left out of the body of this report for simplicity but can be viewed in Appendix 2.

2.4.3 TRENDS IN DUGONG CALF PROPORTIONS

The proportion of calves was modelled using logistic regression R (v 4.3) as an index of population health (Fuentes et al. 2015; Marsh, 2022). The response variable was the proportion of calves weighed by the total number of dugongs present. Year was treated as a continuous covariate and survey region as a categorical covariate. The results from two surveys were removed because not all blocks were surveyed (Moreton Bay 1999 and Hervey Bay 2006).

2.5 SPATIAL MODELLING

We developed spatially explicit models of dugong and distribution using a kernel density smoothing method in ArcMap 10.8.2 (ESRI 2021), similar to those applied in (Bayliss and Hutton, 2017), with an output grid size of 1km^2. Input data were dugong counts corrected for perception and depth-specific probabilities as per the Hagihara method. Survey years used in the models were consistent with this report: 2005-2011-2016-2022. An initial bandwidth of 5000m was applied for the dugong data as an equivalent to the 5000m search neighbourhood radius used in the Empirical Bayesian Kriging (EBK) models developed by (Grech and Marsh, 2007) and (Grech et al. 2011) and used in the most recent sGBR survey report (Sobtzick et al. 2017). This radius was originally chosen as it corresponds with the home range of dugongs at Burrum Heads, Hervey Bay (Sheppard et al. 2006). Subsequent models were developed to compare bandwidths, aiming to find an average bandwidth that most effectively fit the data for all years while achieving a balance in bias and variance. The kernel smoothing interpolation method with the Epanechnikov kernel function was chosen as outputs tended to be analogous to kriging methods and it proved most appropriate for the data and analyses. Because the data from survey years prior to 2022 was treated using the EKB method, we re-analysed all data since survey year

2005 under the kernel smoothing interpolation method. For consistency and comparability, we -manually- used the same dugong density classes as in previous reports (e.g., Sobtzick et al. 2017): Very High (>0.5 dugongs per km^2), High (0.5 – 0.1 dugongs per km^2), Medium (0.1 – 0 dugongs per km^2) and Low (0 dugongs per km^2).

3 RESULTS

3.1 SURVEY FLIGHT SUMMARY

The dugong aerial survey of the urban coast of the Great Barrier Reef, Hervey Bay and Moreton Bay ran from 28th October to 8th December. The urban coast of the GBR from Mission Beach (northern boundary of survey block C11, Figure 2) to Yandaran Creek (north of Bundaberg, southern boundary of survey block S1, Figure 2) was surveyed in 23 days, followed by Hervey Bay in 7 days and Moreton Bay in 12 days (Table 1). Appendix 3 summarizes the details of the daily activities and survey flights.

Table 1. Number of days required to survey the urban coast of the GBR, Hervey Bay and Moreton Bay in 2022

Survey region	Start and end date (year 2022)	Total number of days	Total number of flying days	Total number of down days
Moreton Bay	27th Nov – 8th Dec	12	3	9
Hervey Bay	20th – 26th Nov	7	4	3
Urban coast of the GBR	28th Oct - 19th Nov	23	12	11

Some transects were surveyed twice:

- The Hinchinbrook area is known as one of the most important dugong hotspots in the GBR and was one of our target areas for conducting camera and imagery experiments (Cleguer et al. ongoing). This area (survey block C10) was flown on the 29th of Oct but camera failures on that day resulted in the re-survey of a portion of the survey block on 2nd Nov 2022. All analyses conducted for this report used the data collected during the first survey as this is when the weather conditions were the best of the two surveys and not all transects of block C10 were re-flown in the second survey
- In Hervey Bay, some transects within blocks HB3 and HB4 were surveyed twice as the first survey flight was conducted during sub-optimal logistical conditions. The second survey flight was completed in better conditions and thus the data from that survey was chosen for the analysis conducted here.

Some transects could not be surveyed:

- Four of the transects located north of Shoalwater Bay (southern section of survey block S6) could not be surveyed because of a combination of unsuitable weather conditions and flight restrictions imposed by the Shoalwater Bay Military Training Area.
- Five transects located within the Brisbane Airport controlled area could not be surveyed as we were not granted permission to survey in this area.

Sampling intensities per block varied between 1% and 34.4% in Moreton Bay (mean = 18.0%, stdev = 10.9%, ±se = 4.5%), between 8.4% and 20.1% in Hervey Bay (mean = 12.3%, stdev = 4.7%, ±se = 2.1%), and between 2.6% and 18.6% in the urban coast of the GBR (mean = 12.03, stdev = 5.6%, ±se = 1.2%) (Appendix 4).

3.2 OVERALL CONDITIONS

Overall weather conditions were satisfactory. All-day easterly winds resulted in the survey team being grounded at the start of the survey in the Townsville region (8 consecutive days in early November). Low to moderate easterly to north-easterly sea breeze increased in the late mornings throughout most of the survey period, regularly preventing the team from conducting a survey flight in the afternoons. Glare was comparable to the 2005 and 2011 survey years and less than in 2016 throughout the entire surveyed area. A weather condition summary for the 2005, 2011, 2016 and 2022 surveys is presented in Appendix 5.

3.3 DUGONG DETECTION PROBABILITY

The probability of observers detecting dugongs, given that they were available for detection, was high (Table 2). The generalised Lincoln-Petersen model of best fit, which prove most suitable according to Akaike's Information Criterion, accounted for individual variations in the perception probability among observers. The perception probability estimates suggest that the double-observer teams sighted 96-97% of dugongs that were available (Table 2).

Table 2. Perception probabilities per observer and per tandem team of observers for the 2022 survey.

Observer position in the aircraft	Probability estimates (±se)	Perception probability of each tandem team
Port Primary	0.85 (0.03)	
Port Secondary	0.81 (0.03)	Port: 0.97
Starboard Primary	0.68 (0.03)	Starboard: 0.96
Starboard Secondary	0.89 (0.03)	

3.4 URBAN COAST OF THE GREAT BARRIER REEF

3.4.1 DUGONG SIGHTINGS

During the 2022 survey, we recorded 128 sightings of 179 dugongs in the urban coast of the GBR. The raw counts of dugongs detected in the 2022 survey were the lowest since 2011 (Figure 6 and Appendix 6). Similar to 2011, no dugong herds (groups of greater than 10 individuals) were observed. This contrasts with 2005, which had three herds of 12, 50, and 70 dugongs, representing the highest numbers and largest herds recorded. As in previous survey years, the most common group size encountered during 2022 was single individuals (mean = 1.5, range = 1-6). An example of the distribution of dugong sightings in the Cardwell-Hinchinbrook-Palm Island area in 2022 is presented in Figure 7.

The distribution of dugongs and other species of marine megafauna across all surveyed areas are presented in Appendices 7 and 8. Records of sightings of marine megafauna species other than dugongs and sea turtles are presented in Appendix 9.

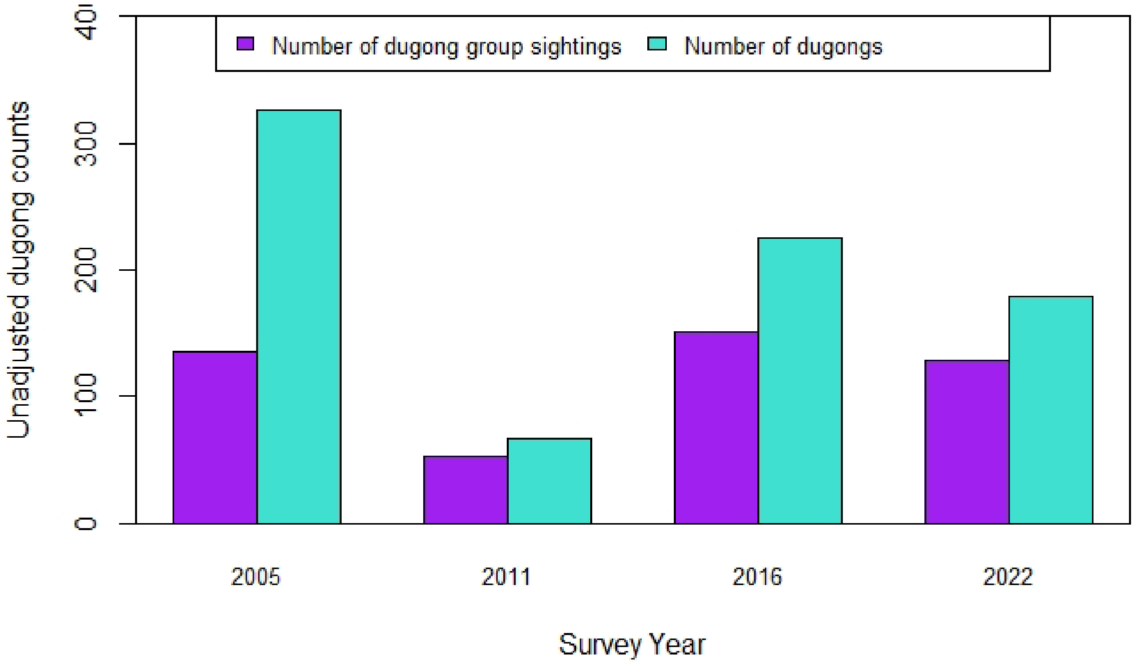


Figure 6. Raw counts of dugong group sightings and individual animals recorded during the 2005, 2011, 2016 and 2022 aerial surveys in the urban coast of the Great Barrier Reef.

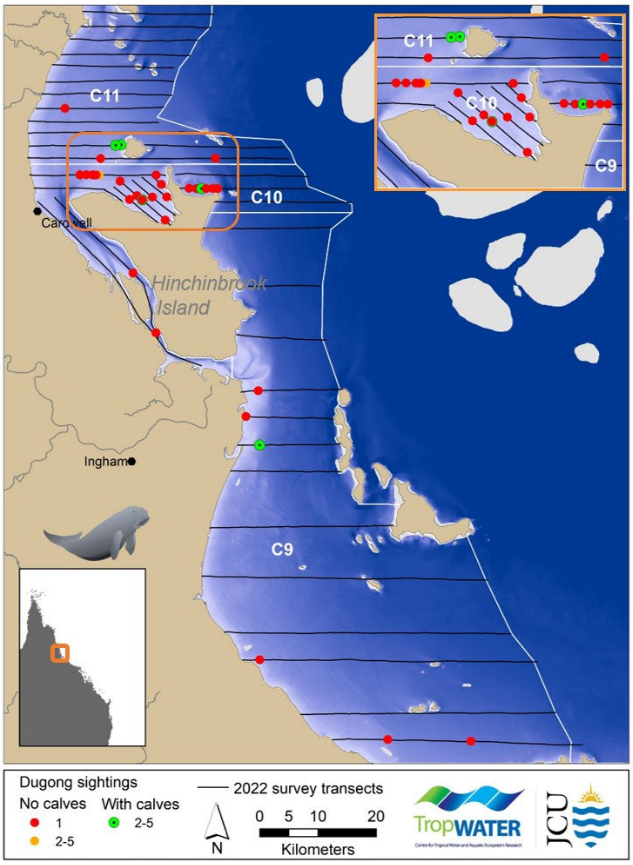


Figure 7. Distribution of dugong sightings in the Cardwell-Hinchinbrook-Palm Island area in 2022. Blue gradient base layer represents water depth. All maps of dugong distribution are presented in appendix 7.

3.4.2 DUGONG POPULATION SIZE ESTIMATES

Using the Hagihara method, we estimated the dugong population in the urban coast of the GBR in 2022 to be 2124 dugongs (±se 476) (Figures 8 and 9, and Appendix 10). Without block C11 (which was not surveyed in 2016) this estimates drops to 2006 dugongs (±se 466) and represents a 29% decrease in the estimated number of dugongs across the urban coast of the GBR compared to the 2016 survey estimates (2822 ±se 600, Appendix 10). The proportion of dugongs estimated to be present in the central region of the GBR (C blocks) continues to be higher than in the southern section of the GBR, in contrast to the earlier survey years (2005 and 2011) (Figure 10). Other notable decreases in the estimated numbers of dugongs across the urban coast of the GBR were in blocks C4 (Edgecumbe Bay) and S5 (Shoalwater Bay, Figures 9 and 11).

Along the urban coast of the GBR, dugongs were most abundant in the region north of Hinchinbrook Island, near Cardwell (block C10, Figures 9 and 11). The estimate of the numbers of dugongs present in this region was the highest since 2005. The region between Hinchinbrook Island and Cleveland and Bowling bays (blocks C9, C8 and C7) along with Shoalwater bay (block S5, Figures 9 and 11) also recorded high dugong numbers. Fewer dugongs were estimated to be in the Townsville-Cleveland Bay area (block C8) at the time of the survey compared to the 2016 survey. However, we note the increase in the estimated numbers of dugongs in the Bowling Green Bay area located immediately south of Cleveland Bay (block C7) and the high numbers of animals around Hinchinbrook (dugongs are known to move between these areas). While still relatively high, the abundance of dugongs in Shoalwater Bay in 2022 was estimated to be the lowest (yet very similar to the 2011 survey) since 2005 (Figure 9 and 11). There was a two-fold increase in the estimated number of dugongs in the Gladstone area, located ~200km north of Hervey Bay, since the 2005 survey. Too few dugong sightings were made in this region in 2011 and 2016 to generate abundance estimates (Figure 9 and 11). Dugong abundance estimates could not be derived for blocks S1, S2, S6, S7, C1, C3, C5, and C6 from the 2022 data because no dugongs were seen or too few sightings were made (Appendix 10). Our inability to calculate abundance for these areas and the tendency for dugongs to undertake temporary emigration makes interpreting changes in abundance between surveys in individual survey blocks extremely tenuous (see Discussion).

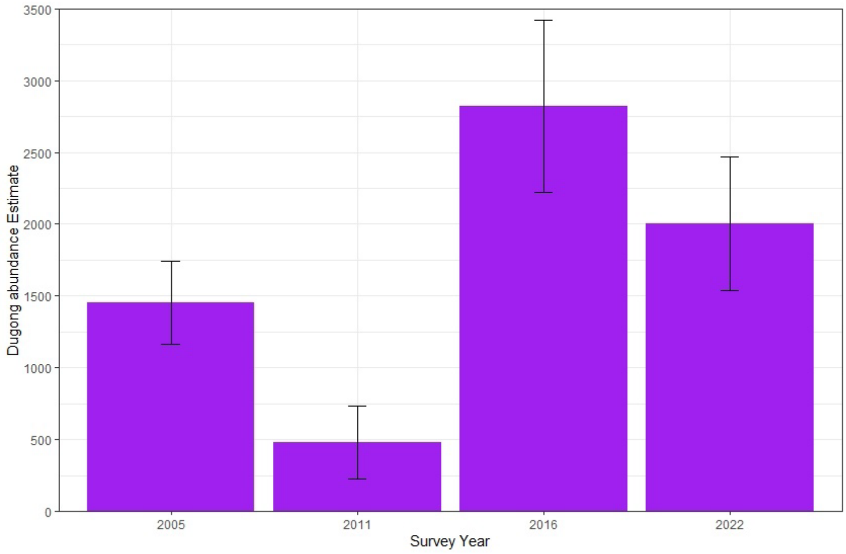


Figure 8. Dugong population size estimates ±se using the Hagihara method in 2005, 2011, 2016 and 2022 in the southern Great Barrier Reef (blocks that were not surveyed in 2016 were removed in the other survey years). Whiskers represent Standard error values around the estimate.

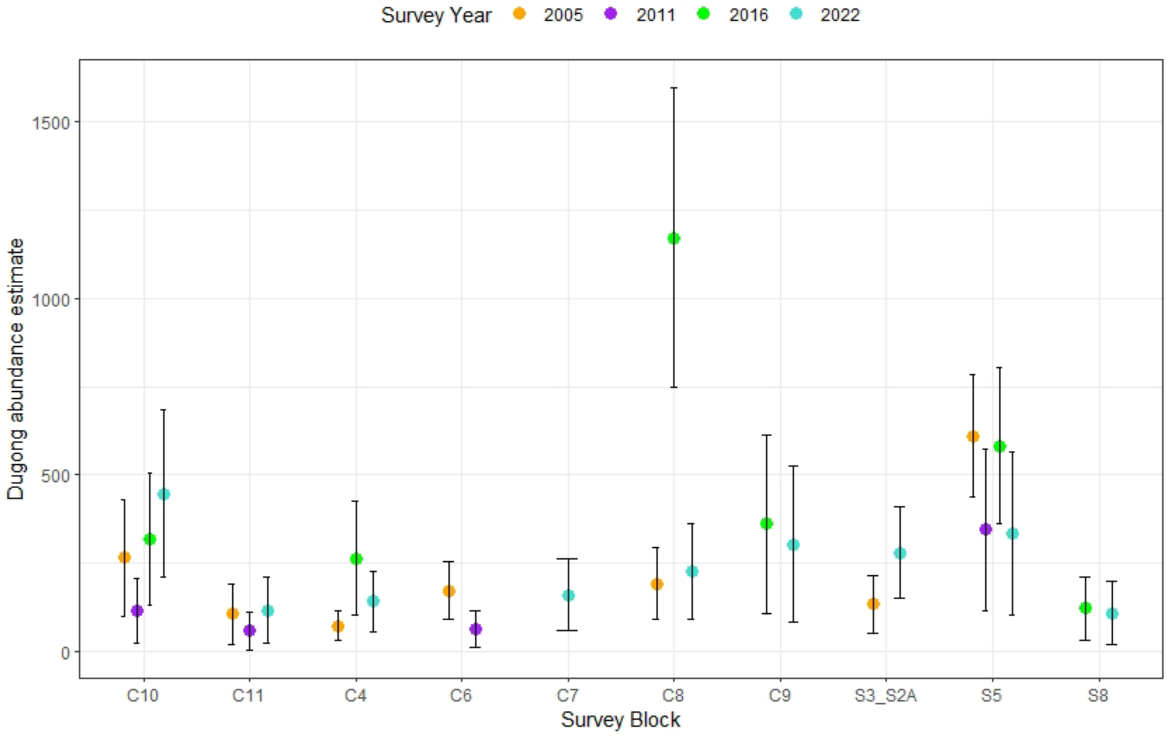


Figure 9. Dugong population size estimates (dots) ±se (whiskers) per block using the Hagihara method in 2005, 2011, 2016 and 2022 in the southern great barrier reef. survey blocks for which no estimate could be generated were removed from the figure (details of survey blocks with or without dugong abundance estimates are presented in Appendix 10). A geographically explicit display of dugong abundance per block is provided in figures 10 and 11.

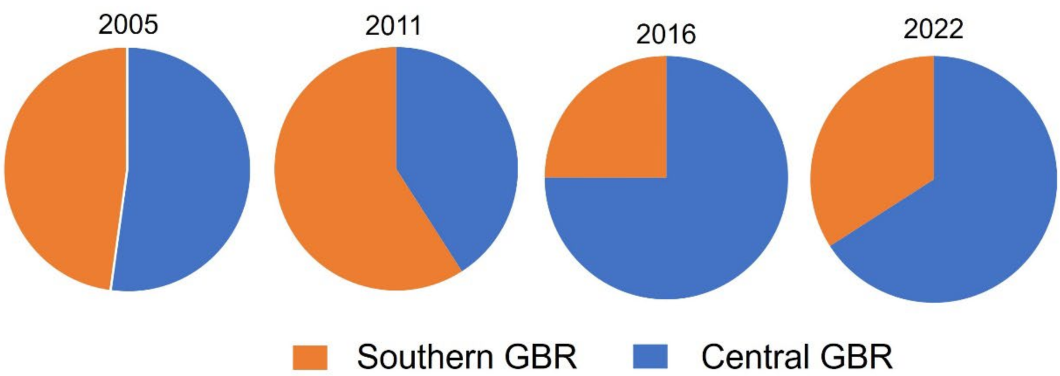


Figure 10. Temporal variation in the proportions of estimated dugong numbers in the central and southern sections of Great Barrier Reef between 2005 and 2022.

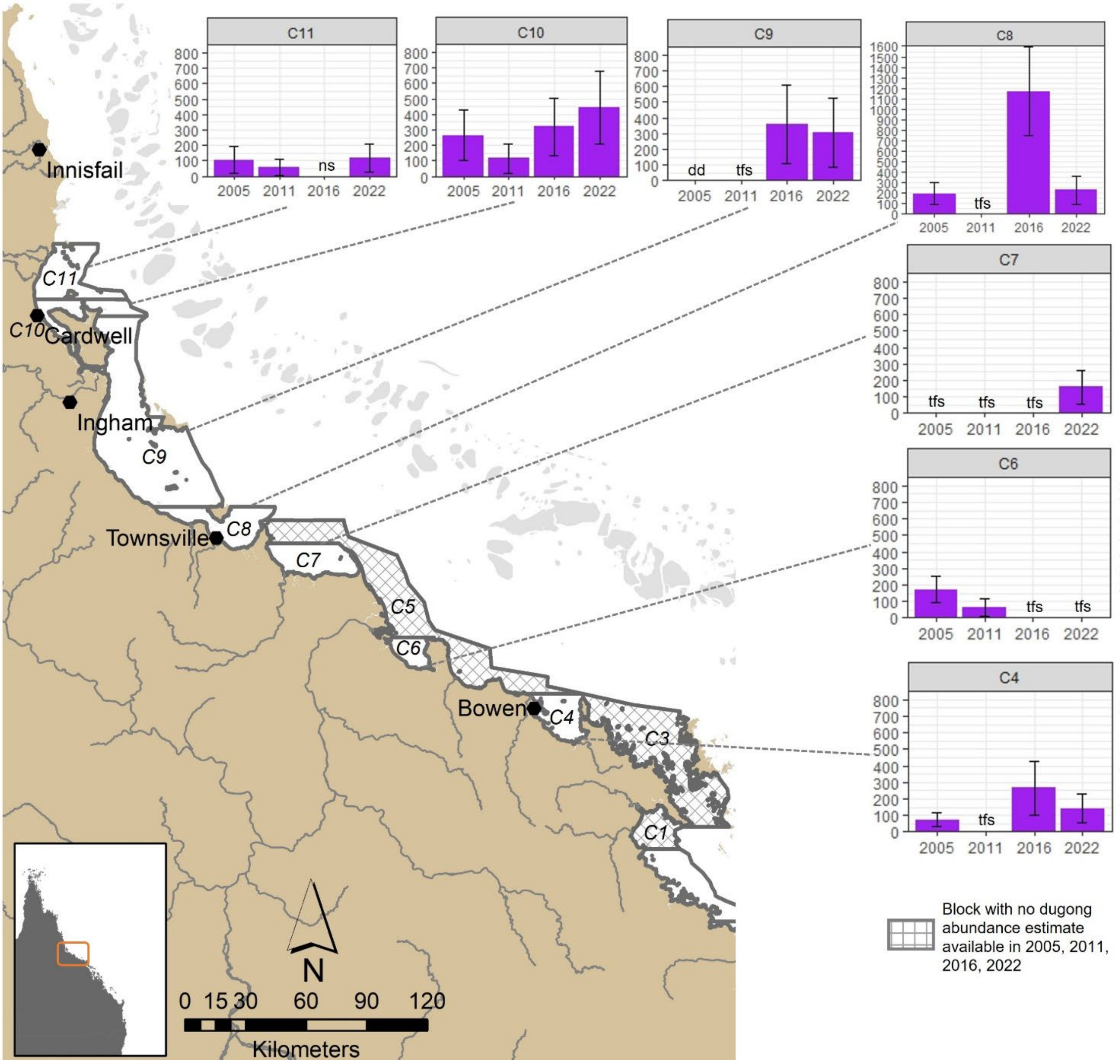


Figure 11. Estimated dugong abundance for the central section of the Great Barrier Reef region between 2005 and 2022. Y axes show the estimated dugong population size for the block. Whiskers represent standard errors. For some year estimates are not available because the survey used a different design (dd) or there were too few sightings (tfs) to estimate population size. Survey blocks for which no estimates are available across all survey years are hashed and details of the reasons are in Appendix 10.

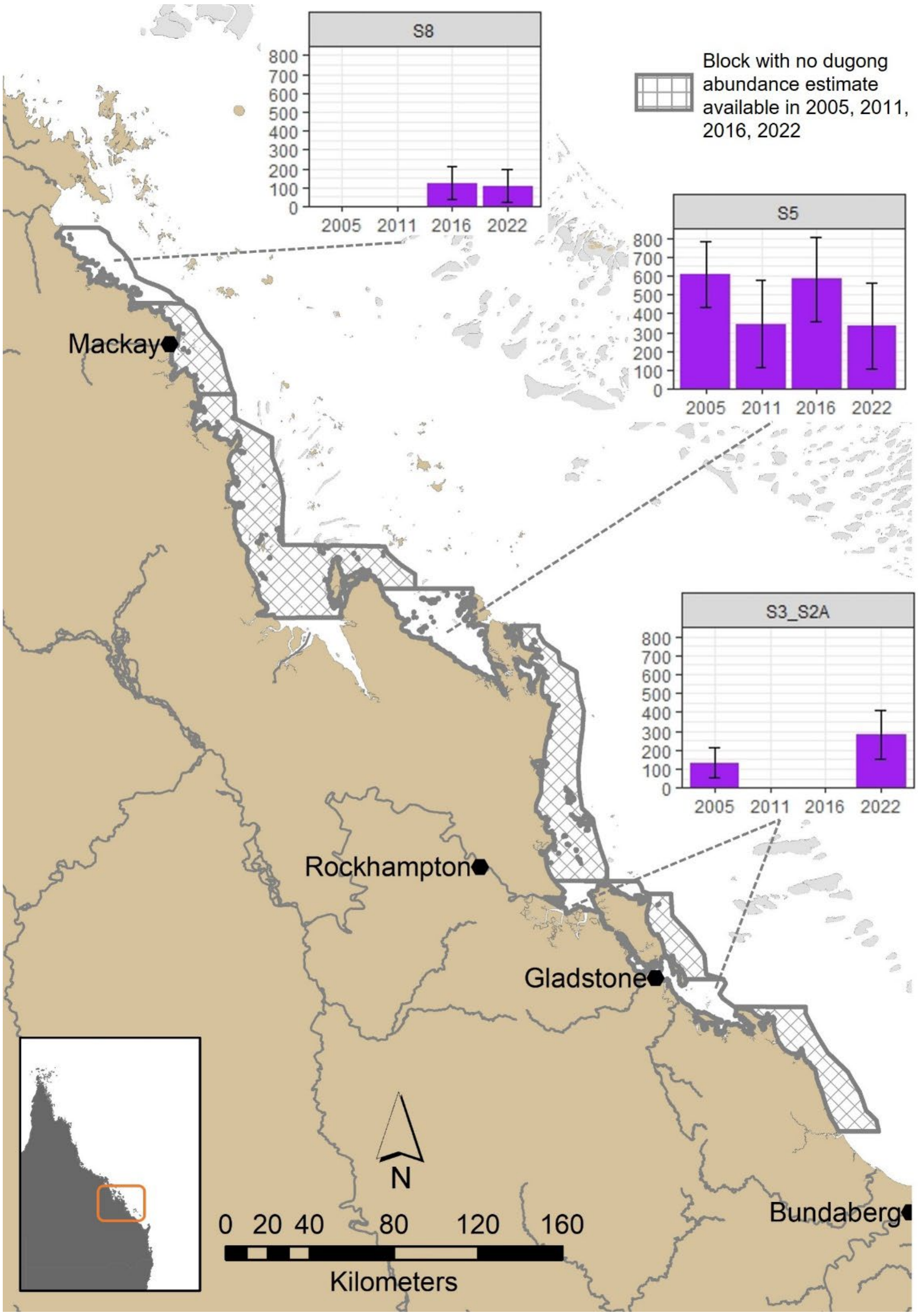


Figure 12. Estimated dugong abundance for the southern section of the Great Barrier Reef region between 2005 and 2022. Y axes show the estimated dugong population size for the block. Whiskers represent standard error. For some year estimates are not available because the survey used a different design (dd) or there were too few sightings (tfs) to estimate population size. Survey blocks for which no estimates are available across all survey years are hashed and details of the reasons are in Appendix 10.

3.4.3 Dugong population density and trends

3.4.3.1 Bayesian analysis

The dugong population density in the urban coast of the GBR as of the 2022 survey was estimated to be 0.086 dugongs/km (±se 0.017) (Figure 13 and Appendix 11). The 2022 posterior dugong densities were 40% smaller than the estimated 2016 dugong densities. Nonetheless, the 95% CI for 2016 and 2022 strongly overlapped.

We estimated a 93.8% probability of decline between 2005 and 2022 for the dugong population in the urban coast of the GBR, with an estimate rate of decline of -2.3% per year (Appendix 12). There was only a 0% and 4% chance of the dugong densities recorded in 2022 being higher than those recorded in 2005 and 2016 respectively, whereas there was a 100% chance that the dugong densities in 2011 were lower than in 2022 (Appendix 13). These figures indicate that the estimates of overall decline are confounded by temporary emigration but that there is strong evidence of overall decline during the entire survey period.

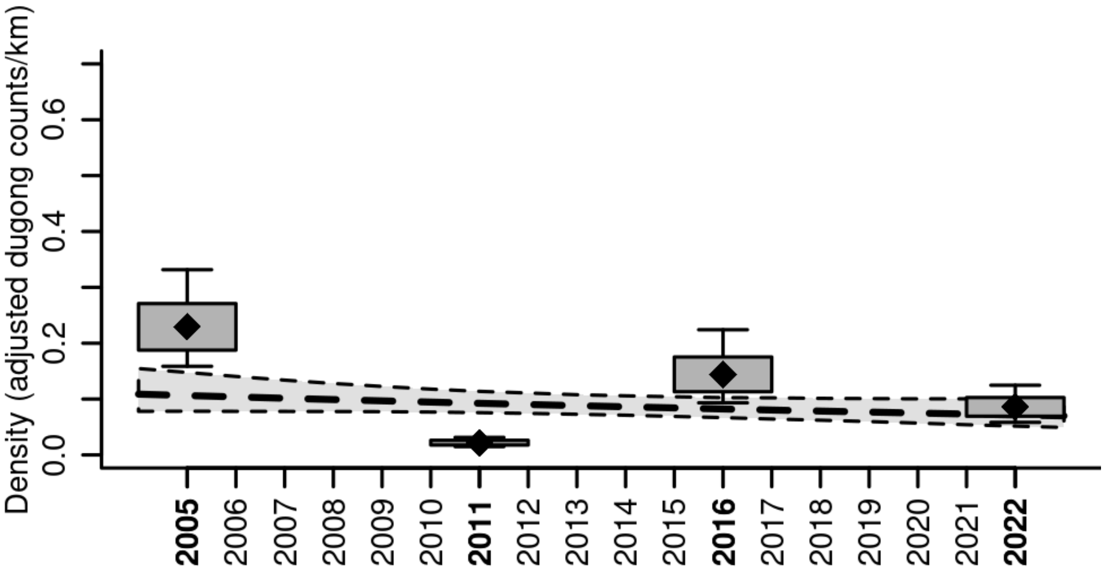


Figure 13. Mean dugong density estimates across the urban coast of the Great Barrier Reef, with ± 1 SE (boxes) and log-linear trend (dashed line). Whiskers represent ± 95% CI.

3.4.4 Dugong calf proportions

The mean estimated proportion of calves between 1974 and 1999 has fluctuated since aerial surveys commenced in 1974. It increased from 4.2% (95% CI 3.0% - 5.3%) in 1974 to 12.6% (95% CI 10.1% - 15.0%) in the early 2000s, followed by a mean estimated decrease in calf proportions until 2022 where was 6.7% (95% CI 4.0% - 9.4%). Very few calves were sighted in the southern section of the GBR in 2022, with only two mother-calf pairs spotted in the Gladstone area (Figure 14). All other calves (n=13, 86.6%) were sighted in the central section of the GBR.

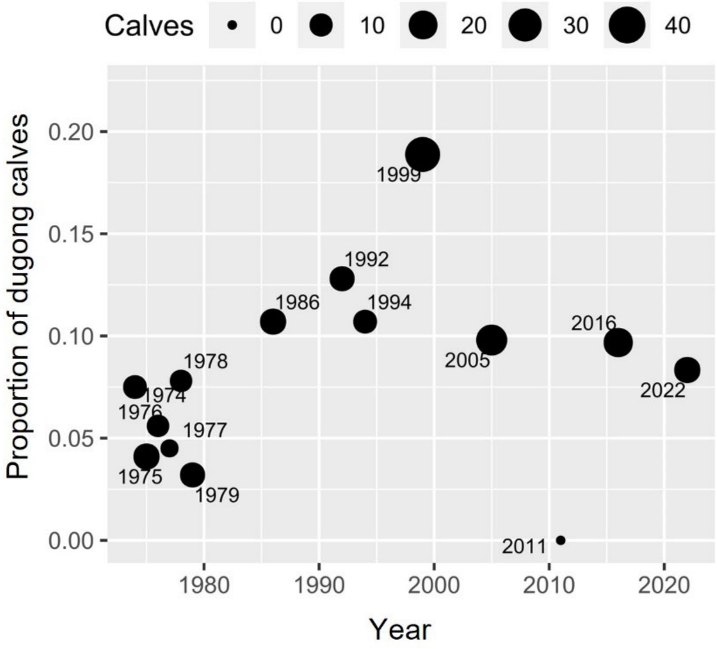


Figure 14. Proportion of calves plotted against survey year in the urban coast of the Great Barrier Reef. The proportion of calves is an index of the health of a dugong population and fluctuates with the status of their seagrass food.

3.4.5 DUGONG DENSITY DISTRIBUTION

The spatially explicit model of dugong distribution and density in the urban coast of the GBR in 2022 reflects the results described in Section 3.4.2, which shows, despite slight inter-survey year variations, areas of consistently high dugong densities such as the Hinchinbrook, Cleveland-Bowling Green Bays around Townsville and Shoalwater Bay (Figures 15 and 16). The decrease in the overall dugong density in the Shoalwater Bay area resulted from a reduced number of dugongs detected at the bottom of the bay and its inshore eastern side (Figure 16). The model also demonstrates the increased dugong density in some areas such as in the Gladstone region where dugongs were spotted in relatively high numbers immediately near the Gladstone Port's mainland facilities and on the Pelican banks. Latitudinal (north-south) and longitudinal (~Inshore-offshore) variations in dugong density hotspots can also be picked up in the model. For example, dugongs detected in the Bowen region in 2022 were spotted inshore, compared to predominant offshore sightings in 2016.

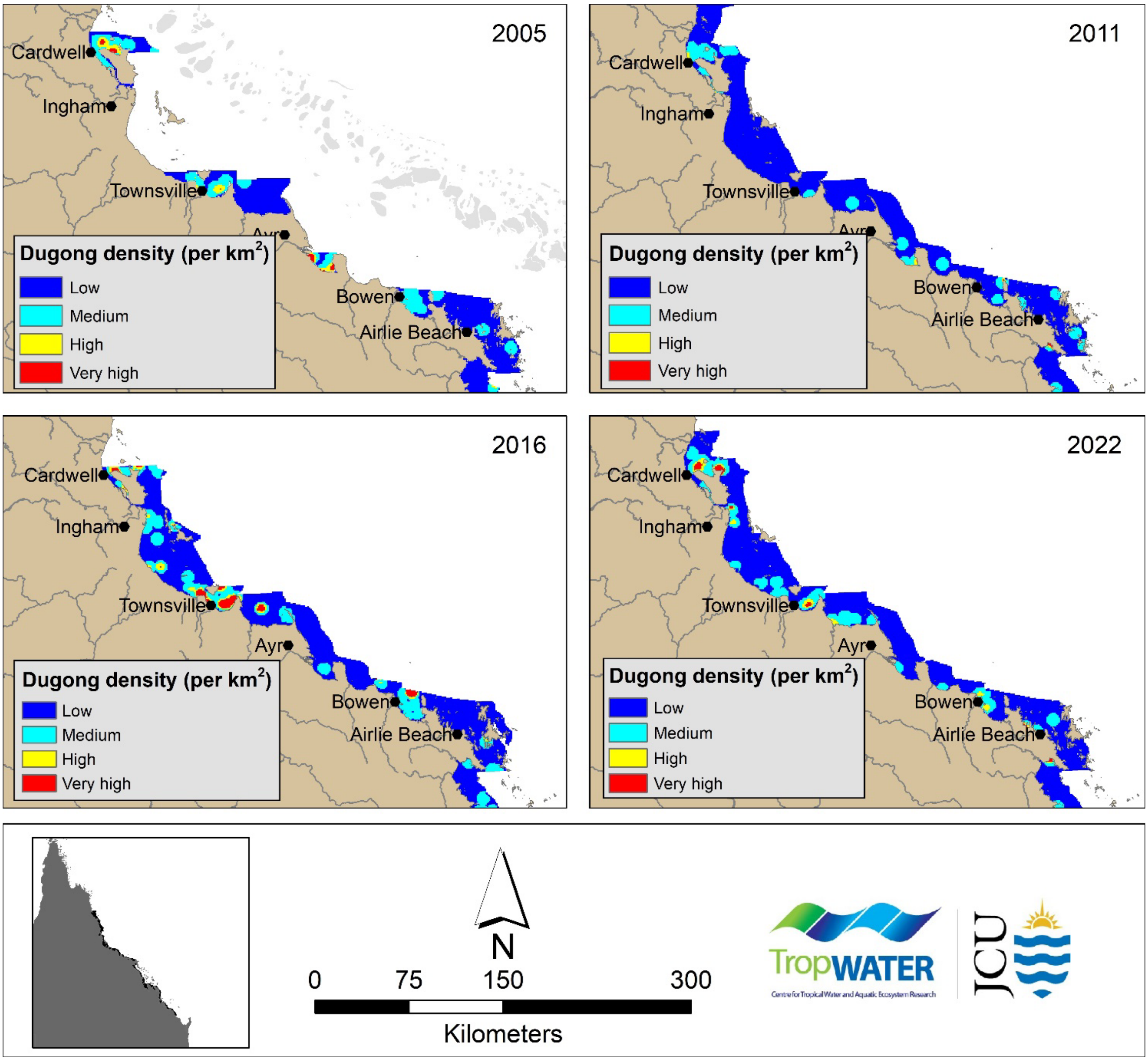


Figure 15. Spatially explicit models of dugong density in the central section of the Great Barrier Reef using data from aerial surveys conducted in 2005, 2011, 2016, and 2022. Dugong density estimations were based on the Hagihara method. Dugong densities were classified as Low (0 dugongs per km^2); Medium (0-0.5 dugongs per km^2); High (0.5-1 dugongs per km^2), and very high (>1 dugongs per km^2). Stretched models (non-classified dugong densities) are available in Appendix 15.

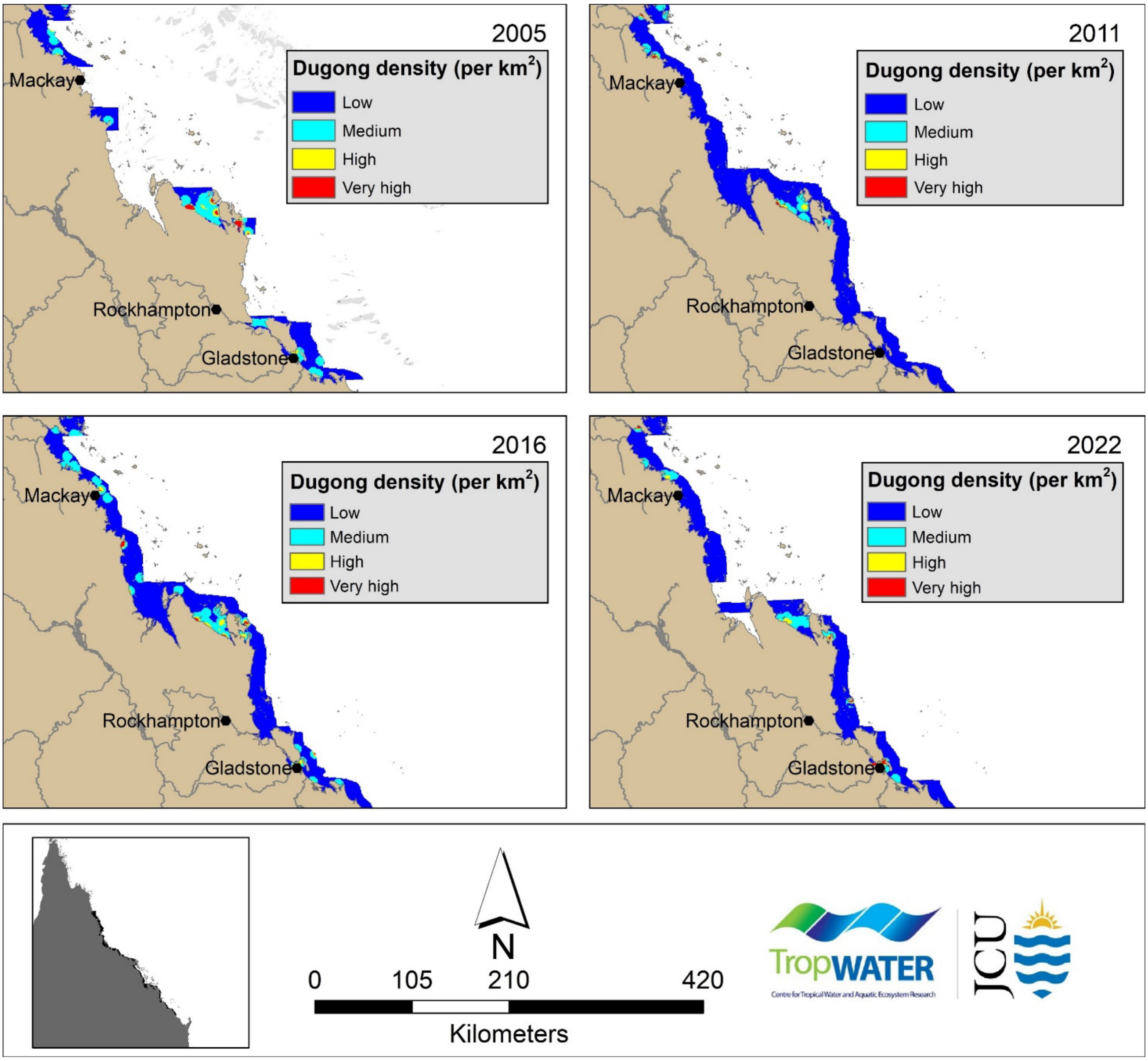


Figure 16. Spatially explicit models of dugong density in the central section of the Great Barrier Reef using data from aerial surveys conducted in 2005, 2011, 2016, and 2022. Dugong density estimations were based on the Hagihara method. Dugong densities were classified as Low (0 dugongs per km2); Medium (0-0.5 dugongs per km2); High (0.5-1 dugongs per km2), and very high (>1 dugongs per km2). Stretched models (non-classified dugong densities) are available in Appendix 15.

3.5 HERVEY BAY

3.5.1 DUGONG SIGHTINGS

A total of 103 dugongs were sighted during the survey of Hervey Bay in 2022. This represents the lowest number of dugongs detected across all survey years considered in this report (Figure 17 and Appendix 6), but is higher than the numbers detected in 1993 (Preen and Marsh 1995). Although a high concentration of dugongs was spotted in the middle of the Bay, the animals were scattered across the area and no herds were recorded. As in previous survey years, dugongs were mostly spotted as single individuals (mode = 1, mean group size = 1.5, range = 1-8, Appendix 6).

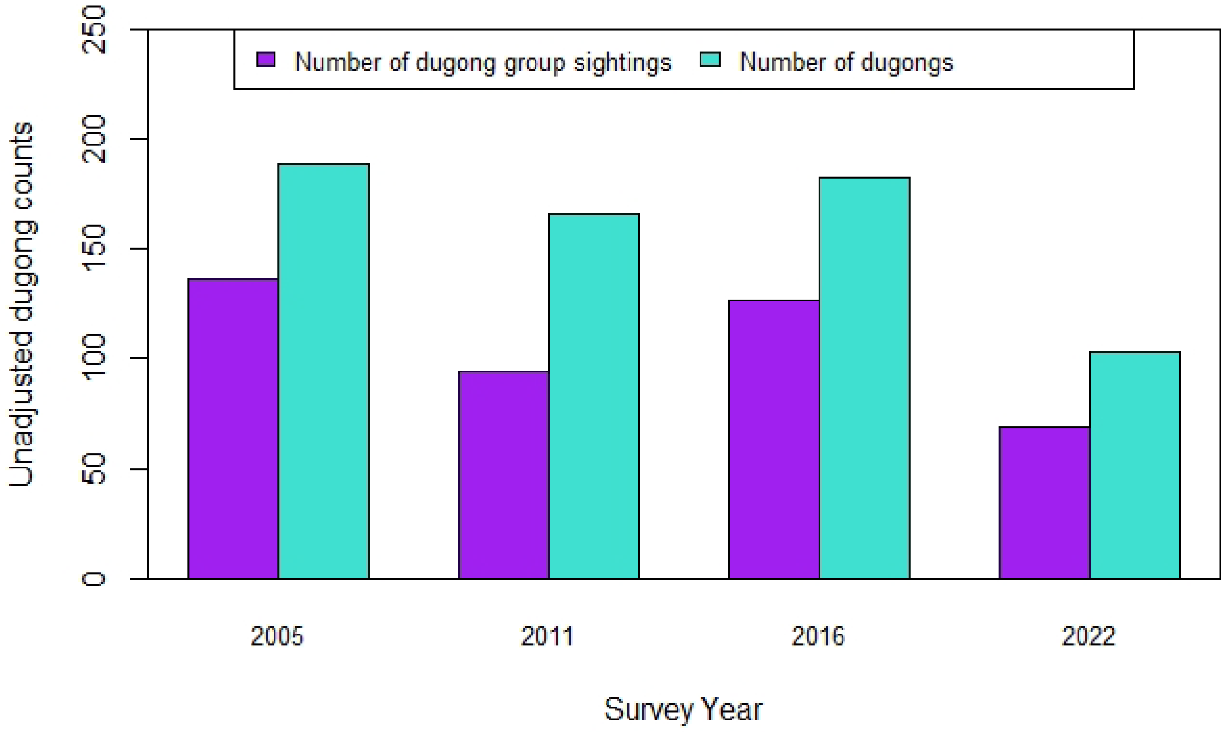


Figure 17. Raw counts of dugong group sightings and individual animals recorded during the 2005, 2011, 2016 and 2022 aerial surveys in Hervey Bay.

3.5.2 DUGONG POPULATION SIZE ESTIMATES

In 2022, the dugong population size in Hervey Bay was estimated to be 1533 ±se 634 animals using the Hagihara method. This estimate is equivalent to the population size estimates from the 2005 (1388 ±se 323) and 2011 surveys (1438 ±se 438) (Figure 18). Nonetheless, the 2022 estimates represent a 1.3-fold decline in the estimated number of dugongs since the last survey conducted in 2016. Changes in dugong distribution in Hervey Bay (see section 3.5.5) influenced the estimates of dugong abundance across the area; for the first time in recent surveys, we did not detect any dugongs in the Great Sandy Strait (block HB1) and thus no population size estimate could be generated for this block (Figures 19 and 20). Similarly, there was a 3.7-fold decrease in the estimated number of dugongs present in the southern section of Hervey Bay (block HB2) since the 2016 survey. Contrastingly, there was a near two-fold increase in the estimated number of dugongs in the middle, deeper part of the bay (block 4) from an estimated 610 (±se 272) to 1025 (±se 592) dugongs.

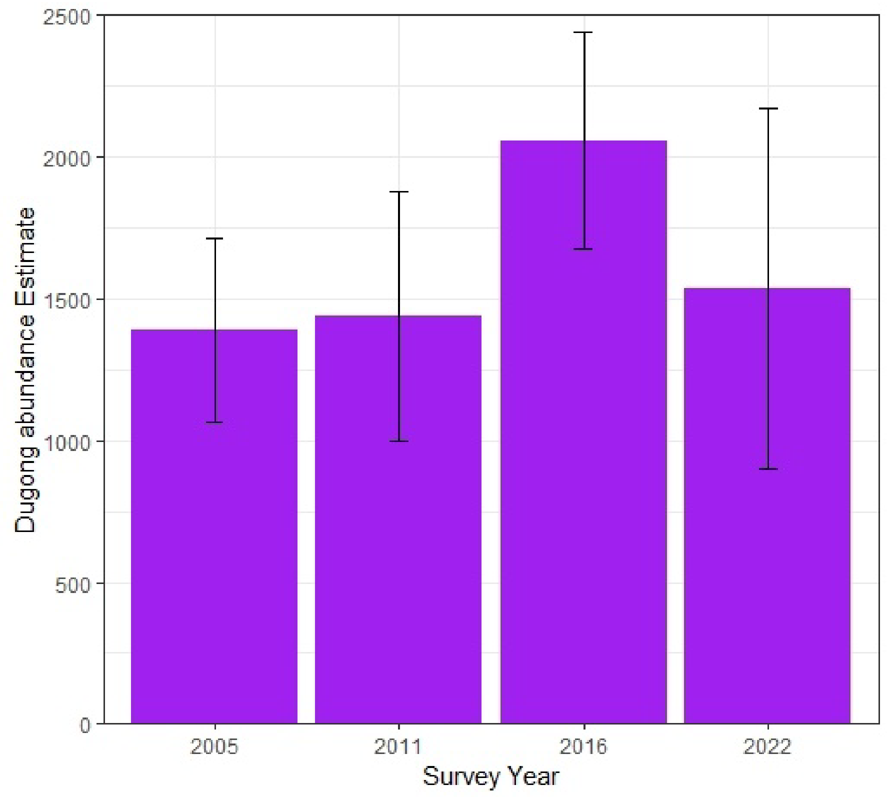


Figure 18. Dugong population size estimates ±se using the Hagihara method in 2005, 2011, 2016 and 2022 in Hervey Bay. Whiskers represent Standard error values around the estimate.

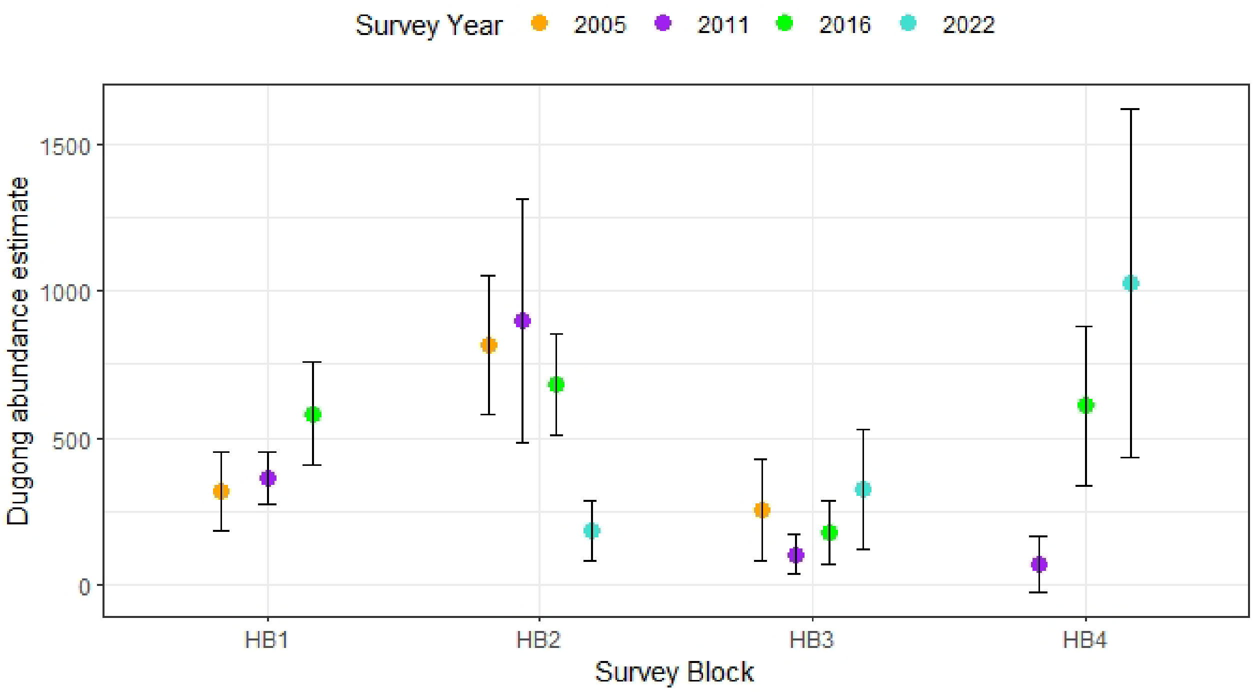


Figure 19. Dugong population size estimates (dots) ±se (whiskers) per block using the Hagihara method in 2005, 2011, 2016 and 2022 in Hervey Bay. blocks for which not estimate could be generated were removed from the figure (details of blocks with or without dugong abundance estimates are presented in Appendix 10). A geographically-explicit map dugong abundance per block is at Figure 20.

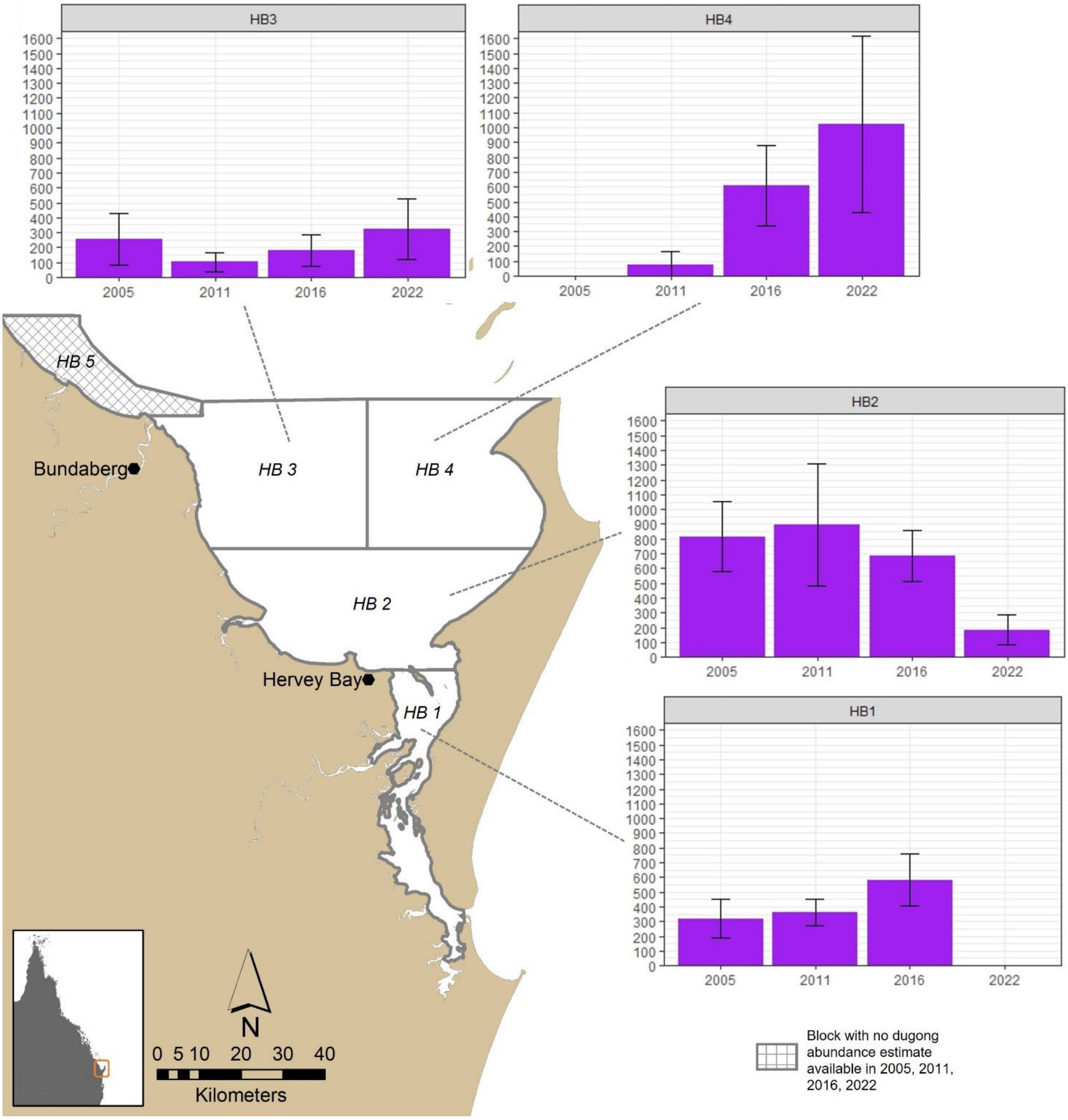


Figure 20. Estimated dugong abundance in Hervey Bay between 2005 and 2022. Y axes show the estimated dugong population size for the block. Whiskers represent standard error. For some year estimates are not available because the survey used a different design (dd) or there were too few sightings (tfs) to estimate population size. survey blocks for which no estimates are available across all survey years are hashed and details of the reasons are in Appendix 10.

3.5.3 DUGONG POPULATION DENSITY AND TRENDS

3.5.3.1 BAYESIAN ANALYSIS

In 2022, the Hervey Bay dugong population density was estimated to be 0.094 dugongs/km (±se 0.030) (Figure 21 and Appendix 11). This represents a 69.7% decrease in dugong density compared to the 2016 survey.

We estimated that the dugong population in Hervey Bay had a very strong probability of following a decline (probability = 0.995, Appendix 12). The 95% credibility interval excluded the zero trendline, suggesting strong confidence in the decline being real. This rate of decline was estimated to be -5.7% per year (Appendix 10). One note of caution is that the 2022 survey data has a strong influence on our trend estimate: without which the estimated trend would be neutral (Rankin and Marsh unpublished 2019). The probability that the 2022 dugong densities were greater than previous survey years was very low (0.2%, 2.2% and 0.2% chances that the dugong density from 2022 was greater than the survey years 2005, 2011, and 2016 respectively, Appendix 13).

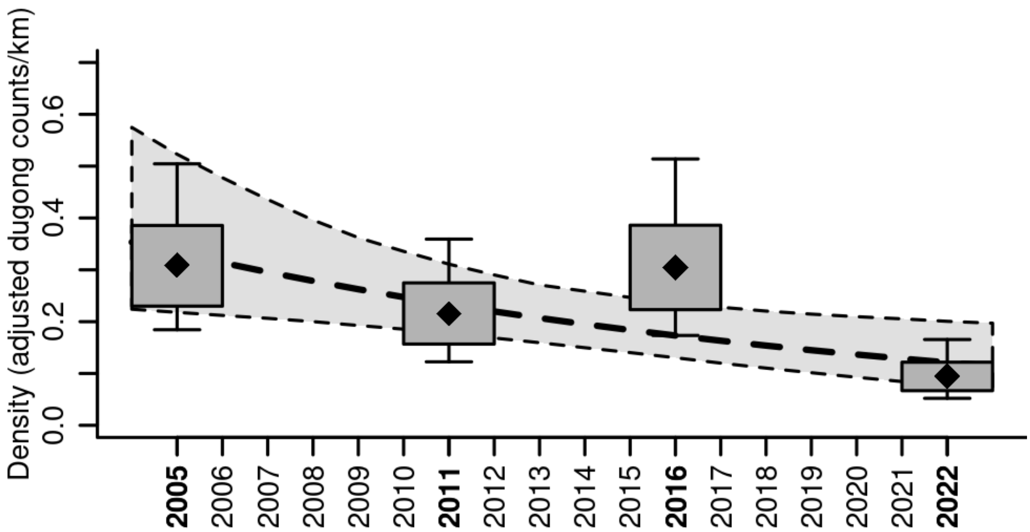


Figure 21. Mean dugong density estimates in Hervey Bay, with ± 1 SE (boxes) and log-linear trend (dashed line). Whiskers represent ± 95% CI.

3.5.4 DUGONG CALF PROPORTIONS

Nine mother-calf pairs were detected during the 2022 survey of Hervey Bay. This represents 9% of the total number of dugongs detected during this survey year within the range of the corresponding data from previous surveys (Figure 22).

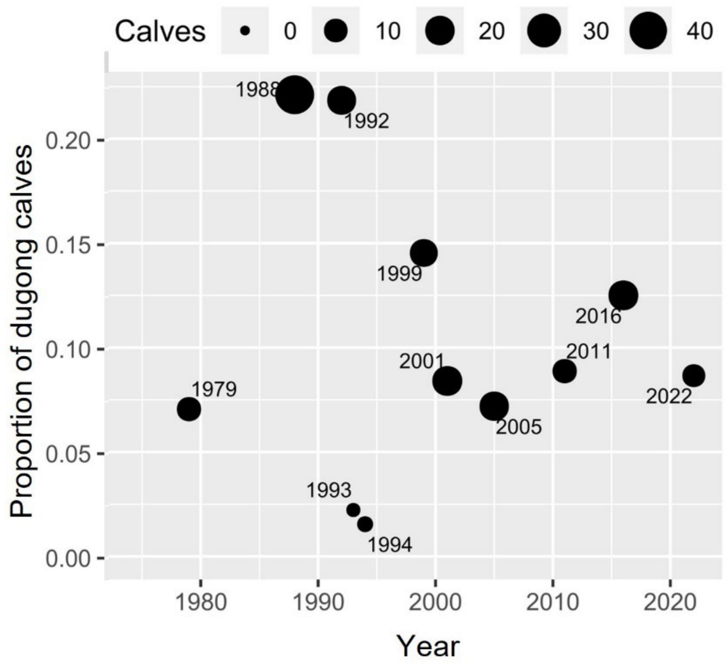


Figure 22. Proportion of calves plotted against survey year in Hervey Bay. The proportion of calves is an index of the health of a dugong population and fluctuates with the status of their seagrass food.

3.5.5 DUGONG DENSITY DISTRIBUTION

The time-series of spatially explicit models of dugong distribution and density helps to visualise the substantial changes in the use of Hervey Bay and the Great Sandy Strait in 2022 compared to previous surveys years (Figure 23). At the time of our survey in November 2022, dugongs were mostly concentrated in the middle, deeper part of the northern section of Hervey Bay. No animals were detected in the Great Sandy Strait region or the inshore habitats in Hervey Bay. The increase in dugong density in survey blocks HB3 and 4 described in Section 3.5.2 can clearly be seen in Figure 23. The distribution of dugongs in 2022 contrasts with that of previous years where dugongs were typically spread out across the bay and Great Sandy Strait[3].

[3] The distribution of dugongs and other species of marine megafauna across all surveyed areas are presented in Appendices 7 and 8. Records of sightings of marine megafauna species other than dugongs and sea turtles are presented in Appendix 9.

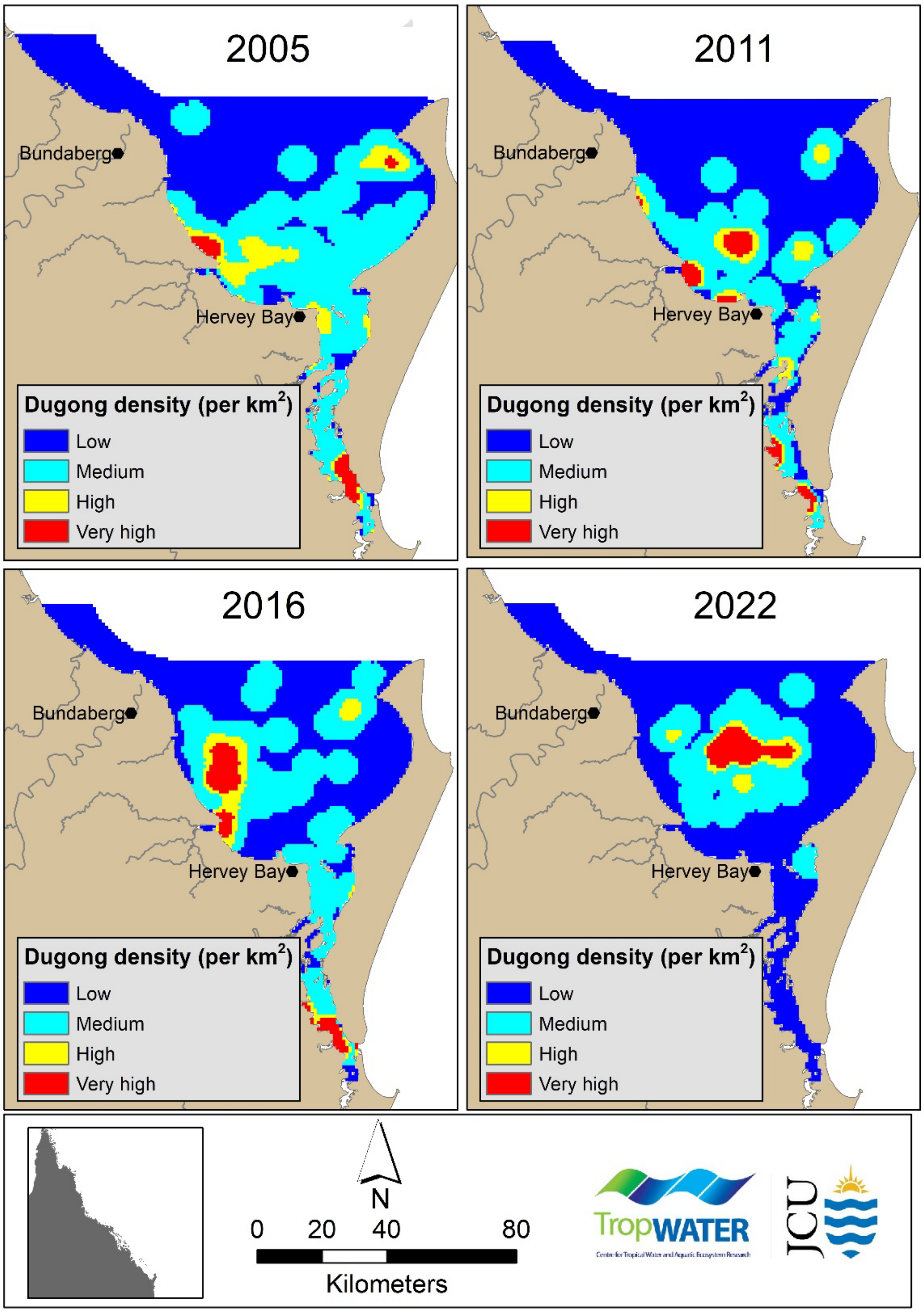


Figure 23. Spatially explicit models of dugong density in Hervey Bay using data from aerial surveys conducted in 2005, 2011, 2016, and 2022. Dugong density estimations were based on the Hagihara method. Dugong densities were classified as Low (0 dugongs per km2); Medium (0-0.5 dugongs per km2); High (0.5-1 dugongs per km2), and very high (>1 dugongs per km2). Stretched models (non-classified dugong densities) are available in Appendix 14.

3.6 MORETON BAY

3.6.1 DUGONG SIGHTINGS

During the 2022 aerial survey, a total of 159 dugongs were sighted in Moreton Bay including a herd of 51 animals (Figure 24 and Appendix 6). This represents the lowest number of dugongs detected across the survey years considered in this report. The single herd detected in our survey also contrasts with the multiple herd sightings made in previous survey years (5 herds of 177 animals in total were sighted in 2016, 3 herds of 391 animals in total in 2011, and 4 herds of 216 animas in total in 2005). As in previous survey years, dugongs were mostly spotted as single individuals (mode = 1, mean group size = 1.5, range = 1-10, Appendix 6).

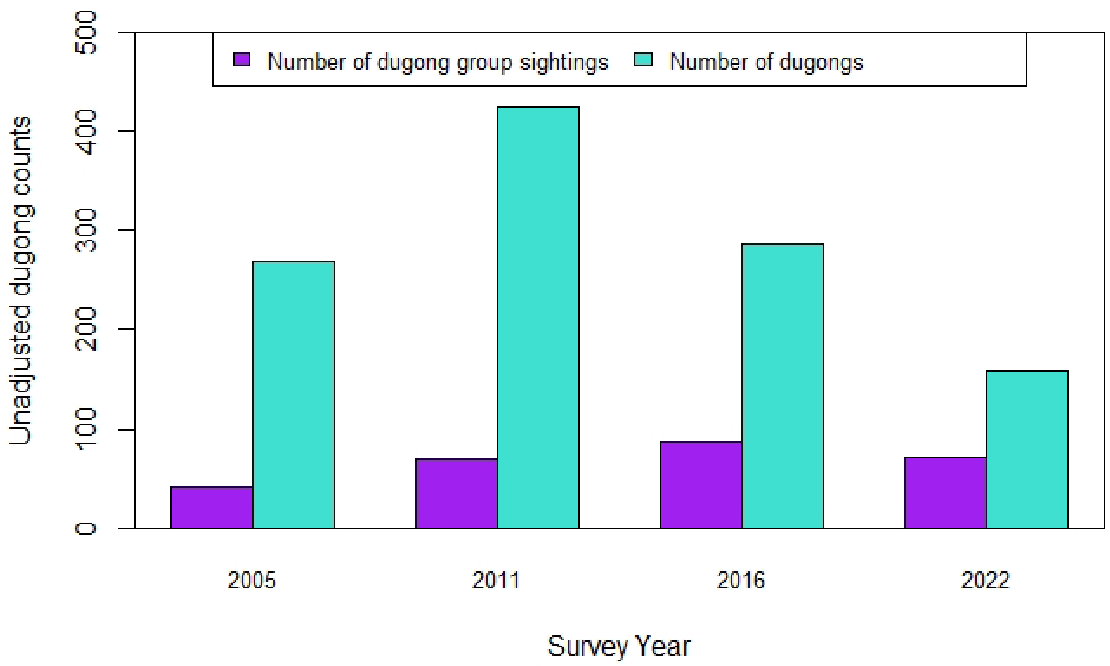


Figure 24. Raw counts of dugong group sightings and individual animals recorded during the 2005, 2011, 2016 and 2022 aerial surveys in Moreton Bay.

3.6.2 DUGONG POPULATION SIZE ESTIMATES

In 2022, the dugong population estimate for Moreton Bay was 400 (±se 116) using the Hagihara method (Figure 25 and Appendix 10). The estimated number of dugongs around the eastern banks (block 4) was similar in 2022 to previous survey years (Figure 26 and Appendix 10). However, there was a decrease in the number of dugong sightings in the southern section of the bay (block MB6) preventing the calculation of a meaningful abundance estimate for this area. In general, and consistent with previous survey assessments, block MB4 (Eastern Banks) had higher dugong densities than any other block in the Moreton Bay Region.

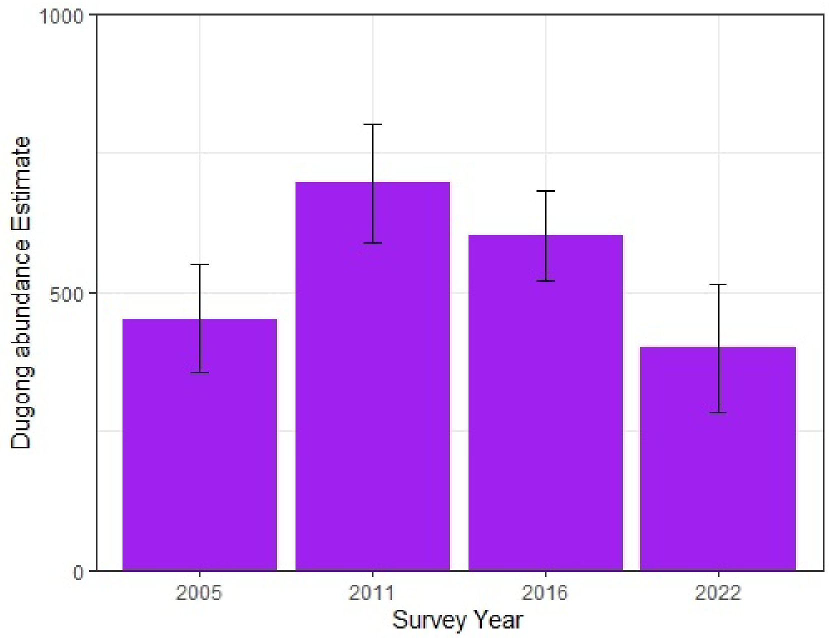


Figure 25. Dugong population size estimates ±se using the Hagihara method in 2005, 2011, 2016 and 2022 in Moreton Bay. Whiskers represent Standard error values around the estimate.

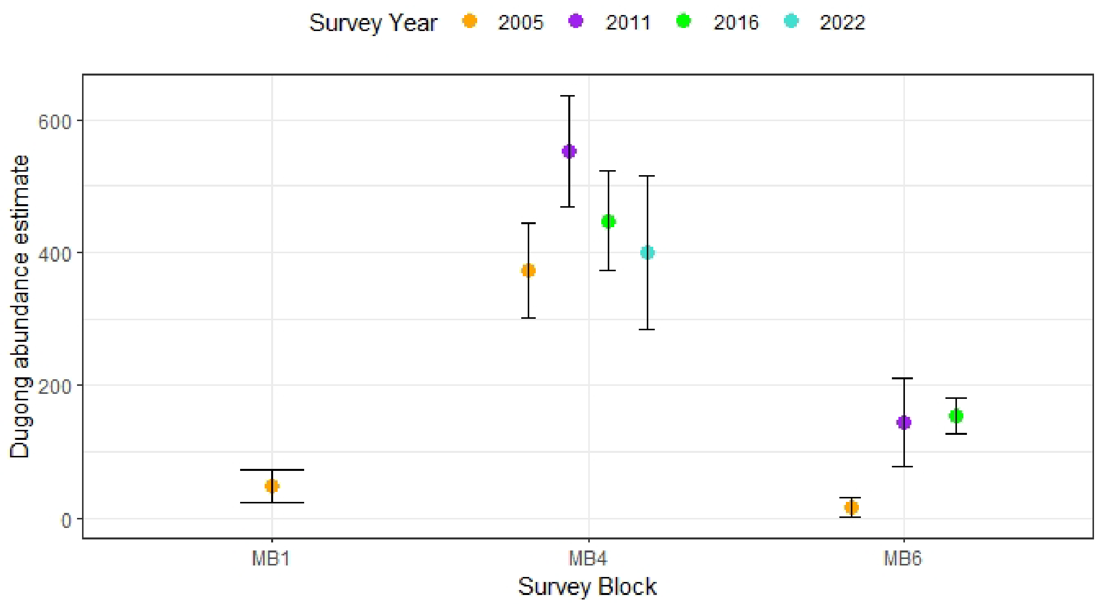


Figure 26. Dugong population size estimates (dots) ±se (whiskers) per block using the Hagihara method in 2005, 2011, 2016 and 2022 in Moreton Bay. blocks for which not estimate could be generated were removed from the figure (details of blocks with or without dugong abundance estimates are presented in Appendix 10). A geographically explicit map of dugong abundance per block is provided in Figure 27.

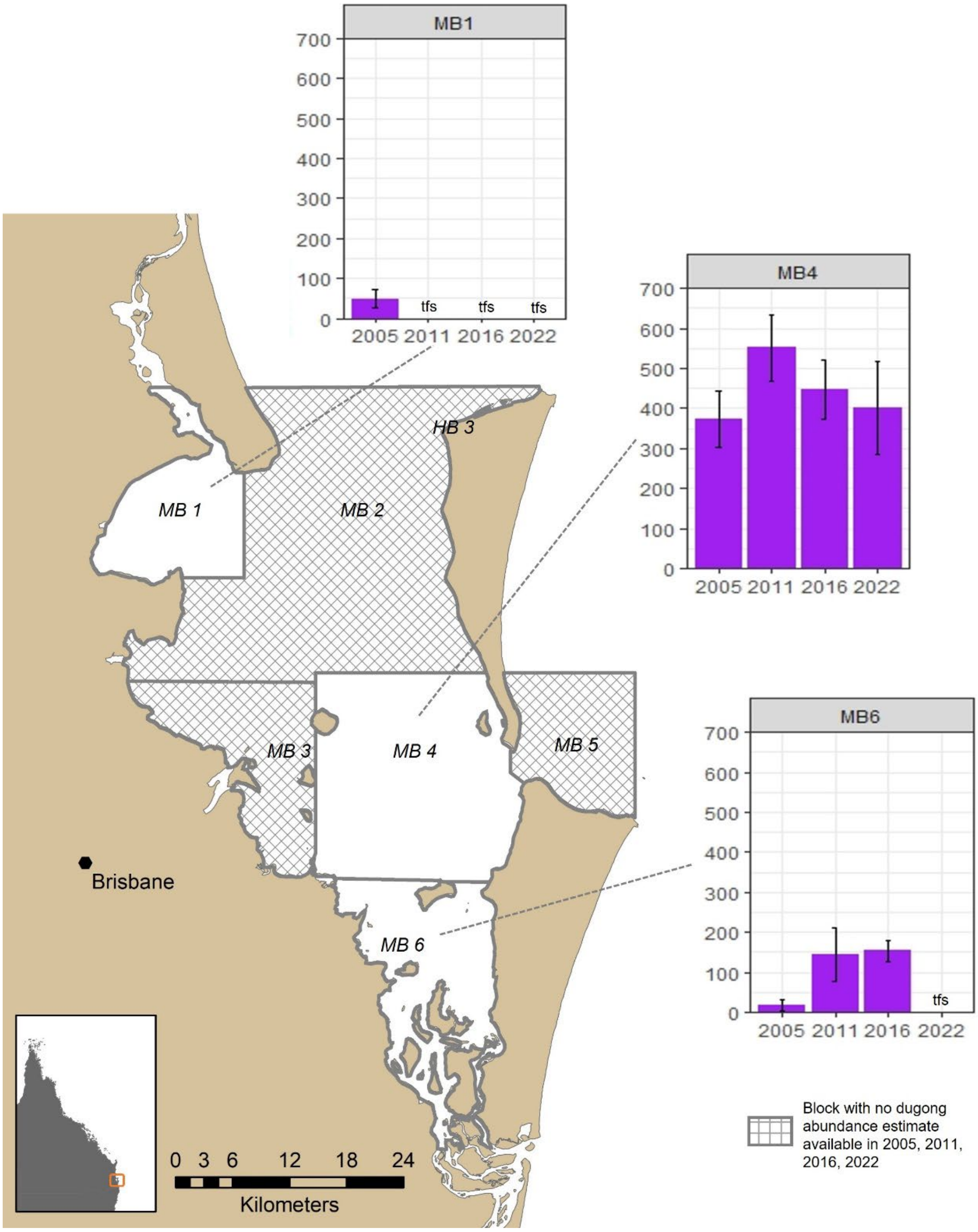


Figure 27. Estimated dugong abundance in Moreton Bay between 2005 and 2022. Y axes show the estimated dugong population size for the block. Whiskers represent standard error. For some year estimates are not available because the survey used a different design (dd) or there were too few sightings (tfs) to estimate population size. survey blocks for which no estimates are available across all survey years are hashed and details of the reasons detailed in Appendix 10.

3.6.3 Dugong population density and trends

3.6.3.1 Bayesian analysis

In 2022, the Moreton Bay dugong population density was estimated to be 0.274 dugongs/km (±se 0.030) (Figure 28 and Appendix 11). This represents a 30% decrease in dugong density compared to the 2016 survey.

Dugong density in Moreton Bay swoed a shallow downward trend since 2005, estimated to be -1.2% per year (Appendix 12). The probability of decline was only 0.720 suggesting only weak confidence in a decline, and that a zero-trend cannot be dismissed (Appendix 12). There was a 31% probability that the dugong densities estimated for Moreton Bay in 2022 were greater than the densities of 2005. This probability decreased in subsequent years (8.4%, 16.2% chances of the dugong density from 2022 being greater than survey years 2011, 2016 respectively, Appendix 13).

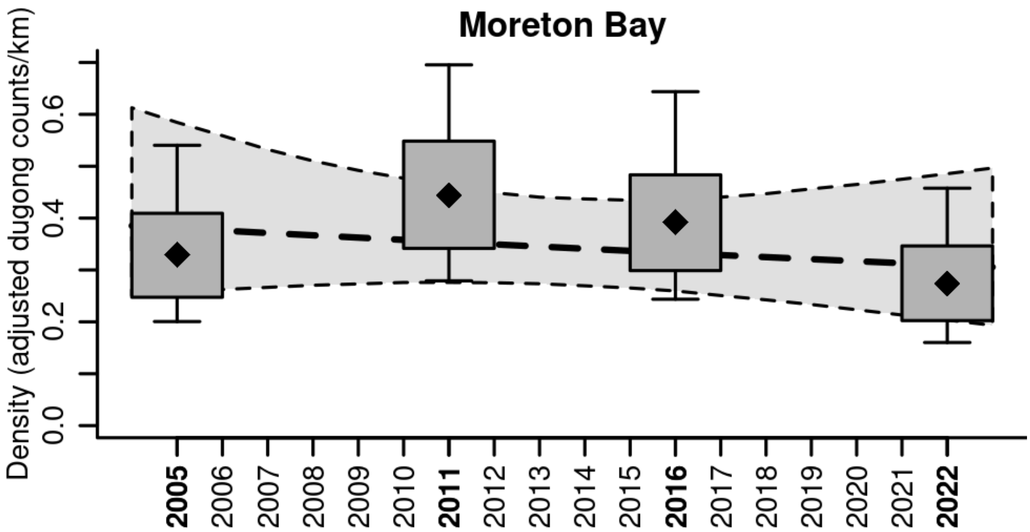


Figure 28. Mean dugong density estimates in Moreton Bay, with ± 1 SE (boxes) and log-linear trend (dashed line). Whiskers represent ± 95% CI.

3.6.4 DUGONG CALF PROPORTIONS

Six mother-calf pairs were detected during the 2022 survey of Moreton Bay. This represents 5.5% of the total number of dugongs detected during this survey year, the lowest proportion recorded since 2005.

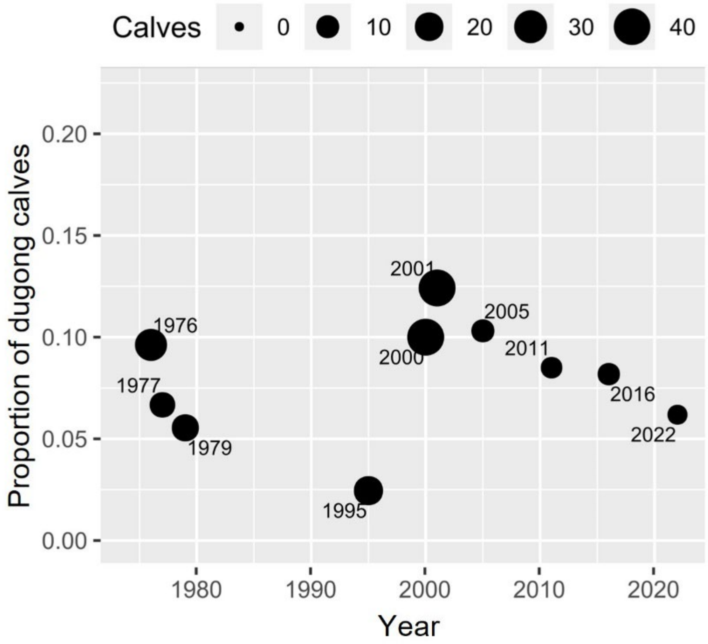


Figure 29. Proportion of calves plotted against survey year in Moreton Bay. Each line represents the proportion of calves predicted by the logistic regression and the 95% CI is represented by the grey-shaded area.

3.6.5 DUGONG DENSITY DISTRIBUTION

The spatially explicit model of dugong distribution produced from the 2022 survey confirms the spatial distribution recorded in previous survey years with consistently very high dugong densities located over the eastern banks (Figure 30). There was a reduced use by the dugongs of the northern Moreton Banks (inshore western side of Moreton Island) and of the southern section of the bay between Peel Island and the Southern Moreton Bay islands compared with previous survey years considered in this report[4].

[4] The distribution of dugongs and other species of marine megafauna across all surveyed areas are presented in Appendix 7 and 8.

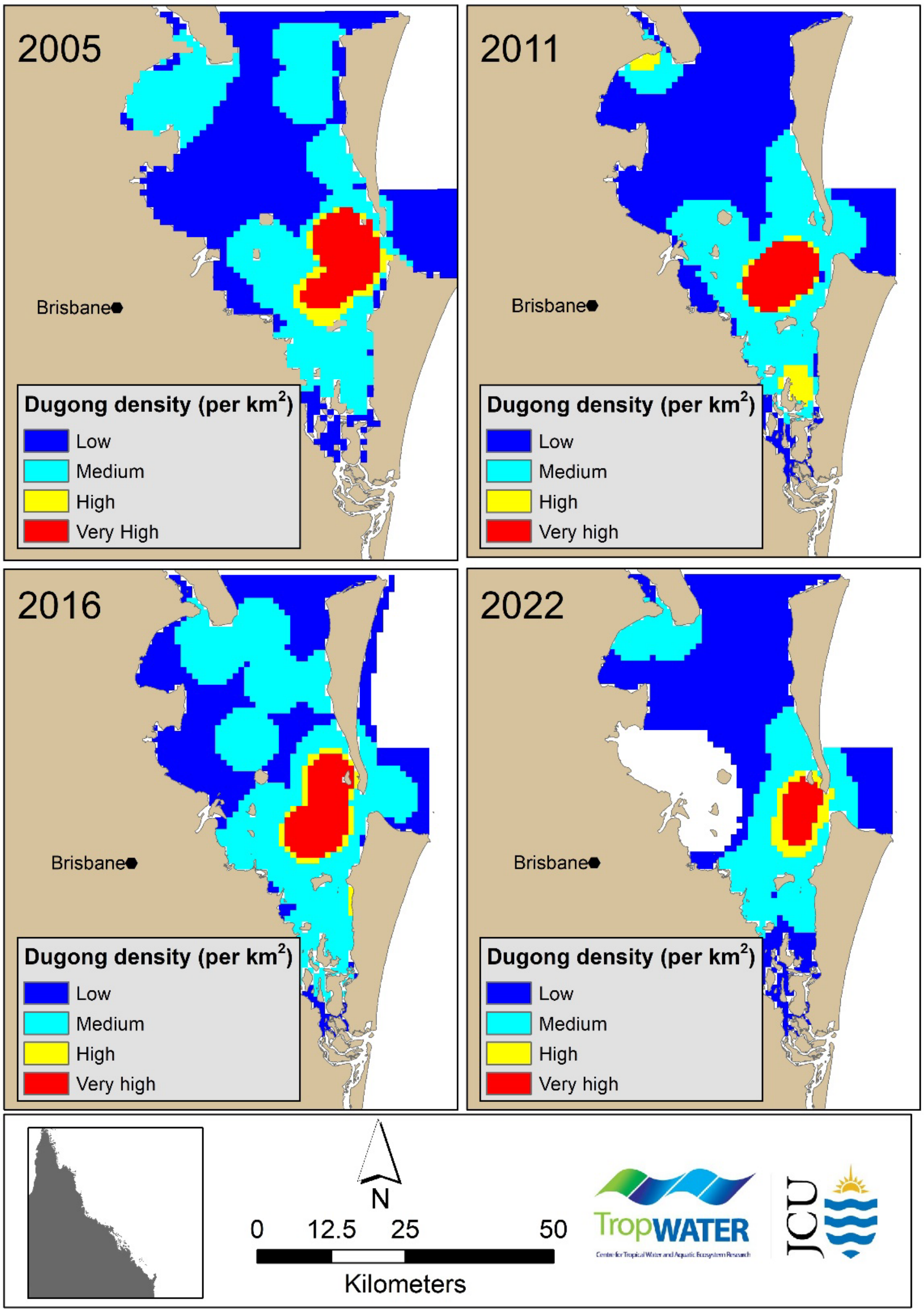
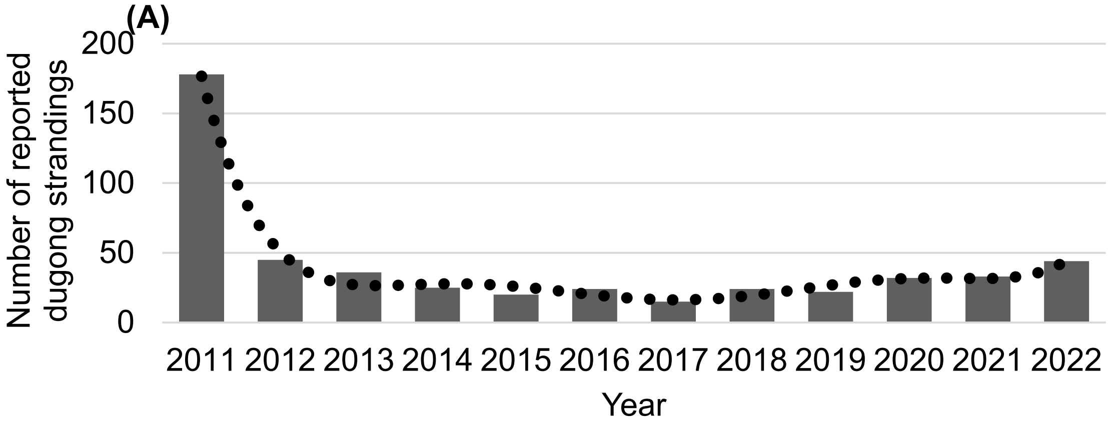


Figure 30. Spatially explicit models of dugong density in Moreton Bay using data from aerial surveys conducted in 2005, 2011, 2016, and 2022. Dugong density estimations were based on the Hagihara method. Dugong densities were classified as Low (0 dugongs per km2); Medium (0-0.5 dugongs per km2); High (0.5-1 dugongs per km2), and very high (>1 dugongs per km2). The area in the vicinity of the city of Brisbane could not be surveyed in 2022 so the model did not cover this area. Stretched models (non-classified dugong densities) are available in Appendix 15.

3.7 REPORTED DUGONG STRANDINGS ACROSS THE SURVEYED AREA

We extracted data on the number of dugong reported to the Queensland marine wildlife stranding program StrandNet during the period 2011-2022 (https://www.qld.gov.au/environment/plants-animals/wildlife/marine-strandings/stranding-data).

Overall, the number of reported dugong strandings across the urban coast of the GBR and Hervey Bay and Moreton Bay regions in 2022 (n = 44) was equivalent to 2012 and these years yielded the second highest dugong stranding records since 2011 (n = 178 dugong strandings for that year; Figure 31). Dugong stranding records reached a minimum in 2017 (n = 17 dugong strandings) but have continued to increase since then. Despite the unusually high records of dugong strandings in the Townsville region in 2011 (year of cyclone Yasi), Hervey Bay has the highest proportion of dugong strandings (23.7%) across all regions since 2011 followed by Moreton Bay (23.5%) and Townsville (22.0%). Hervey Bay is also where the most dugong strandings were recorded in 2022. Dugong stranding records are also tabulated in Appendix 16.



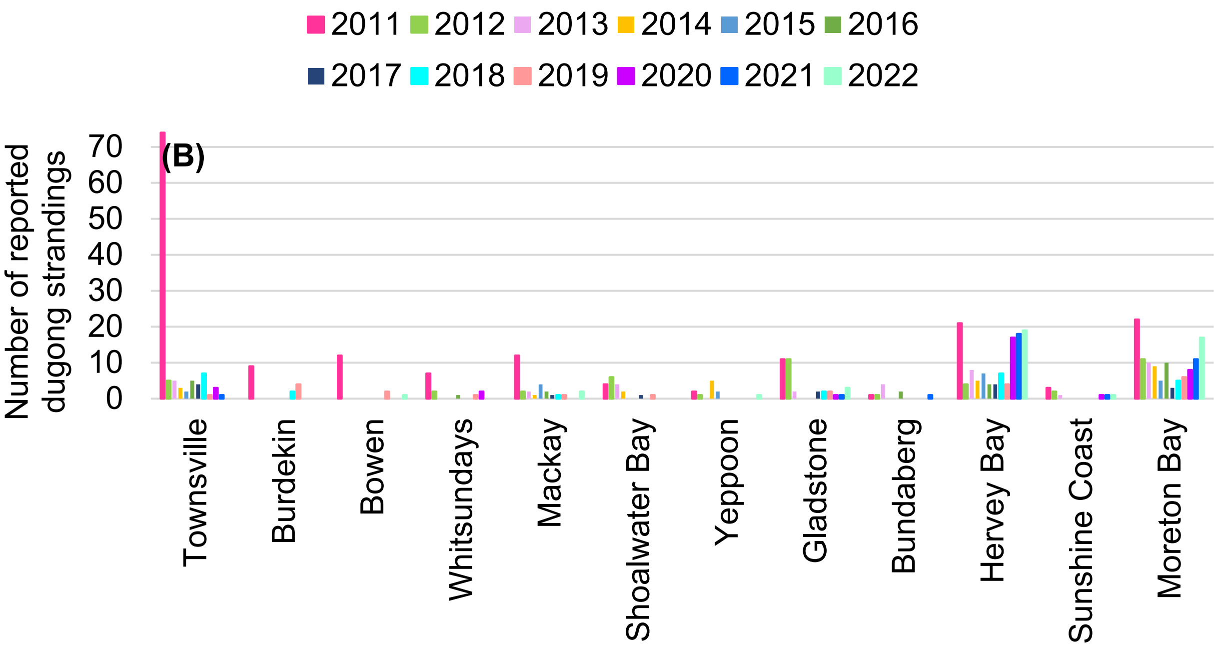


Figure 31. Cumulative number of dugong stranding records per year between 2011 and 2022 (A) and temporal variations in the number of records per region in the urban coast of the Great Barrier Reef, Hervey Bay, and Moreton Bay. The dotted line in (A) is a Polynomial trend line with 6 orders.

3.8 INDIGENOUS ENGAGEMENT PROCESS

With a project start officialised a month before the start of the survey our capacity to engage with Traditional Owners across the entire Eastern coast of Queensland was limited. Despite that, the following engagement activities were conducted prior to and during the survey (more details are provided in Table 3):

- Project webinar: the project lead invited all listed Traditional Owner groups to a webinar during which the history, objectives, methodological approach, and opportunities for involvement were addressed.
- A project flyer was sent out to all Traditional Owner groups to raise awareness around the dugong survey project and inform people of the timing of the survey.
- A project website was developed and blogs were posted during the survey and relayed via Twitter.

Through our engagement it appeared clear that while First Nations People approved of our survey approach and showed genuine interest in hearing about the outcome of the surveys, most groups were interested to discuss future opportunities to be trained to conduct dugong surveys at geographical scales that are more culturally significant to the groups, i.e., local scales within sea countries. Traditional Owners and rangers were also interested to be upskilled to conduct these local surveys themselves. Opportunities for such training are discussed in section 4.3.2.

Table 3. Details of the engagement process prior and during the survey of the urban coast of the Great Barrier Reef, Hervey Bay, and Moreton Bay.

Traditional Owner group	Location	Date and nature of involvement	No. of TOs participating	No of TOs funded/employed
Online meetings				
All accredited & under development TUMRA groups; NTRBs; RNTBCs, Sea country Values Mapping groups; Indigenous corporations and ranger groups from Hervey and Moreton Bay, research partners (H. Marsh, R. Groom), stakeholders (GBRF, DCCEEW, GBRMPA)	Online (Zoom)	7 Oct 2022	- Clayton Enoch (Wuthati aboriginal corporation) - Michael Winer (Cape York Partnership, Starky) - Matt Gillis (Girringun Aboriginal Corporation) - John Wilson (Gunggandji Mandingalbay Yidinji Peoples Aboriginal Corporation)	na
Yintjingga Aboriginal Corporation | Lama Land Trust	TUMRA meeting (guest speaker) - Online (TEAMS)	20 October 2022	- Cheryl Prestipino and Alison Liddy (meeting coordinators) - Lama Lama TOs and L&S rangers	>20

Drop-in sessions				
Yuwi Aboriginal Corporation	Drop-in, YAC office, Mackay	15 Nov 2022	Irene Adams	2
QPWS (DES-QLD) – visit funded by DCCEEW	Drop-in, QPWS Hervey Bay office	25 Nov 2022	Renee Burgess	2
Phone conversations				
Gidarjil Development Corporation	Phone call	18 Oct 2022	Angela Huston	1
Gunggandji-Mandingalbay Yidinji Peoples Prescribed Body Corporate Aboriginal Corporation	Phone call	7 Nov 2022	Helen Tait	1
Butchulla Aboriginal Corporation	Phone call	25 Nov 2022	Veronica Bird	1

4 DISCUSSION

4.1 STATUS OF DUGONGS IN THE SURVEY AREA

Population trends

From 2005 to 2022, dugong populations of Hervey Bay, Moreton Bay, and the urban coast of the Great Barrier Reef show evidence of large-to-moderate population declines. While there is large inter-annual variation and uncertainty with the statistical outputs, the overall results are of great concern.

<u>Urban coast of the Great Barrier Reef</u>

The urban coast of the GBR had the lowest dugong population density of all surveyed regions, as well as very high inter-survey density variation. Results from the 2022 survey increased the longevity of the trend of long-term decline in the dugong population off the urban coast. The estimated decline was approximately -2.3% per year between 2005 and 2023 compared with -4% per year from 2005 to 2016. The probability of long-term decline of the dugong population continued to be very high (0.97 based on survey data from 2005 to 2016 and 0.94 from 2005 to 2022). The dugong density in 2005 was 2.3 times larger than our 2022 estimated population density. The dugong density in 2011, after the floods and cyclones of the summer of 2010-2011 (Sobtzick et al. 2012), was much lower than the 2022 population density but recovered by 2016. In section 4.2 we discuss how some of this uncertainty could be explained by emigration of dugongs between survey regions after extreme weather events.

In 2022, the relative abundance estimates for dugongs across the urban coast of the GBR between Mission Beach and Bundaberg, using the Hagihara method, were 2124 ±se 476 dugongs. The decrease in the dugong population size estimates for this region compared to 2016 can be mostly attributed by a reduction in the estimated number of dugongs found in Townsville-Cleveland Bay (Block C8) where there were an estimated 1,171 ±se 423 dugongs in 2016 compared to 228 ±se 135 animals in 2022. Estimates of dugong numbers have increased in the Bowling Green Bay area, located immediately south of Cleveland Bay, and Hinchinbrook to the north, suggesting that movements of dugongs between these areas occur and may have influenced our results. Past satellite tracking studies have shown movements of dugongs across these areas (Marsh and Rathbun, 1990, Preen, 2000).

Other notable decreases in the estimated numbers of dugongs across the urban coast of the GBR were in Blocks C4 (Edgecumbe Bay) and S5 (Shoalwater Bay). Variations in dugong densities across survey blocks is a common observation in the time series of aerial surveys and have mostly been attributed to temporary migration into and out of survey areas (e.g., Marsh et al. 2020; Sobtzick et al. 2017).

Of concern is the apparent overall decline in the numbers and densities of dugongs in the southern section of the GBR (S blocks) except for the Gladstone region. Gladstone is also the only area in the sGBR where calves were sighted, with the remaining sightings (86.6%) located in the central section of the GBR. The southern section of the GBR is in the Fitzroy and Burnett-Mary catchments where, seagrasses remain in poor and declining condition (McKenzie et al. 2023). The deterioration of seagrass health in these regions can be attributed to either recent extreme events, such as cyclones, or localized disturbances. The most important effects of climate change on dugongs are likely to be from changes to their seagrass habitats as detailed in Marsh et al. (2022) and Marsh and Cleguer (2023). These changes will exacerbate the ongoing loss of seagrass caused by anthropogenic pressures in the coastal zone (Waycott et al. 2009). Based on their findings, McKenzie et al. (2023) suggested that seagrass ecosystems in the Fitzroy and Burnett–Mary regions could be increasingly susceptible to future adverse or severe disturbances. Such a trend could have severe long-term repercussions on resident megaherbivore populations including dugongs.

The results shown in this report add to the body of evidence from past aerial surveys (e.g., Preen, 1995) and satellite tracking work (Sheppard et al. 2006) that dugongs move between Hervey Bay and the GBR (this is further discussed below). The baseline frequency and extent of these movements are unknown, but our report shows that when habitats are degraded in Hervey Bay dugongs move to and rely on seagrass habitats within the southern section of the GBR. Continuing decline in the extent and condition of seagrasses in the southern GBR could thus have important implications on dugong population connectivity and recovery.

<u>Hervey Bay</u>

Hervey Bay exhibited the most pronounced estimated population decline among the three regions covered in the 2022 survey, resulting in an estimated decline of approximately -5.7% per year between 2005 and 2022 with a probability of decline of 99.5%, which is substantial evidence in favour of a declining population. Nonetheless, this result is at variance with the results from the analysis of the data from 2005 through 2016, which suggested a slight increase from 2005 to 2016 of +0.28% and a probability of decline of 0.47 (i.e., <50%). Taken together, these results suggest that the two large flood events in early 2022, which resulted in extensive loss of seagrass, had a major effect on the population, and that the apparent long-term trend may be confounded by temporary emigration as well as mortality as happened in the 1990s. Nonetheless, the fact that evidence of substantial temporary emigration from Hervey Bay was not detected elsewhere in the survey region is very concerning.

The Hervey Bay dugong abundance estimate from the 2022 survey (1533 ±se 634) was equivalent to the estimated population sizes in 2005 (1388 ±se 323) and 2011 (1438 ±se 438) but less than 2016. The estimated dugong numbers may be deceiving given the strong declining trends in population density detected in the Bayesian models. The uncorrected counts of dugongs detected in Hervey Bay during the 2022 survey was the lowest since 2005 but much higher than after the 1992 floods (Preen and Marsh 1995).

The most logical explanation for the discrepancy in the inter-year comparison between uncorrected dugong counts and the abundance estimates is in the mathematical corrections made to account for availability bias (animals not available to observers). We used the Hagihara et al. method (2014; 2018) which corrects for differences in dugong diving behaviour at different depths. Given that most dugongs detected in Hervey Bay in 2022 were in deep water >10m, there was an increased probability of animals being missed by observers in this habitat, which was accounted for in the abundance estimates, this adjustment in the dugong numbers is the most likely explanation for the 2022 population estimate to level with past surveys years despite the clear declining trend in their density.

<u>Moreton Bay</u>

The estimated total number of dugongs in Moreton Bay (400 ±se 116 dugongs) was within the range of estimates recorded since 2005 albeit showing a small decline compared to 2016. Moreton Bay had the weakest population decline of all the regions: it had an estimated decline of -1.2% per year since 2005. The 95% CI and p-decline statistic (0.720) were not strong enough to clearly refute the hypothesis that the population is stable. Although prior years have had higher population densities, especially in 2011 and 2016, the population in 2005 was similar to the density in 2022.

Herds have a large influence on density estimates, and slight decrease in the estimated dugong numbers in Moreton Bay could be attributable to our inability to detect multiple large herds over the eastern banks compared to previous years. In our 2022 survey, we identified one herd of 51 dugongs, which is much less than the five herds (totalling 177 dugongs) detected in 2016, as well as the three herds (totalling 391 dugongs) detected in 2011, and the four herds (totalling 216 dugongs) in 2005.

The 2022 survey was conducted in similar -good- weather conditions compared to previous years and timed with tides to increase the chances of detecting dugongs over the eastern banks where their main seagrass food resources are. So, it is unlikely that the approach to survey dugong in Moreton Bay in 2022 had an impact on the counts. Seagrass habitats across the Moreton Bay Marine Park (MBMP), on the other hand, were impacted by the February/March 2022 flood event, which transported large quantities of turbid water to Moreton Bay (Udy et al. 2023). Seagrass extent declined by 33.2% between pre and post flood surveys in the portion of the Marine Park covered by Udy et al. (2023)'s surveys. While most of the seagrass loss was in subtidal habitats, a decline in the proportion of all meadow types was recorded the shallow subtidal areas (< 2 m) post flood. There was also a reduction in the occurrence of dense seagrass including *Z. muelleri* and sparse seagrass in the intertidal zone. These changes in the size, distribution, and composition of seagrasses across the surveyed area could have affected the use and herding behaviour of dugongs as was already observed in the past (Udy et al. 2023).

4.2 EFFECTS OF CLIMATE CHANGE ON SEAGRASSES AND DUGONGS: THE CASE OF HERVEY BAY

Two large flood events at the start of 2022 (January and February-March) in Hervey Bay resulted in the highest river flows recorded in the Mary River in over 110 years resulting in persistent flood plumes along the western shore of Hervey Bay and throughout Great Sandy Strait (Lewis et al. 2022) and the decline of seagrass ecosystems across the region (Bryant et al. 2023; York et al. 2022). The seagrasses Hervey Bay have experienced large declines in the past coinciding with floods from La Nińa climate events such as in 1992 (Preen et al. 1995) and 1999 (McKenzie et al. 2000). The effect of these floods on seagrasses and their reliant dugong population was documented before (e.g., Preen and Marsh 1995), and, as expected, the impact of the 2022 floods in Hervey Bay on dugongs spanned the expected range of possible responses: decrease in the number of animals throughout the region, increased mortality, movement of animals and shift in their habitat use.

Most of the dugongs sighted during the 2022 survey were concentrated in the middle, deepest part of the Bay with no animals detected across the entire GSS nor in the inshore intertidal eastern and western parts of the bay. Our survey was coincidently undertaken at the same time as the November 2022 seagrass assessment conducted by Bryant et al. (2023) which showed that most of the remaining seagrass in the area was indeed located where dugongs were found (Figure 32). In their report, Bryant et al. (2023) explained that the deep-water seagrasses in the middle of Hervey Bay were less affected by the flood plume and coped better than the shallow and intertidal meadows although the area of seagrass in May 2022 was reduced to around a third the size compared to the previous historical survey in 1998 when the seagrass had not been impacted by flooding (McKenzie, 2017). Poor water quality was the likely main cause for the decline of the seagrasses reported in Hervey Bay.

Deeper water seagrasses tend to recover more quickly than intertidal and subtidal seagrasses after losses caused by cyclones (Rasheed et al. 2014; Preen et al. 1995) because their seed banks are less likely to have been damaged by sheer stress. By the November 2022 survey the deep-water seagrasses were already showing good signs of recovery with expansion of the meadow and an increase in abundance measured as above ground biomass and percentage cover of the seabed. This is possibly a quicker recovery than during the 1992 events when the seagrasses in deep water in Hervey Bay had also died and it took between 10 months and 2 years for them to start making a recovery (Preen et al. 1995). Of concern is the likelihood and timing of recovery of seagrasses in the inshore areas of Hervey Bay, which will likely dictate the immigration of dugongs back into this area.

Interestingly, the lack of dugongs in the Great Sandy Strait and high concentrations of animals in the middle, deeper section of Hervey Bay in November 2022 contrast with the observations made post-1992 flooding events when dugong density plummeted in the Bay but increased in the GSS (Preen and Marsh 1995). The differences are almost certainly because the major floods in 1992 were in the Burrum River catchment rather than the Mary River catchment. The Burrum River mouth is close to a key inshore dugong habitat in the Hervey Bay region (e.g., Sheppard et al. 2007, 2009, 2010) likely resulting in the much more severe effects of the 1992 floods and cyclone when compared to those in 2022. Some eight months after the 1992 floods, the estimated dugong population of southern Hervey Bay was only 71 ±se 40 dugongs; 21 months after the floods the regional dugong population was estimated to be 600 ±se 126 dugongs. Many dugongs died and a total of 99 carcasses were recovered, far more than the 19 in 2022 (Appendix 16). Nonetheless, the population had recovered to an estimated 2077 ±se 543 by 2005 (see Sobtzick et al. 2017), a recovery that can only be explained by temporary migration.

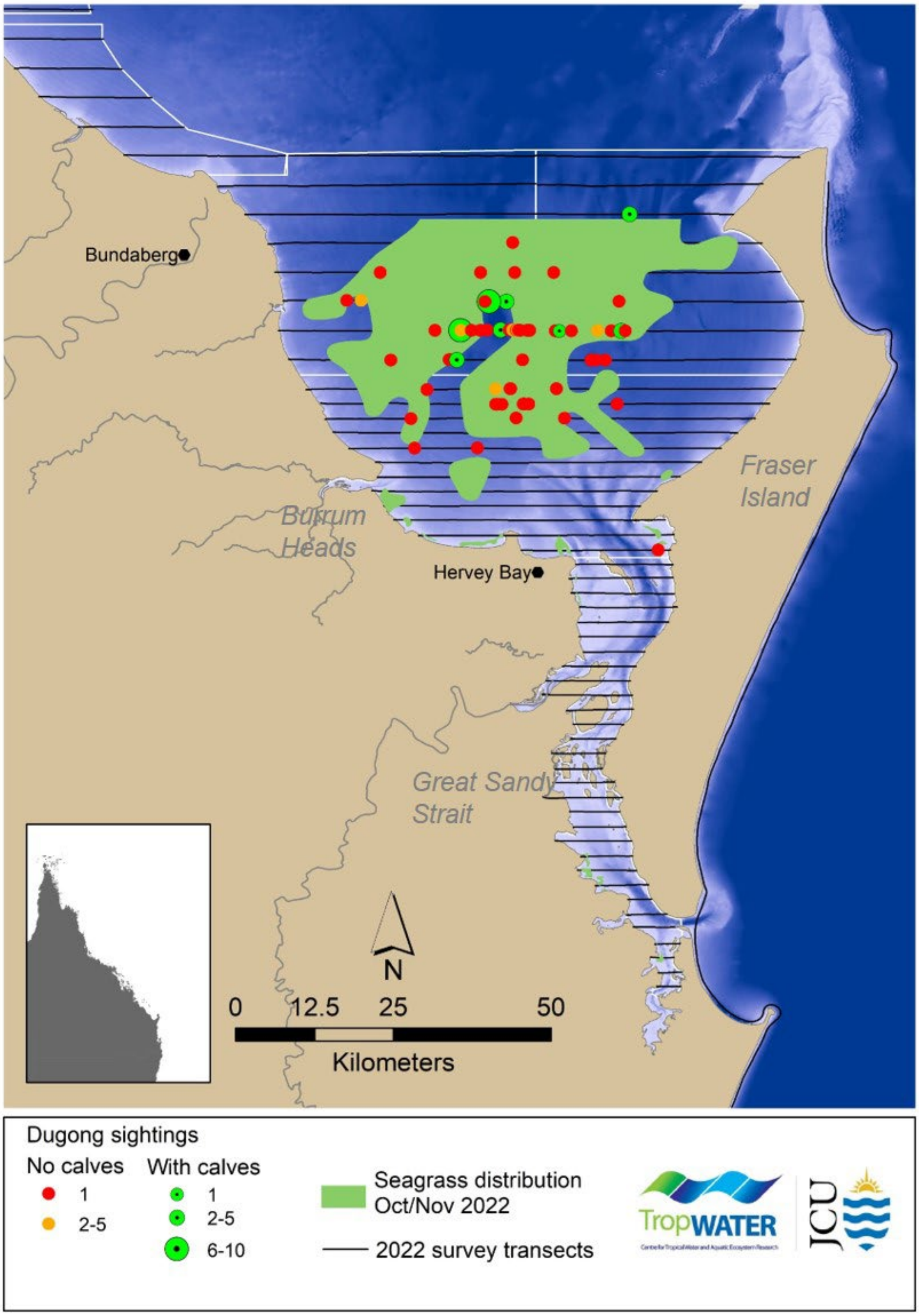


Figure 32. Dugong distribution over seagrass as of the November 2022 dugong and seagrass surveys conducted in Hervey Bay.

The timing and behavioural mechanisms associated with the recovery by dugongs of an area historically known as important to them remains to be studied. Dugongs can be highly mobile and move between regions, including the areas surveyed in this study. For example, there is evidence from satellite tracking (Zeh et al. 2016) as well as genetic pedigree analysis (Cope et al. 2015) of dugongs moving between Hervey Bay and Moreton Bay. Dugong movements were also recorded between Hervey Bay and Shoalwater Bay in the GBR (Sheppard et al. 2006) as well as within the GBR (Marsh and Rathbun 1990; Sheppard et al. 2006; Marsh et al. 2011; Cleguer et al. 2015; Gredzens et al. 2014; see Deutsch et al. 2022b for a review). The data collected using satellite tracking systems suggest that dugongs have a keen sense of spatial memory which likely informs movements and habitat use at variable spatial scales. For example, Sheppard et al. (2006) recorded two dugongs moving north from Hervey Bay to Great Keppel Island and Clairview in the southern section of the GBR, passing by Rodds Bay, an area of high seagrass density 185 km north of Burrum Heads. Such knowledge of the spatiotemporal distribution of their food resources should enable dugongs to exploit their heterogeneous environments effectively and, to a certain unknown extent, adapt to sudden disturbance of the seagrass habitats they rely on.

Historical aerial survey results suggest that some dugongs temporarily migrate after large-scale loss of the seagrasses communities on which they depend for food. Unless dugongs are fitted with some telemetry tracking systems immediately after a weather event (which is ethically sensitive with the current tracking technology), it is impossible understand how the animals behave and how many may move to other places. In addition, if animals move individualistically, (which is likely see Deutsch et al. 2022a), dugongs may have dispersed into the survey blocks where we did not see sufficient dugongs to calculate population estimates. Nonetheless, compared with 2005 we detected a two-fold increase in the abundance of dugongs in the Gladstone area, the first main seagrass and dugong habitat north of Hervey Bay, there were too few sightings in the Gladstone area in 2011 and 2016 to derive abundance estimates. Together with our understanding of the alteration of the seagrass meadows in Hervey Bay in 2022, these results strongly suggest that some dugongs from Hervey Bay may have emigrated to the Gladstone area. Emigration to Moreton Bay is less likely given our survey results showing a stable if not slight decrease in the dugong population in this area and the seagrass losses also reported in 2022 (Udy et al. 2023).

There is increasing evidence, that sirenian calves learn the locations of key resources and the timing and direction of movements during years of calf dependency (Deutsch et al. 2022b; O'Shea et al. 2022). Whether this knowledge is transmitted among adult dugongs is unknown. The speed at which new behaviours can spread through dugong populations is unknown but may become a prominent criterion of survival if critical dugong habitats become more frequently altered or disappear because of climate change (Marsh 2022).

The dugong aerial surveys have covered the coastal distribution of seagrass in the GBRWHA (Carter et al. 2021) since the 1980s. However, the vast offshore subtidal communities in the urban coast of the GBR have never been surveyed for dugongs. As described above, deeper water seagrass can recover more quickly from disturbance than seagrasses in shallow water sites (Preen et al. 1995; Rasheed et al. 2014) and the results of our survey in Hervey Bay emphasise how important deep seagrasses may become to maintain a dugong population afloat when severe storms and/or floods damage their coastal feeding grounds. The furthest offshore that dugongs have been confirmed in the GBRWHA is around Raine Island, on the outer edge of the northern GBR about 130 km off the Cape York coast where a dugong was filmed using a drone in the summer of 2014-2015 at the western end of the reef flat (Raine Island Recovery Project *pers. comm.* 2023; see also

Marsh and Cleguer (2023). Thus, the role that offshore seagrasses have on dugong distribution, abundance, and movements in eastern Queensland merits further investigation.

4.3 NEW, COMPLEMENTARY APPROACHES TO HELP ASSESS THE STATUS, BEHAVIOUR AND HABITAT USE OF DUGONGS IN THE GBRWHA, HERVEY BAY AND MORETON BAY

To enhance our capacity for evaluating dugong populations and the interplay between dugongs and their biophysical environment, it is crucial to adopt a multidisciplinary strategy. In Australia, aerial surveys have provided information on dugong distribution and abundance for many parts of their national distribution (Cleguer and Marsh 2023). These surveys have been a relatively cost-effective approach to assess the distribution and abundance of dugongs at vast spatial scales (>tens of thousands of km^2). Nonetheless, the emergence in new technologies is opening new avenues to conduct local-scale studies, which could in turn feed into regional assessments of dugong populations. Below, we present a few suggestions regarding potential avenues for conducting this research.

4.3.1 E-DNA

The utilization of Environmental DNA (eDNA) has emerged as a promising technique for both identifying individual species and monitoring biodiversity (Thomsen and Willerslev, 2015). Dugongs, while breathing and diving, likely leave a distinct "mark" in surface waters that contains genetic materials derived from their skin, mucus, and/or faeces. Once a reliable eDNA method is developed specifically for dugongs (we are aware of a few research groups conducting developmental research but did not find published work yet), it could be employed to detect the presence of dugongs in regions of the GBRWHA that have not been surveyed via aerial methods. Areas where dugong presence is identified through eDNA analysis could then be given priority for subsequent aerial surveys.

4.3.2 USING SMALL DRONES TO MAP DUGONGS AND ASSESS THEIR BODY CONDITION AT THE LOCAL SCALE

In recent times, readily available and affordable small drones have become increasingly utilized by citizen scientists and communities throughout the Great Barrier Reef (GBR). These drones, being user-friendly and cost-effective, can be employed in collaborations between Traditional Owners, TUMRA representatives, land and sea ranger programs, and scientists conducting local-scale surveys of seagrass and dugongs. The engagement work we have done during this survey indicated that First Nations people were more attracted to the idea of being upskilled to conduct dugong aerial surveys at the scale of their sea country rather than being involved in cross-country large scale observer surveys.

The small drone approach holds great potential for enhancing our understanding of the intricate relationship between the fine-scale habitat utilization of dugongs and their biophysical environment. Pending design alignment and method validation, the images captured by these small drones could be utilized to measure the body size and estimate the physical condition of marine mammals. A PhD to develop such method will start in 2022 and is supported by James Cook University and the National Environmental Science Program. Techniques developed for manatees (e.g., Ramos et al. 2022) can be adapted to evaluate the impact of extreme weather on the well-being of dugongs in the GBR.

4.3.3 TRACKING DUGONGS TO DOCUMENT THEIR SEASONAL, TIDAL AND DIURNAL HABITAT USE

Satellite tracking has played a crucial role in providing more detailed insights into the movements and habitat preferences of dugongs across various regions in Australia and abroad (see Deutsch et al. 2022a,b for a review). Findings from these studies have indicated that dugongs can be movements exhibit heterogeneity while also showing region-specific responses to seasonal, tidal, and diel cycles (e.g., Sheppard et al. 2006; Derville et al. 2022). In certain areas, dugongs tend to frequent inshore locations during night-time, often foraging over intertidal seagrass meadows during high tide (Campbell et al. 2010; Sheppard et al. 2009). Information on diurnal changes in habitat use is very important to inform adaptive management, particularly for places where night-time costal activities are important.

Telemetry data, obtained through satellite tracking, can be a valuable addition to the existing knowledge of dugong distribution and habitat acquired from aerial surveys conducted for population assessments. While aerial surveys offer population-level data, they provide only a snapshot of information at a specific moment in time. On the other hand, telemetry data offers continuous temporal information but is limited to a smaller number of individuals. Through model cross-validation Derville et al. (2022), have identified that aerial dugong aerial surveys in New Caledonia exhibit temporal bias and have failed to identify certain crucial dugong habitats. Specifically, these surveys underestimated the significance of very shallow waters, which are intensively utilized by dugongs during night-time. Consequently, the inclusion of satellite tags, even in relatively small numbers, proves valuable in validating and complementing the broader-scale distribution data obtained through aerial surveys. This integration helps bridge ecological knowledge gaps and provides a more comprehensive understanding of dugong ecology.

4.4 REDUCING EXCESS UNCERTAINTY AND VARIATION IN FUTURE SURVEY WORK

A key principle of this study has been the earnest attempt to incorporate multiple sources of variation, such MCMC imputation of missing data imputation, proper accounting of uncertainty in availability biases, model-selection uncertainty in the capture-recapture models, and accounting for dugongs that went undetected. By accounting for these multiple sources of variation and uncertainty, we prevent ourselves from making strong conclusions where none are warranted. But we also risk missing strong trends and patterns (i.e., low statistical “power”) due to excess noise. Our previous studies (Rankin and Marsh, 2020) performed prospective power analyses and simulations, and devised the present N-Mixture methodology to improve the statistical detection of biologically meaningful population trends in the face of multiple sources of uncertainty.

In the present study, one indication that we could do much better at reducing excess variation and uncertainty is the Negative Binomial overdispersion parameter: the estimated value of 0.305 is concerningly low (a low value means more overdispersion). High overdispersion blunts our ability to detect meaningful population changes because the trends must be very large to stand out against the high variation in counts.

In some respects, large overdispersion is to be expected for herding animals like dugongs. For example, in some regions, dugongs can be encountered in groups of just a few animals, as well as massive herds of dozens or hundreds of animals. A priori, with just this knowledge of their herding behaviour, we would expect very high statistical overdispersion.

Nonetheless, we recommend some possible techniques to help reduce excess statistical uncertainty and strengthen our ability to confidently detect subtle population trends. These include improvements in the survey-design for future surveys, as well as statistical techniques that can be applied retrospectively (see section below).

4.4.1 SURVEY-DESIGN RECOMMENDATIONS

4.4.1.1 POPULATION TREND DETECTION

As part of the Reef Integrated Monitoring and Reporting Program, R. Rankin (in Marsh et al. 2019) performed prospective power analysis to estimate annual trends using hypothetical datasets across various scenarios. The accompanying retrospective analyses employed the Negative Binomial distribution. Rankin's objective was to evaluate the capability of large-scale aerial surveys in detecting future declines under different simulated sampling strategies, including declines of -1 percent and -3 percent per year. The prospective analysis indicated that a -3 percent decline could be identified with a probability of 0.8 at intermediate time-horizons (eight years and beyond), but shorter time periods and more frequent surveys were unlikely to yield sufficient statistical power for trend detection. Marsh et al. (2019) recommended strict adherence to the existing five-year survey frequency for dugong aerial surveys and emphasized their utilization as one of several evidential lines to assess significant trends in dugong abundance within the Great Barrier Reef World Heritage Area (GBRWHA). This recommendation was based on the limited improvement in statistical power achieved by increasing survey frequency, the mandatory five-year reporting period specified in the Great Barrier Reef Marine Park Act 1975 for the Outlook Report, and the obligations outlined in the Reef 2050 Plan (Great Barrier Reef Marine Park Authority, 2015). Considering the findings presented in the conducted surveys, we find no compelling rationale to modify this advice.

4.4.1.2 UNCERTAINTY AND EXCESS VARIATION

Even with very high detection probabilities, dugongs may be undetected at very high rates due to their diving behaviour. A simple way to improve this could be through repeat surveys within the same survey event. Assuming population closure, the effective availability probability (*a*) of two surveys of the same transect would be approximately: $1-(1-a)(1-a) \gg a$. This would substantially increase the availability of dugongs, especially in turbid and deep waters where availability is estimated to be very low.

Repeat surveys within the same survey event have been mainly hampered by monetary constraints and the need to complete the survey in a reasonable timeframe, despite weather constraints. Thus, it could be more efficient to focus additional survey effort in just a few high-priority blocks/transects. The selection of such blocks could be based on *a priori* criteria, such as areas where availability is reduced and *a* is small (e.g., deep and/or turbid waters). Alternatively, there could be a data-driven selection, such as targeting blocks with measurable excess variation (see Appendix 2) and knowledge about the ecological importance of these blocks/regions to dugongs. As an example, we have plotted the excess variance for all survey years combined (2005, 2011, 2016, 2022) in Figure 33. This provides a spatially explicit representation of survey blocks with excess variance in the data. In future surveys, blocks MB 2 (variance index = 2.7) and MB 4 (variance index = 3.2) in Moreton Bay, HB 1 (variance index = 2.4) and HB 3 (variance index = 1.3) in Hervey Bay, and C8 (variance index = 2.1) and C9 (variance index = 2.5) in the Townsville-Cardwell area would constitute good candidates for repeat surveys within a survey period as they all have relatively high excess variances and are known as ecologically important to dugongs.

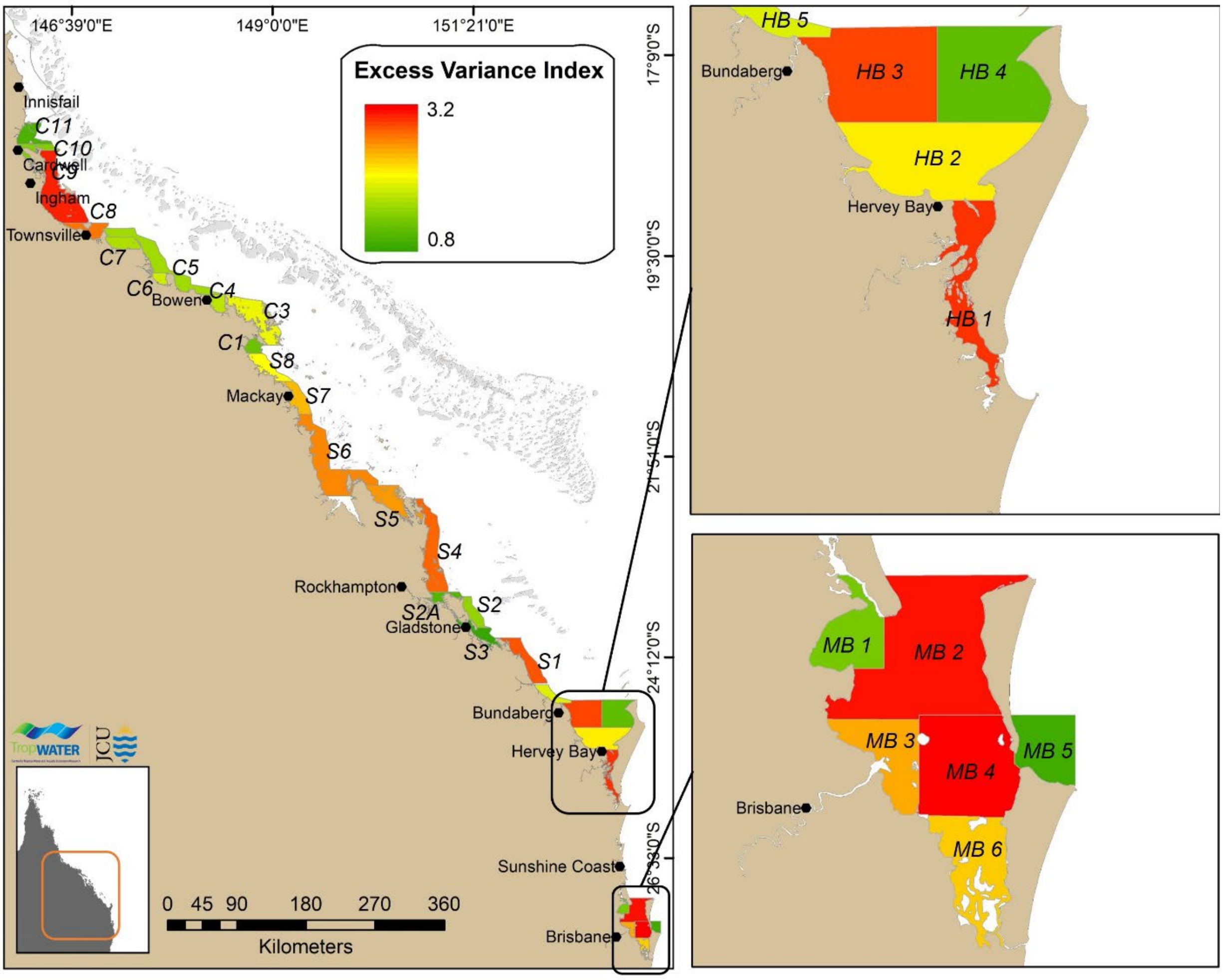


Figure 33. Excess variance in dugong aerial survey data between survey years 2005 and 2022.

4.4.1.3 MULTIPLE PLATFORMS

Parallel to this study, an effort is underway to explore aerial imagery settings and compare the detection of dugongs and other species of marine megafauna in images versus human observers. This method of data collection effectively amounts to a "double observer" experiment – with more independent observations, which can in turn reduce the number of missed dugongs and improve the statistical precision of estimates. Additionally, using drones as survey platforms in the future may provide an increased ability (and cost-effective way) to conduct repeat surveys. Having more data (especially repeated surveys) will almost always reduce statistical variance and uncertainty. Because this effort is currently underway, we will not discuss it further, aside to highlight its importance alongside other recommendations to reduce excess variation and improve precision of estimates.

4.4.2 Statistical Recommendations

While having a better survey-design could improve the informational-quality of future data, there may be statistical approaches that can be applied retrospectively on the data that has already been collected, at little-to-no cost.

4.4.2.1 HETEROGENEITY AMONG TRANSECTS

One of the simplifying assumptions embedded in the Negative Binomial likelihood function (Eqn 1) is the assumption of "exchangeability" among transects within the same region. Mathematically, this is expressed as the assumption that the expected counts of dugongs for transect *s* in location *l* is equal to the expected number of dugongs in location *l* (adjusted for transect length A_s), i.e, $\mathbb{E}[N_{s \in l}] = \mathbb{E}[\lambda_l] \cdot A_s$.

In reality, this may not be the case. Instead, some blocks and/or transects have persistently higher counts than other transects/blocks. This has been identified and dealt with in previous frequentist analyses but not to date in the Bayesian analyses which are more powerful in detecting trends.

By measuring transect-level or block-level heterogeneity, we could effectively remove excess spatial and regional variation that is currently being absorbed into other process parameters, like the overdispersion parameter. One statistical method to accommodate such transect-level or block-level heterogeneity is by "random effects", in which all sub-regional spatial units are allowed to vary around a regional mean.

A similar but more complex formulation could be to include spatial-autocorrelation via random-effects. For instance, instead of each transect's random-effect being independent, we could induce a correlation structure among random-effects, whereby nearby-transects would be more correlated to each other than transects further away. Technically, we would sample the random effects from a Multivariate Normal Distribution whose covariance matrix would be a function of transects' geographic distances.

4.4.2.2 SPATIAL COVARIATES

The different regions surveyed in this study clearly have differentiated dugong population-densities and trends. Such regions represent coarse spatial heterogeneity, but there may be more fine-grained spatial variation that can be modelled as well. Modelling fine-grained spatial variation would likely alleviate some of the excess uncertainty that is manifesting as overdispersion and parameter uncertainty.

In the previous section, we mentioned random effects as one possible method to accommodate spatial heterogeneity among transects. An alternative approach could be to include spatial "fixed effects" at the transect level, such as environmental covariates or spatial basis functions. Which environmental covariates to include would need to be carefully considered environmental covariates but could include:

- a north-south coordinate,
- bathymetric features (slope),
- distance to shore (average distance-to-shore, maximum distance-to-shore),
- depth (average depth, minimum depth, maximum depth),
- seagrass (percent transect overlap with seagrasses),

Alternatively, if the above covariates cannot be measured or added to the model as explanatory variables, we could also use spatial basis functions to fit unexplained spatial variation. These techniques include, for example, spatial splines, Bayesian kriging, and/or principal coordinates of neighbour matrices (PCNM; Borcard et al. 2004).

There are additional challenges that are introduced when the model includes high-dimensional spatial covariates, such as: overfitting, computational expense, and multicollinearity among similar-but-different covariates. Such challenges behove us to do some sort of feature selection to find the best combination of important covariates and weed-out frivolous covariates. Such model-selection substantially increases the complexity of the analysis.

In addition, the priors inherent the Bayesian analyses of trends in dugong abundance could be refined by linking the results of the dugong surveys to the spatial information on and modelling of seagrass distribution and community composition held by TropWATER at JCU. Such analysis is planned as a PhD study.

4.5 KEY FINDINGS

- The 2022 aerial survey confirmed the long-term importance of the following sub-populations of dugongs in the survey region: Hinchinbrook, Townsville region, Shoalwater Bay, Hervey Bay and Moreton Bay.
- The trends in the times series of aerial surveys for the urban coast of the GBR, Hervey Bay and Moreton Bay, all suggest long-term declines in dugong abundance in all three survey regions. Nonetheless this conclusion is more robust for the urban coast of the GBR than for Hervey Bay or Moreton Bay for the following reasons:
    a) Results from the 2022 survey increased the longevity of the trend of long-term decline in the dugong population off the urban coast. The estimated decline was approximately -2.3% per year between 2005 and 2023 compared with -4% per year from 2005 to 2016. The probability of long-term decline of the dugong population continued to be very high [0.97 based on survey data from 2005 to 2016 and 0.94- 2005 to 2022].
    b) Hervey Bay exhibited the most pronounced estimated population decline among the three regions covered in the 2022 survey, resulting in an estimated decline of approximately -5.7% per year between 2005 and 2022 with a probability of 0.995, substantial evidence in favour of a declining population. Nonetheless, this result is at variance with the results from the analysis of the data from 2005 through 2016, which suggested a slight increase from 2005 to 2016 of +0.28% and a probability of decline of 0.47 (i.e., <50%). Taken together, these results suggest that the two large flood events in early 2022, which resulted in extensive loss of seagrass, had a major effect on the population, and that the apparent long-term trend may be confounded by temporary emigration as well as mortality as happened in the 1990s. Nonetheless, the fact that evidence of substantial temporary emigration from Hervey Bay was not detected elsewhere in the survey region is very concerning.
    c) Moreton Bay had the shallowest estimated trend in population size 2005-2022: -1.2% per year. The probability of decline was 0.72, which means that a conclusion of population decline is more warranted than a population increase, but that this conviction should be weakly held. A zero-trend cannot be dismissed, especially as the results from 2005 to 2016 suggested an increase of 1.63% per year with a probability of decline of only 0.28.
- The proportion of calves is a 2-3 year lagged measure of population health and varies with the status of the seagrass on which dugongs depend for food. The percentage was 6.7% along the urban coast of the GBR, 9% in Hervey Bay, and 5.5% in Moreton Bay. All these results are within the range recorded for previous surveys but the results for the urban GBR and Moreton Bay are at the low end of their ranges, presumably reflecting the recent wet years. The result for Hervey Bay is surprising and suggests that mothers with calves may have remained in that Bay after the flood.
- The study highlights the considerable inter-annual variation and uncertainty of the statistical analyses, whereby few of the inferential outputs achieved conventional levels of "statistical significance" (i.e., low statistical power). We make recommendations to improve statistical power of subsequent surveys.

4.6 ADVICE FOR POLICY MAKERS

- The findings from the 2022 survey add to the evidence highlighting the significant impact of climate and weather on the abundance, distribution, and reproductive capacity of dugongs. This impact is primarily attributed to the influence of climatic drivers on seagrass habitats, which are essential ecosystems for dugongs.
- The result highlights the need to reduce non-climate impacts on dugongs and their seagrass habitats by improving water quality, decreasing the risk of incidental capture of dugong in gillnets throughout the east cost of Queensland as recently agreed by the Commonwealth and Queensland Ministers and working with Traditional Owners to manage their dugong populations.
- Hervey Bay seems particularly prone to extensive seagrass loss after extreme flood events, which emphasises the need to reduce non-climate impacts on dugongs and their seagrass habitats in this region as well as the southern section of the GBR.
- The Townsville area also needs particular attention given the proximity of the seagrass meadows in which dugongs depend to coastal development including port development. A baseline on the spatial-temporal dynamics of habitats use by dugongs in the region is required to help detect any deviation from the 'norm' due to added stressors.
- To better understand the response of dugongs to extensive seagrass loss after extreme weather events, consideration should be given to conducting annual local scale dugong surveys for several years after major flood events in conjunction with seagrass surveys. To this end it would be important to conduct repeat dugong aerial surveys of Hervey Bay region in coordination with the seagrass monitoring, to monitor the response of dugongs to changes in the seagrass habitats in the region.

4.7 ADVICE FOR TRADITIONAL OWNERS IN THE SURVEY AREA

- The status of the dugong in coastal areas of sea countries surveyed in 2022 is very concerning. Thus, we suggest that discussions should be initiated for a moratorium on traditional hunting within communities until the situation improves.
- Consider partnering with researchers in the design and implementation of local scale research relevant to the management of dugongs and seagrasses in sea country.

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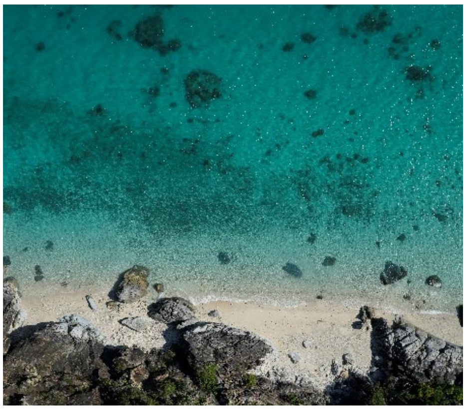
6 APPENDICES

6.1 APPENDIX 1: SCALES USED TO DESCRIBE THE ENVIRONMENTAL CONDITIONS ENCOUNTERED DURING THE AERIAL SURVEYS.

Table 1.1. Water visibility Scale

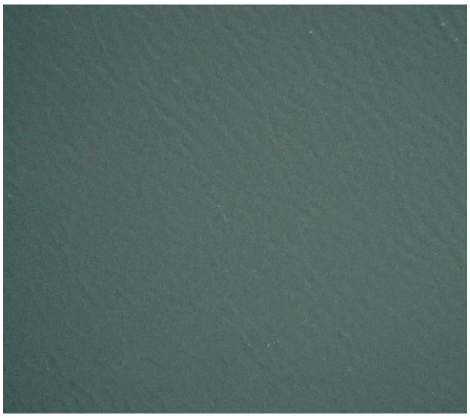
Visibility	Water Quality	Depth Range	Visibility of Sea Floor
1	Clear	Shallow	Clearly visible
2	Variable	Variable	Visible but unclear
3	Clear	Deep	Not visible
4	Turbid	Variable	Not visible



Turbidity 1

Turbidity 2

Turbidity 3



Turbidity 4

Table 1.2. Glare Scale

Glare	Proportion of view affected
0	No glare
1	< 25% of view affected
2	25-50% of view affected
3	> 50% of view affected

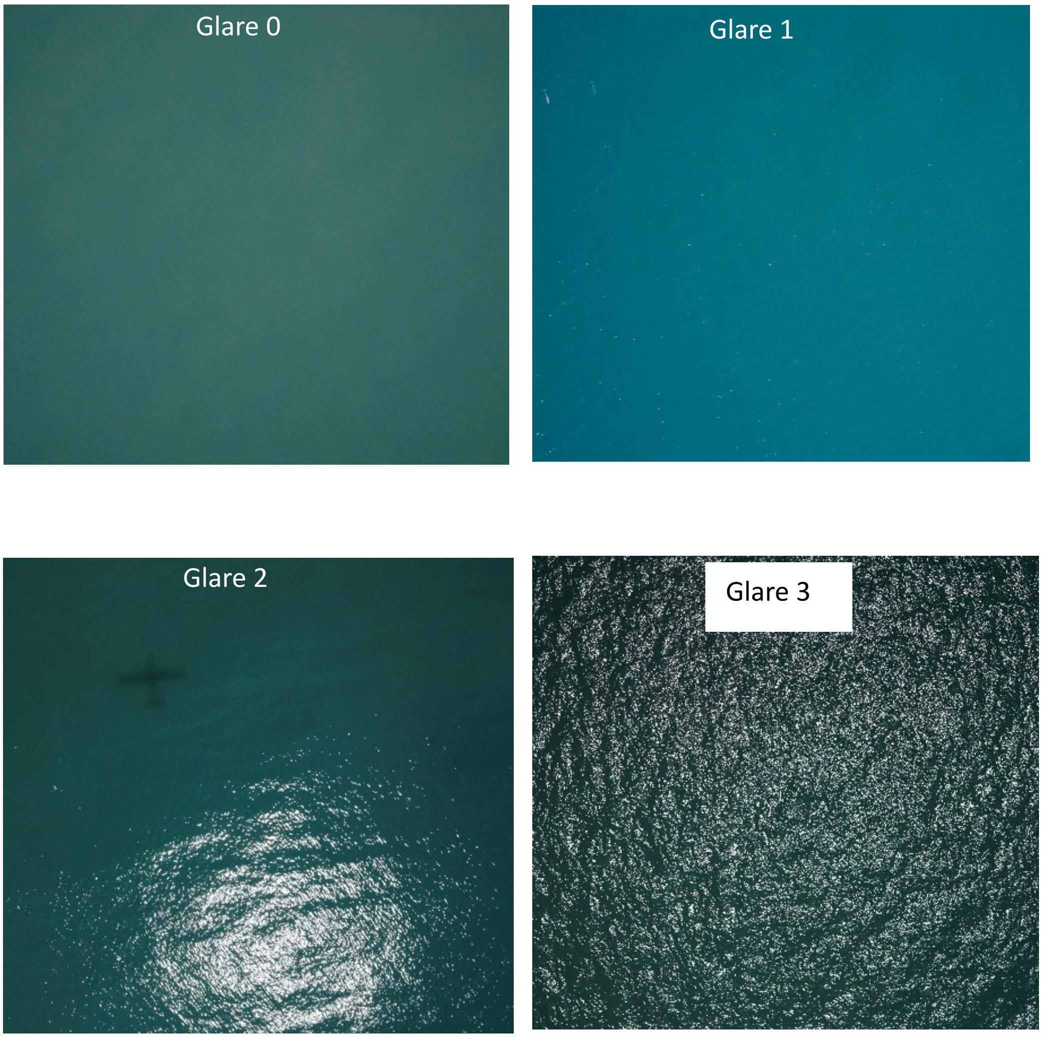
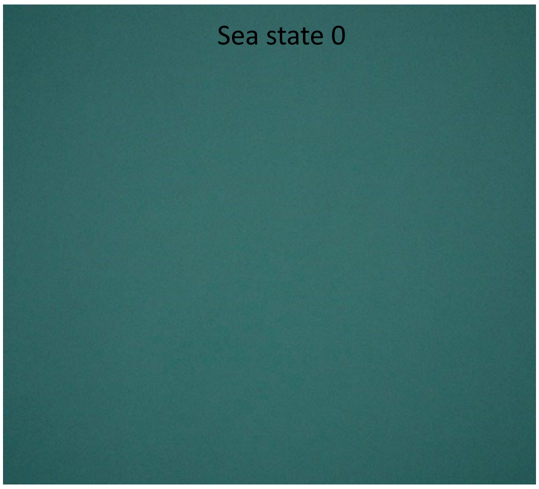
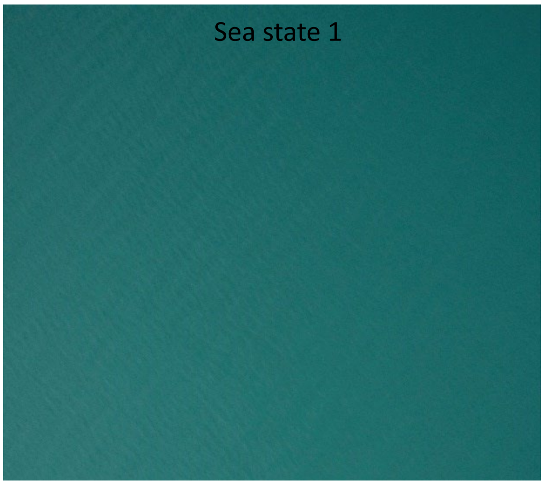


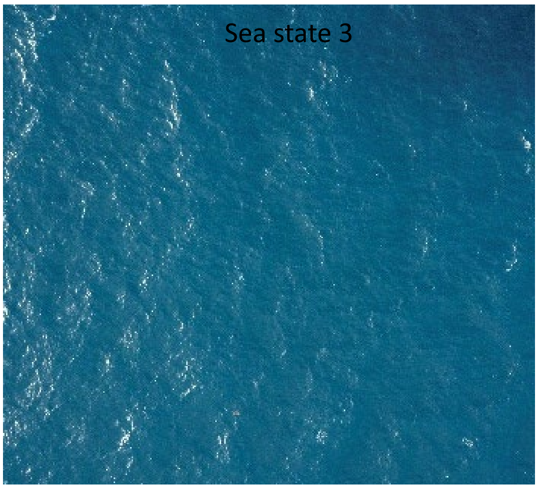
Table 1.3. Sea state Scale

Beaufort Sea state	Description
0	Calm; like a mirror
1	Light air; ripples, no foam
2	Light breeze; small wavelets, smooth crests with glassy appearance
3	Gentle breeze; large wavelets, some crest breaks, some white caps
4	Moderate breeze; small waves, frequent white caps – Abort survey

Sea state 1







6.2 APPENDIX 2: DETAILS OF THE BAYESIAN ANALYSIS OF DUGONG DENSITIES IN THE URBAN COAST OF THE GBR, HERVEY BAY, MORETON BAY FOR SURVEY YEAR 2005, 2011, 2016, 2022.

1. Priors on Negative Binomial Parameters

To complete Equation (1) and sample from the posterior distributions of the regression coefficients ($\boldsymbol{\beta}$), we used independent Normal priors on the Negative Binomial regression coefficients, using the same prior-parameters for all priors, including the intercept β_0 and the per-year/per-location marginal densities $\beta_{t,l}$ for $t \in \{2005, 2011, 2016, 2022\}$ and $l \in \{\mathrm{HB}, \mathrm{MB}, \mathrm{SGBR}\}$. We used a uniform prior on the overdispersion parameter.

$$p(\beta) = \mathcal{N}(0, 10^2) \text{ for all } \beta \in \boldsymbol{\beta}$$
$$p(\theta) = \mathcal{U}(0.3, 10)$$

We combine priors with the NB likelihood function to yield an unnormalized posterior function that can be sampled via MCMC:

$$p(\beta|\mathbf{N}) \propto \mathrm{NB}(\mathbf{N}|\boldsymbol{\beta}, \theta)p(\beta)$$

… which is conditional on the (adjusted) counts of dugongs, $\mathbf{N} = \left[\left[N_{s,t}^{\mathrm{adj}}\right]_s^S\right]_t^T$ per transect *s* and year *t*.

Note: the adjusted counts are themselves stochastic and sampled from an N-Mixture distribution, conditional on the detection parameters and availability biases (which are covered in more detail in Sections 3.2.3 and 3.2.4).

2. Inference

Using MCMC, we generated posterior samples of the regression coefficients $\boldsymbol{\beta}$ and densities $\boldsymbol{\lambda}$ to drive inference about other quantities of interest, including:

e) the log-linear trend of dugong populations at each location over 17 years, as the annualised percent change, including 95%CIs,

f) the posterior probability of a decline at each location,

g) the posterior probability that dugong densities in year 2022 are higher than densities in prior years (2005, 2011, and 2016), and

h) indices of excess variation and uncertainty, at sub-region levels, such as survey 'blocks'.

The above statistics help us to understand the *magnitude* and *significance* of dugong population declines. For instance, the magnitude of the trend may be large or small, whereas the probability of decline quantifies how *certain* we are of a decline, regardless of its magnitude. The index of excess variation can help prioritise regions of the survey-area that deserve additional scrutiny and survey effort.

2.1. Trend estimation

Let $\hat{\tau}_l$ be the log-linear trend, as estimated from the dugong adjusted-counts at location *l* over 17 years, then $(\exp(\hat{\tau}_l) - 1) \times 100\%$ is the annualised percent change in dugong population density at location *l* (e.g., a log-linear estimate of -0.0512 equals a -5.00% annualised change).

We used a technique called "MCMC line-fitting" to estimate the posterior distribution of the population trends ($\hat{\tau}$), by fitting a trendline through density estimates $\hat{\lambda}_{t,l}$ for each MCMC iteration, yielding a distribution over all MCMC samples.[5]

In other words, for each *i^th^* MCMC sample of $\log(\lambda_{t,l})^{(i)}$, we did a simple least-squares regression using $\log(\lambda_{t,l})^{(i)}$ as the dependent variable, and year *t* and location *l* as the independent variables (plus an intercept). In this least square regression, τ_l is the regression coefficient representing the slope of the trendline. When averaged over all MCMC samples of the densities $[\log(\lambda_{t,l})^{(i)}]_{i=1}^{n_{\mathrm{mcmc}}}$ we get an approximate posterior distribution for dugong population trends. More formally...

$$p(\tau_l|\mathbf{N}) \approx \left[\hat{\tau}_l^{(i)}\right]_{i=1}^{n_{\mathrm{mcmc}}}$$

$$\hat{\tau}_0^{(i)}, \hat{\tau}_l^{(i)} = \underset{\tau_0,\tau_l}{\operatorname{argmin}} \sum_{t \in T} \left(\log(\lambda_{t,l})^{(i)} - (\tau_0 + \tau_l \times t)\right)^2 \quad \text{for each } i \text{ in } 1\!:\!n_{\mathrm{mcmc}}$$

for $l \in L = \{\mathrm{SGBR,\ MB,\ HB}\}$ and $t \in T = \{2005, 2011, 2016, 2022\}$

[5] Although we treat trend as a derived quantity, an alternate method would be to directly incorporate the log-linear trend as a parameter in the Negative Binomial regression model (i.e., $\log(\lambda_i) = \beta_0 + \beta_t t + \epsilon_i$) and use "random effects" to represent the per-year/per-location deviations from the trend, $\epsilon_i \sim \mathcal{N}(\mu_{\mathrm{re}}, \sigma_{\mathrm{re}})$. This is a preferred formulation and future goal.

Line 1 of the equation states that we are approximating the posterior distribution of τ from MCMC samples of $\hat{\tau}^{(i)}$. Line 2 of the equation states that each MCMC estimate of $\hat{\tau_l}^{(i)}$ is a simple least-squares solution of $\log(\lambda_{t,l})^{(i)}$ vs. the trend-line expectation $\tau_0 + \tau_l \times t$, where *t* is the survey-year.

Using the MCMC samples of τ, we compute posterior quantities like 95%CI and SE, to help quantity the overall uncertainty of the estimates.

2.2. Probability of decline

Given the posterior distribution of dugong population trends (τ), we can directly compute probabilities for questions like "*what is the probability that a population is in decline?*" We call this statistic *p-decline*.

A high value for *p-decline*, such as > 0.95, is strong evidence of a declining population, irrespective of the actual magnitude of the decline. Moderate values (0.51-0.95) tell us that, according to the balance of probabilities, we should have greater conviction in a population decline versus a population increase, but it should not be a very strong belief.

The probability of a decline is calculated as:

$$\hat{p}_l\text{-decline} \approx \sum_{i=1}^{n_{\text{mcmc}}} \frac{\mathbb{I}[e^{\hat{\tau}_l^{(i)}} - 1 < 0]}{n_{\text{mcmc}}} = \sum_{i=1}^{n_{\text{mcmc}}} \frac{\mathbb{I}[\hat{\tau}_l^{(i)} < 0]}{n_{\text{mcmc}}}$$

In other words, the probability of a decline is estimated as the proportion of MCMC samples where the estimated trend ($\hat{\tau}^{(i)}$) is less than 0.

Note: the *p-decline* statistic should not be confused with a Frequentist p-value, which is used as evidence against a null-hypothesis of no-trend. Instead, the *p-decline* is a more natural statistic directly in support the "alternative hypothesis" that there was a decline.

2.3. Comparison of 2022 dugong densities to previous survey years

Conservation managers often wish to know "*how does this year's population compare to previous years?*" To help answer this question, we calculate a probability statistic $p_l(2022 > t)$, which is the probability that the dugong density at location *l* in year 2022 is greater than the population density in year *t.*

$$\hat{p}_l(2022 > t) \approx \sum_{i=1}^{n_{\text{mcmc}}} \frac{\mathbb{I}[\lambda_{l,2022}^{(i)} > \lambda_{l,t}^{(i)}]}{n_{\text{mcmc}}}$$

The statistic is calculated using posterior samples of the per-year densities.

2.4. Index of excess variation

Given MCMC samples of $N_{s,t}$, the adjusted counts at transect *s* in year *t*, we can aggregate the adjusted counts to "blocks", which are groups of related transects.

Theoretically, count-distributed data should have a variance that is equal to its mean. However, the dugongs are expected to have a lot of excess variation (as discussed in the next Section 3.1.3) meaning that the count-variance will be much greater than the mean.

The ratio of the posterior-variance of $N_{b,t}$ to the posterior mean of $N_{b,t}$ could be considered an index of "excess variance" ($I_{b,t}$) for block *b* in year *t*.

$$I_{b,t} = \frac{\mathbb{V}\left[\sum_{t \in b} N_{b,t}\right]_{i=1}^{n_{\text{mcmc}}}}{\mathbb{E}\left[\sum_{t \in b} N_{b,t}\right]_{i=1}^{n_{\text{mcmc}}}}$$

A value of 1 would mean no excess variation. Values much greater than one could point to blocks that deserve additional scrutiny.

In addition to per-year indices, there may be blocks that have persistently high excess variation over all survey years. Therefore, we take the geometric mean of each block's per-year $I_{b,t}$ over all four years, to get an overall index of excess variation. Blocks with high all-year indices could be the focus of additional survey effort in future surveys.

3. Multiple sources of excess variation and uncertainty

The Negative Binomial model in Equation (1) has additional sources of uncertainty and excess variation, which we will briefly enumerate here. Readers are referred to the next (Section 3.2) for more technical details.

- Missing Zeros – Not all dugong groups were successfully detected during the surveys, i.e., there are missing zeros in the count-data. Our simulation studies (Rankin and Marsh 2020) revealed considerable bias in methods to estimate the adjusted-counts if they did not account for missing zeros properly (such as the Horvitz-Thompson Estimator). This motivated us to develop an N-Mixture model (Royle 2004, Rankin and Marsh 2020) to generate posterior distributions of the missing dugongs, and yield "adjusted counts" N^{adj} that included both observed and hypothetically undetected dugongs. Several quantities are necessary to robustly estimate the counts of missing dugongs, including:

- Imperfect detection (*p*) – due to observer error in spotting dugong groups by the 4-person teams of aerial observers, dugongs were detected with probability $p_m<1$. The detection probabilities were estimated per team using four capture-recapture models (M; Marsh and Sinclair 1989, Pollock *et al.* 2006). Herds seen on transects were assumed to be detected with 100% probability. The capture-recapture models and their *p*-estimates were computed offline via Maximum Likelihood estimation, then incorporated into the Bayesian NB model as priors, via Monte-Carlo (MC) integration: for each MCMC iteration, we drew a random capture-recapture model *M* (according to its wAIC model-weights) and then drew a sample of p_m from its prior distribution, conditional on *M*. See Section 3.2.4 for more details.
- Availability bias (*a*) – due to water turbidity and depth, dugongs were only visible at the surface for a fraction of time during surveys. This fraction is called the availability bias *a*. A model (Hagihara *et al.* 2014, 2018) was used offline to compute *a* for each dugong sighting, based on the environmental covariates (depth and turbidity) at the time of sighting. The availability biases were incorporated into the model via MC-integration, by sampling *a* from its prior distribution, which was taken directly from the ML-estimated distribution of *a.* See Section 3.2.3 for more details.
- Conditions among missed dugongs – for each hypothetically undetected dugong, there was an associated *p* and *a* which contributed to it being missed. However, by definition of it being missed, we have no measurements of its environmental conditions (turbidity, depth), nor do we know which side of the plane it should have been seen from. In lieu of such information, we instead sampled from a background distribution of environmental conditions at each transect to impute the hypothetical dugongs' *p* and *a* values. The background conditions were based on continuous measurements of depth and turbidity by the aerial observers, irrespective of the presence of dugongs, and indexed to each transect. For each missing dugong at each MCMC iteration, we randomly sampled from the empirical distribution of conditions, as a type of "MC-integration", in order to

marginalise over the entire background distribution of turbidity, depth, and side-of-plane.

- Missing Data – in 2005, there were two herds of 29 and 146 animals that were spotted but whose location information were lost. We randomly assigned the herds to two of four plausible transects, per MCMC iteration, to marginalise over the uncertainty associated with their location.
- Overdispersion – the Negative Binomial distribution has a parameter to accommodate excess count-variance called "overdispersion", as represented by θ. Overdispersion is common among herding animals, where group-sizes can be as small as 1-3 animals, as well as dozens or hundreds of animals. Such situations are poorly modelled by the canonical Poisson distribution and make count-modelling difficult. Values of $\theta \ll 3$ are generally indicative of high overdispersion.

There were many other plausible sources of excess variation, but these will not be addressed in the present study. These could be the focus of future investigations, including:

- spatial autocorrelation, as possibly addressed by spatial splines or spatial random-effects.
- heterogeneity among transects within regions, as possibly addressed via transect-level random-effects.

4. Overview of the Gibbs sampling procedure

With the introduction to the multiple sources of variation described above, we can now provide an overview of the MCMC sampling procedure. More technical details of each step are provided afterwards.

For each *i* iteration in $1{:}n_{mcmc}$, do:

1. Sample a detection model $m_j^{(i)}$ from its wAIC probabilities, for each observer-team *j.*
2. Sample detection probabilities $p_m^{(i)}$ from their MLE-derived prior distribution, conditional on model $m_j^{(i)}$.

3. Sample availability biases $a^{(i)}$ from their MLE-derived prior distribution, for each sightability class (based on turbidity and depth).

4. Impute missing data.

5. Randomly sample the environmental conditions (turbidity, depth) for each putative missing dugong, at each transect, from the empirical background sample of environmental conditions. Randomly assign each missing dugong a side of the plane.

6. Conditional on $(\boldsymbol{\beta}^{(i-1)}, p_m^{(i)}, a^{(i)})$, sample the adjusted counts $\boldsymbol{N}^{adj}$ per transect from the N-Mixture distribution.

7. Conditional on $\boldsymbol{N}^{adj}$ and priors, update regression coefficients $\boldsymbol{\beta}^{(i)}$

Steps 1-5 have a simple sampler. For step 6, we developed a fast sampler of the N-Mixture distribution, described in 3.2.1. For step 7, we developed a Slice Sampler (Neal 2003), as a replacement for JAGS/BUGS, which is available at: https://github.com/faraway1nspace/Flexible-R-SliceSampler. Everything was run in R version 3.6.3.

6.3 APPENDIX 3: DAILY ACTIVITIES DURING THE 2022 DUGONG AND MARINE TURTLE AERIAL SURVEY.

Date	Activity	Block surveyed	Flying hours (hh:mm)	Notes
25/10/2022	Training course in Townsville			
26/10/2022	Training flight and data transcription	C8	1:42	
28/10/2022	Survey - Townsville	C9	4:02	Too much wind for a second survey flight
29/10/2022	Survey - Townsville	C9, C10, C11	6:22	Great weather conditions. Fitted 2 flights in the morning. Glare good at 12 in low wind condition (BFT 1). Camera battery failed. No images recoded on transect across the 2 flights.
30/10/2022	Survey - Townsville	C8, C7	5:28	Cleveland Bay was surveyed at low tide. Images collected during the 2 surveys
31/10/2022	No flight	-	-	Unsuitable weather. Finish data transcription in the morning. Intro to WISDAM in the afternoon.
1/11/2022	No flight	-	-	Unsuitable weather. Image review
2/11/2022	Survey - Townsville	C10		Re-did Hinchinbrook for imagery capture. Conditions less good than when surveyed the first time
3/11/2022	Survey - Townsville	C6, C5	3:04	
4/11/2022	No flight	-	-	Unsuitable weather. Image review
5/11/2022	No flight	-	-	Unsuitable weather. Image review
6/11/2022	No flight	-	-	Unsuitable weather. Image review
7/11/2022	No flight	-	-	Unsuitable weather. Image review
8/11/2022	No flight	-	-	Unsuitable weather. Image review
9/11/2022	No flight	-	-	Unsuitable weather. Image review

10/11/2022	No flight	-		Unsuitable weather. Image review
11/11/2022	No flight	-		Unsuitable weather. Image review
12/11/2022	Survey - Bowen/Whitsundays	C5, C4, C3	5:45	
13/11/2022	Survey - Whitsundays	C3, C1, S8	4:39	
14/11/2022	Survey - north Mackay area	S8, S7, S6	3:12	
15/11/2022	No flight	-	-	Engine problems.
16/11/2022	Survey - south Mackay/Clairview area	S6	2:59	
17/11/2022	Survey - Yeppoon/north Gladstone area	S4, S2	3:13	
18/11/2022	Survey - Gladstone region	S2A, S2, S3	3:04	
19/11/2022	Survey - Gladstone region	S3, S1	2:55	
19/11/2022	Transit Bundaberg-Hervey Bay	-	0:35	
20/11/2022	No flight	-	-	Unsuitable weather. Image review
21/11/2022	No flight	-	-	Unsuitable weather. Image review
22/11/2022	No flight	-	-	Unsuitable weather. Image review
23/11/2022	Survey - Hervey Bay-GSS	HB1, HB5, HB4, HB3	5:49	
24/11/2022	Survey - Hervey Bay-GSS	HB2	3:14	
25/11/2022	Survey - Hervey Bay-GSS	HB2, HB4, HB3	3:07	

26/11/2022	Survey - Hervey Bay-GSS + transit to Moreton Bay	HB4, HB3	4:43	
27/11/2022	No flight	-	-	Unsuitable weather. Image review
28/11/2022	No flight	-	-	Unsuitable weather. Image review
29/11/2022	Survey - northern Moreton Bay	MB1, MB2		Unsuitable weather. Image review
30/11/2022	No flight	-	-	Unsuitable weather. Image review
1/12/2022	No flight	-	-	Unsuitable weather. Image review
2/12/2022	No flight	-	-	Unsuitable weather. Image review
3/12/2022	No flight	-	-	Unsuitable weather. Image review
4/12/2022	No flight	-	-	Unsuitable weather. Image review
5/12/2022	No flight	-	-	Unsuitable weather. Image review
6/12/2022	No flight	-	-	Pilot sick
7/12/2022	Survey - south and central Moreton Bay	MB6, MB4, MB3	3:23	
8/12/2022	Survey - central Moreton Bay + transit to Rockhampton	MB3, MB4, MB5	5:28	
9/12/2022	Survey - Shoalwater Bay	S5	2:45	
10/12/2022	Survey - Shoalwater Bay	S4	4:45	
11/12/2022	Survey - Shoalwater Bay	S5	2:35	
12/12/2022	Transit Rockhampton-Townsville.		2:30	

6.4 APPENDIX 4: SAMPLING INTENSITIES FOR INDIVIDUAL SURVEY BLOCKS SINCE 2005.

Moreton Bay								
Block	2005[1]		2011[2]		2016		2022	
	Block size (km^2)	Sampling intensity (%)	Block size (km^2)	Sampling intensity (%)	Block size (km^2)	Sampling intensity (%)	Block size (km^2)	Sampling intensity (%)
MB 1	166	24.7	166	19.7	165	19.9	165	20.0
MB 2	691	13.4	691	10.9	687	11.2	685	9.9
MB 3	188	35.7	189	6.9	187	4.19	186	1.0
MB 4	389	50.1	389	37.5	386	37.6	385	34.4
MB 5	155	43.3	155	18.1	154	20.9	153	19.7
MB 6	226	29.7	226	18.8	224	19.5	224	23.0
Hervey Bay-GSS								
Block	2005		2011		2016		2022	
	Block size (km^2)	Sampling intensity (%)	Block size (km^2)	Sampling intensity (%)	Block size (km^2)	Sampling intensity (%)	Block size (km^2)	Sampling intensity (%)
HB 1	517	25.31	519	16.8	519	16.1	515	20.1
HB 2	1414	20.3	1415	15.5	1416	15.9	1404	16.0
HB 3	1235	11.2	1246	16.8	1248	9.0	1236	9.0
HB 4	1224	11.4	1233	8.5	1371	8.9	1357	9.0
HB 5	546	10.8	409	11.4	411	8.1	407	8.4
Southern Great Barrier Reef								
Block	2005		2011		2016		2022	
	Block size (km^2)	Sampling intensity (%)	Block size (km^2)	Sampling intensity (%)	Block size (km^2)	Sampling intensity (%)	Block size (km^2)	Sampling intensity (%)
S1	Zzt[3]	zzt	1054	10.06	1096	8.8	1001	6.8
S2	836	10.9	515	9.5	521	8.7	522	4.7
S2A	ne[4]	ne	328	16.5	332	14.2	326	15.9
S3	1021	21.1	568	17.6	574	15.9	560	13.6

S4	zzt	Zzt	2304	10.1	2343	8.9	2010	5.4
S5	1271	21.8	1165	19.1	1189	17.3	1162	18.2
S6	Ns[5]	ns	3715	8.1	3803	7.2	3068	2.6
S7	zzt	zzt	736	9.8	758	8.7	750	4.4
S8	796	17.9	710	15.2	734	13.3	710	14.1
C1	371	18.2	342	18.7	354	16.4	342	16.6
C2	Ns	ns	332	6.3	344	5.4	ns	ns
C3	1733	14.6	1701	13.4	1763	12.5	1700	10.7
C4	466	19.6	428	18.5	444	16.6	428	17.1
C5	ns	ns	2097	9.8	2186	8.5	2043	5.9
C6	244	23.3	221	19.5	230	16.7	221	17.5
C7	579	23.7	557	19.6	581	16.9	557	18.0
C8	620	32.6	572	19.2	598	18.2	573	18.6
C9	zzt	zzt	2905	9.2	3045	8.3	2700	5.4
C10	288	23.6	456	20.4	480	18.3	456	18.1
C11	351	18.1	675	19.6	n/a	ns	675	17.4
C12	zzt	zzt	5511	9.5	n/a	ns	ns	ns

[1] Data from Marsh et al. (2007); [2] Data from Sobtzick et al. (2012); [3] Zigzag transect; [4] non-existent; was part block S3 at that time; [5] not surveyed

6.5 APPENDIX 5: WEATHER CONDITIONS ENCOUNTERED DURING THE 2022 AERIAL SURVEYS OF MORETON BAY, HERVEY BAY-GSS AND THE SOUTHERN GBR IN COMPARISON TO PREVIOUS SURVEYS OF THE SAME AREAS.

Weather conditions	Moreton Bay			
	2005	2011	2016	2022
Max wind speed (in km/h)	<10	<22	<19	<4
Cloud cover range (in oktas)	0-6	0-6	0-8	2-5
Min cloud height (in ft)	2000	3000	3000	3500
Beaufort Sea state# (range)	1.8 (1-4)	1.9 (1-3)	1.4 (1-4)	1.3 (0-3)
Glare North#	1.8	1.7	2.3	1.7
Glare South	1.2	1.1	2.2	1.9
Glare overall	1.5	1.5	2.3	1.8
Air visibility (in km)	>10	N/A	>10	>10

Weather conditions	Hervey Bay-GSS			
	2005	2011	2016	2022
Max wind speed (in km/h)	<10	<22	<22	≤13
Cloud cover range (in oktas)	1-7	1-6	0-8	(0-7)
Min cloud height (in ft)	2000	1900	3500	2000
Beaufort Sea state# (range)	2.2 (1-3)	1.3 (1-3)	1.6 (1-4)	1.1 (1-2)
Glare North#	1.4	2.2	2.8	2.2

Glare South	1.3	1.8	2.9	2.1
Glare overall	1.4	2.0	2.8	2.1
Air visibility (in km)	>10	N/A	>10	>10

Weather conditions	Southern Great Barrier Reef			
	2005	2011	2016	2022
Max wind speed (in km/h)	<10	<31	<28	≤13
Cloud cover range (in oktas)	0-5	1-8	0-4	0-6
Min cloud height (in ft)	1000	1450	1000	1000
Beaufort Sea state[#] (range)	1.5 (0-4)	1.9 (0-3)	1.5 (0-4)	1.5 (0-3)
Glare North[#]	1.5	1.8	2.3	1.7
Glare South	1.5	1.8	2.2	1.9
Glare overall	1.5	1.8	2.3	1.8
Air visibility (in km)	>10	>8	>10	>10

[#] Means of modes for each transect

6.6 APPENDIX 6: SUMMARY OF THE NUMBER OF DUGONGS, CALVES, AND HERDS ENCOUNTERED ON TRANSECT (I.E. WITHIN THE OBSERVATION STRIP) IN MORETON BAY, HERVEY BAY AND THE URBAN COAST OF THE GBR SINCE 2005. NEW DATA FROM THE 2022 SURVEY ARE IN BOLD.

Survey region	# dugong group sightings (# dugongs)				# calves sighted (% of calves)				Group Size Mode | Mean | Range				# dugong herds (# dugongs)			
	2005	2011	2016	**2022**	2005	2011	2016	**2022**	2005	2011	2016	**2022**	2005	2011	2016	**2022**
Moreton Bay	37 (53)	67 (94)	82 (110)*	**70 (108)**	10 (18.9)	8 (8.5)	11 (10.0)	**6 (5.5)**	1 | 1.4 | 1-6	1 | 1.4 | 1-7	1 | 1.3 | 1-9	**1 | 1.5 | 1-10**	4 (10, 29, 31, 146)	3 (44, 117, 170)	5 (14, 33, 36, 45, 49)	**1 (51)**
Hervey Bay	136 (189)	93 (141)	126 (168)	**69 (103)**	15 (7.9)	12 (8.5)	22 (13.0)	**9 (8.7)**	1 | 1.4 | 1-8	1 | 1.5 |1-6	1 | 1.3 | 1-4	**1 | 1.5 | 1-8**	No distinct herd	1 (25)	1 (15)	**No distinct herd**
Urban coast of GBR	133 (194)	52 (66)	150 (217)	**128 (179)**	10 (5.1)	0	22 (10.1)	**15 (8.3)**	1 |1.5 |1-6	1 |1.3 | 1-6	1 | 1.4 | 1-5	**1 | 1.4 | 1-6**	3 (12, 50, 70)	No distinct herd	1 (8)	**No distinct herd**

* Based on data that includes the second survey of block 4 in Moreton Bay (see table 4 in Sobtzick et al. 2017).

6.7 APPENDIX 7: DISTRIBUTION OF DUGONG SIGHTINGS FROM THE 2022 SURVEY OF THE URBAN COAST OF THE GBR, HERVEY BAY AND MORETON BAY

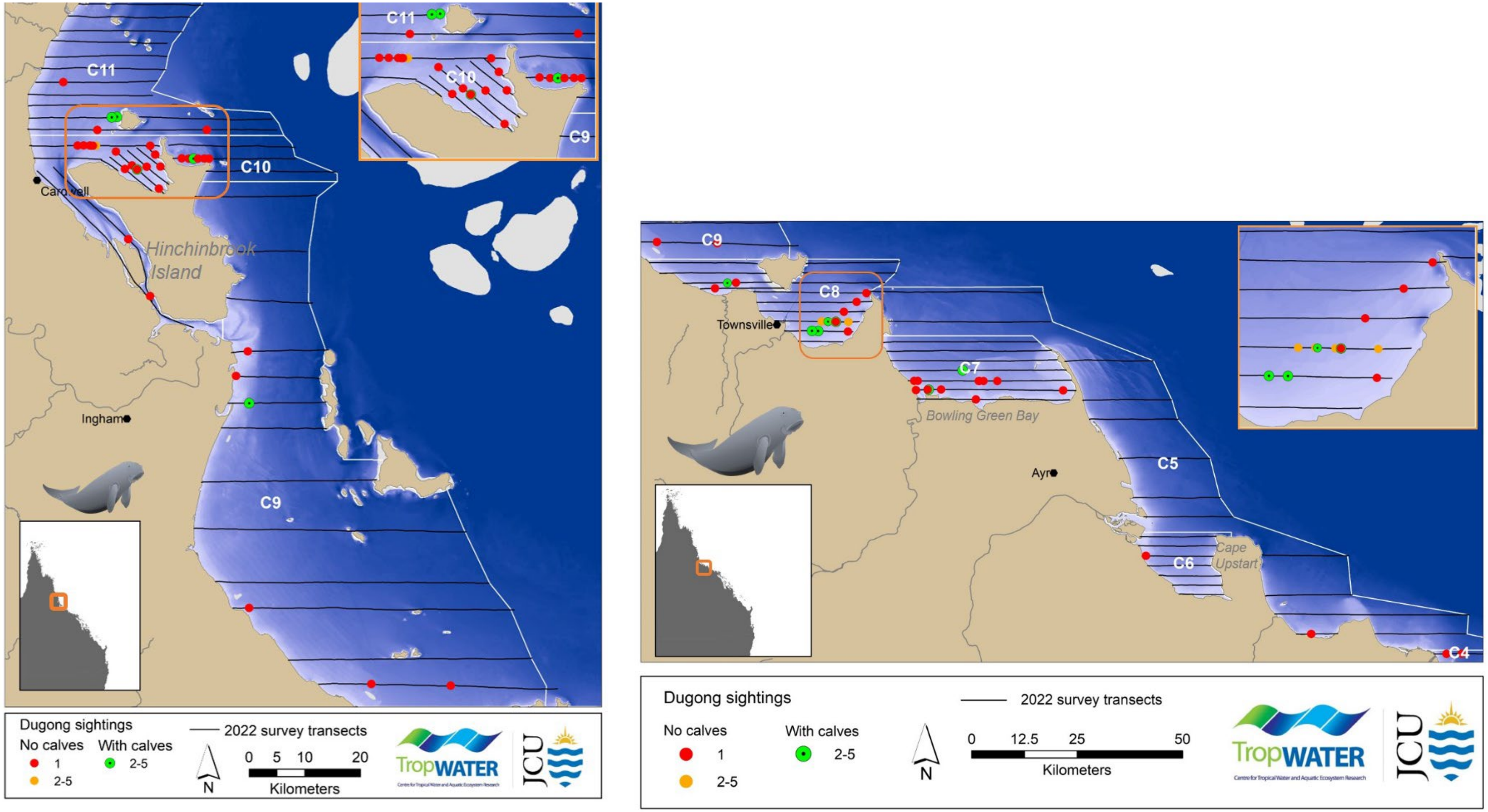


Figure 7.1. Distribution of dugong sightings in the Cardwell (left panel) and Townsville-Ayr (right panel) regions in 2022.

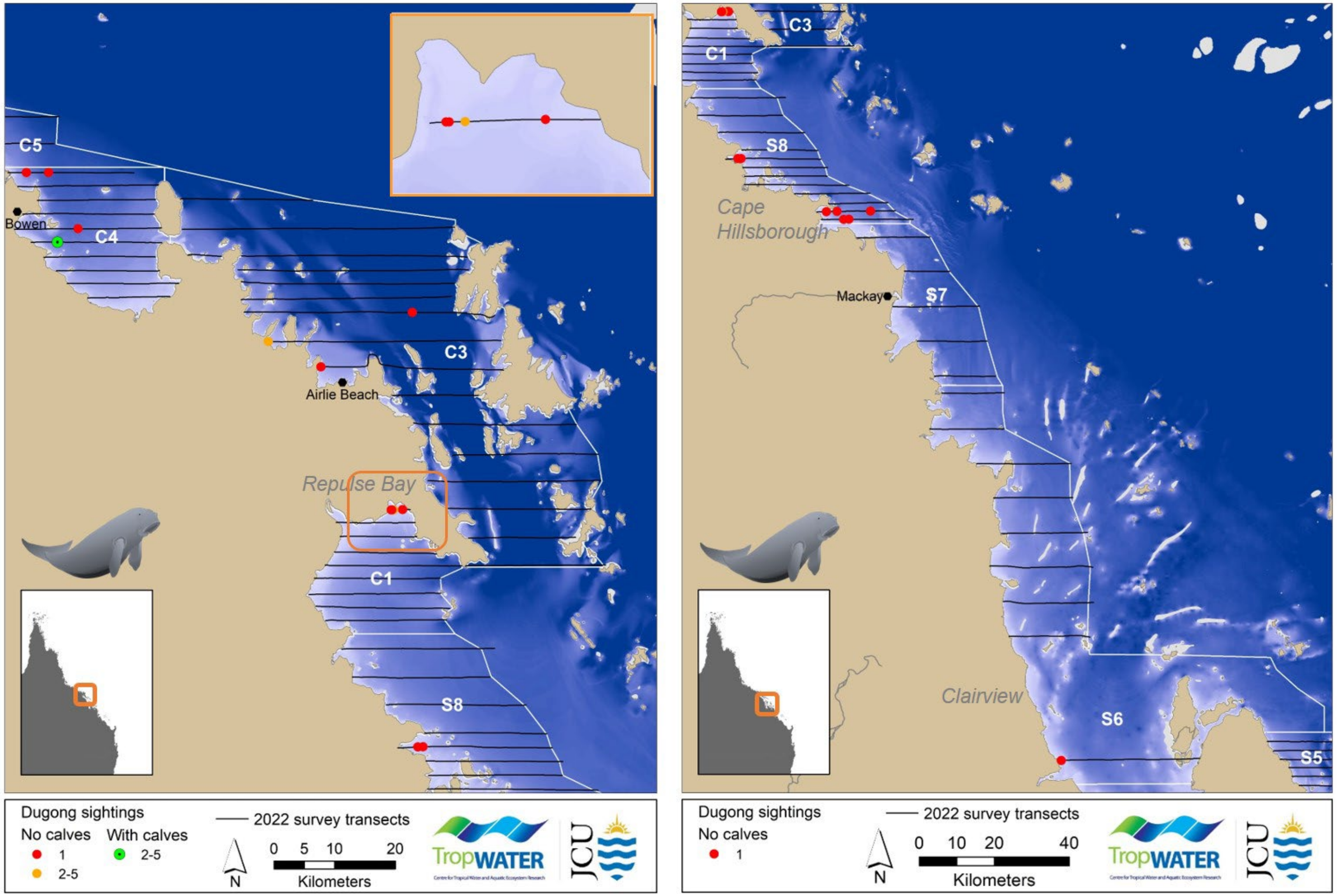


Figure 7.2. Distribution of dugong sightings in the Whitsundays (left panel) and Mackay (right panel) regions in 2022.

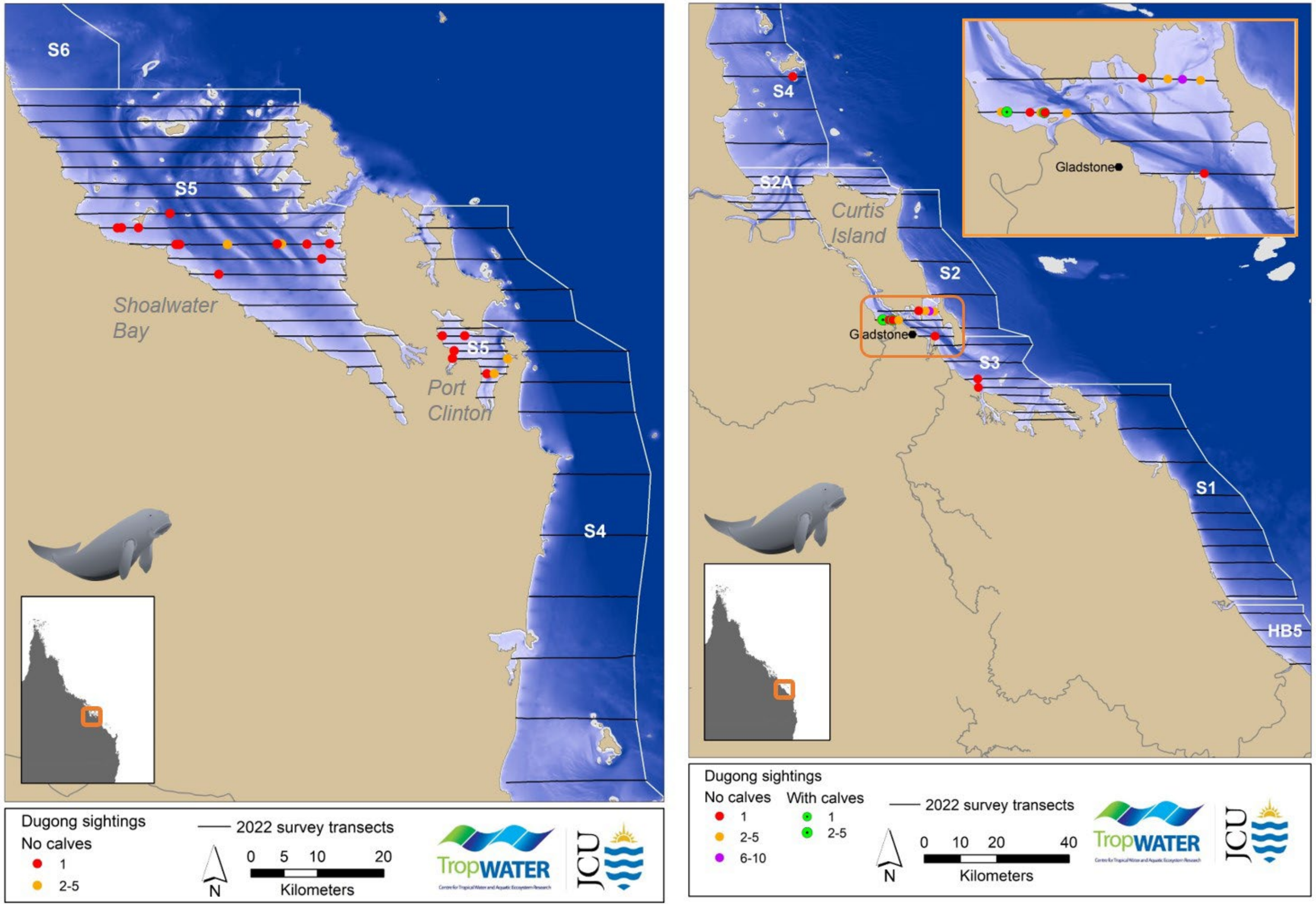


Figure 7.3. Distribution of dugong sightings in the Shoalwater Bay (left panel) and Gladstone (right panel) regions in 2022.

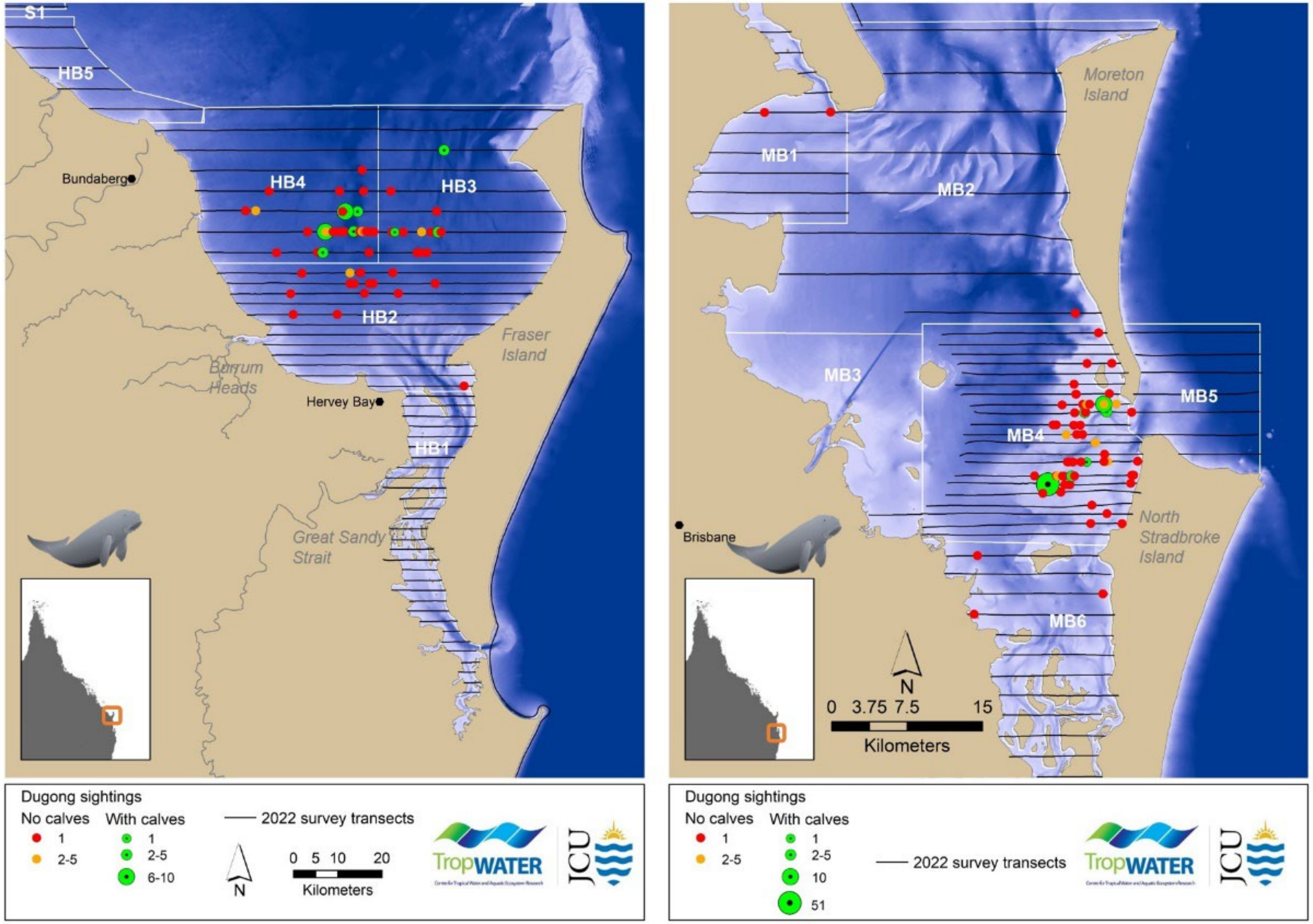
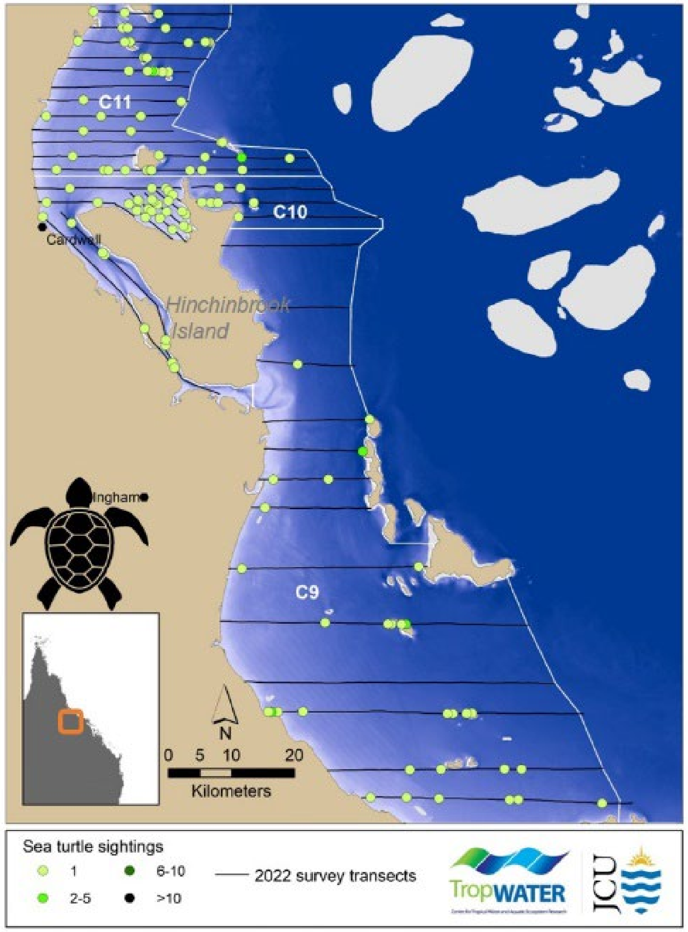


Figure 7.4. Distribution of dugong sightings in the Hervey Bay (left panel) and Moreton Bay (right panel) regions in 2022.

6.8 APPENDIX 8: DISTRIBUTION OF MARINE MEGAFAUNA SIGHTINGS OTHER THAN DUGONGS FROM THE 2022 SURVEY OF THE URBAN COAST OF THE GBR, HERVEY BAY AND MORETON BAY



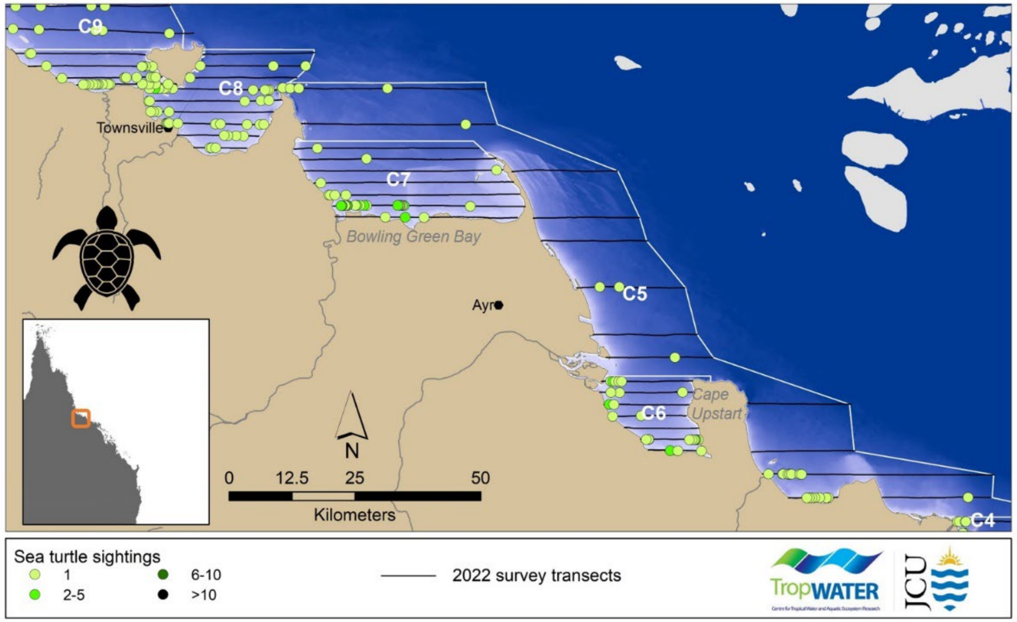


Figure 8.1. Distribution of sea turtle sightings in the Cardwell (left panel) and Townsville-Ayr (right panel) regions in 2022.

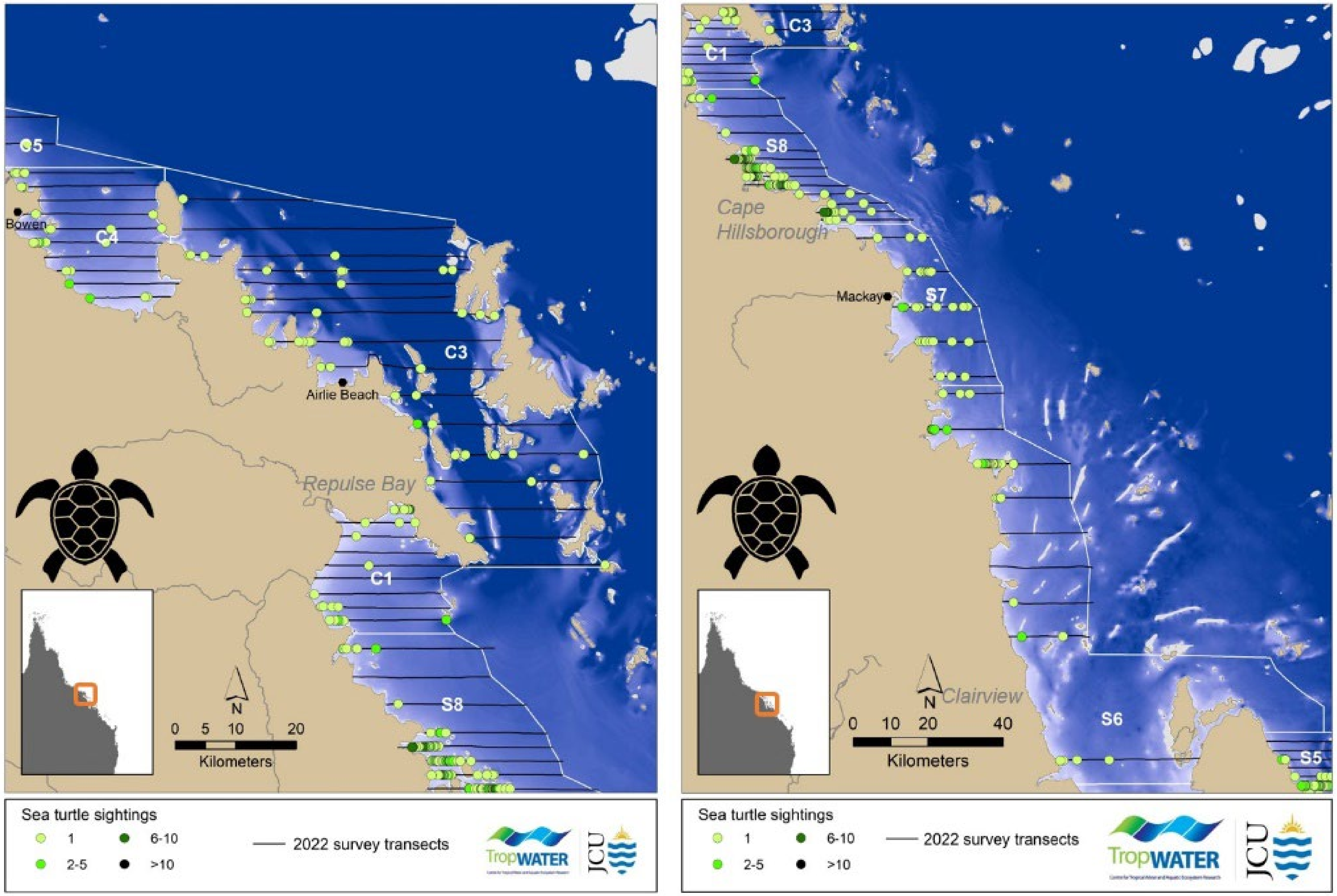


Figure 8.2. Distribution of sea turtle sightings in the Whitsundays (left panel) and Mackay (right panel) regions in 2022.

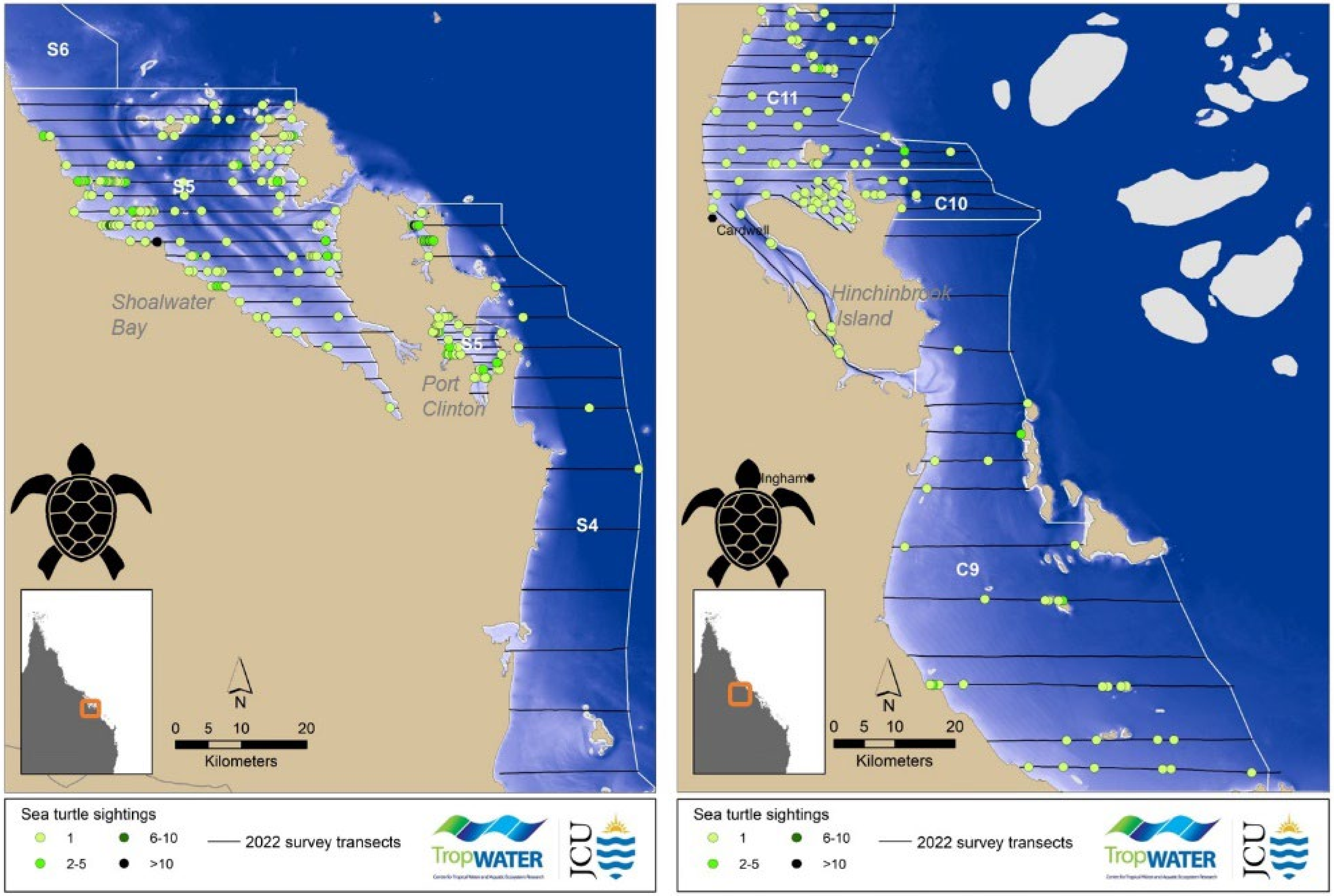


Figure 8.3. Distribution of sea turtle sightings in the Shoalwater Bay (left panel) and Gladstone (right panel) regions in 2022.

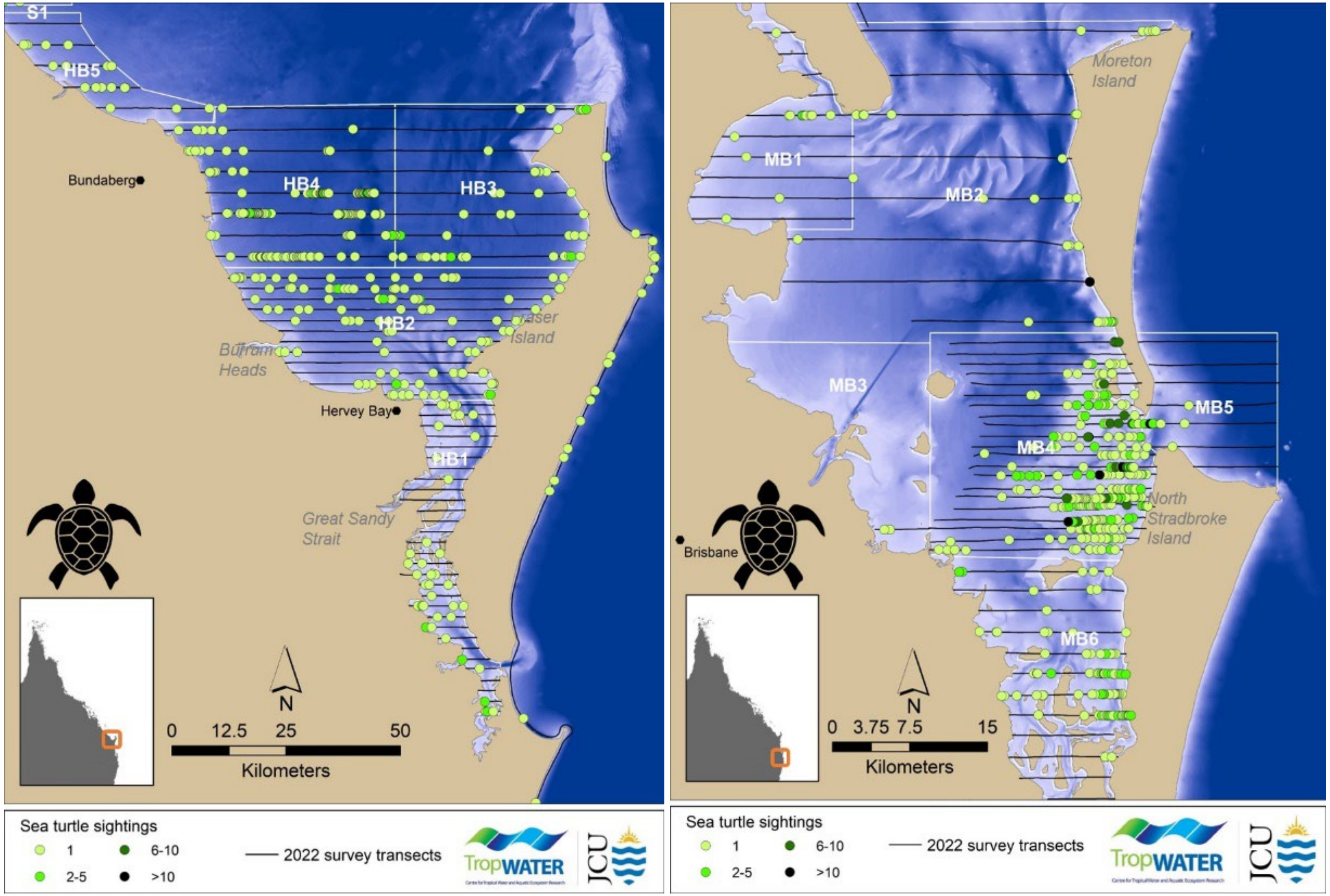


Figure 8.4. Distribution of sea turtle sightings in the Hervey Bay (left panel) and Moreton Bay (right panel) regions in 2022.

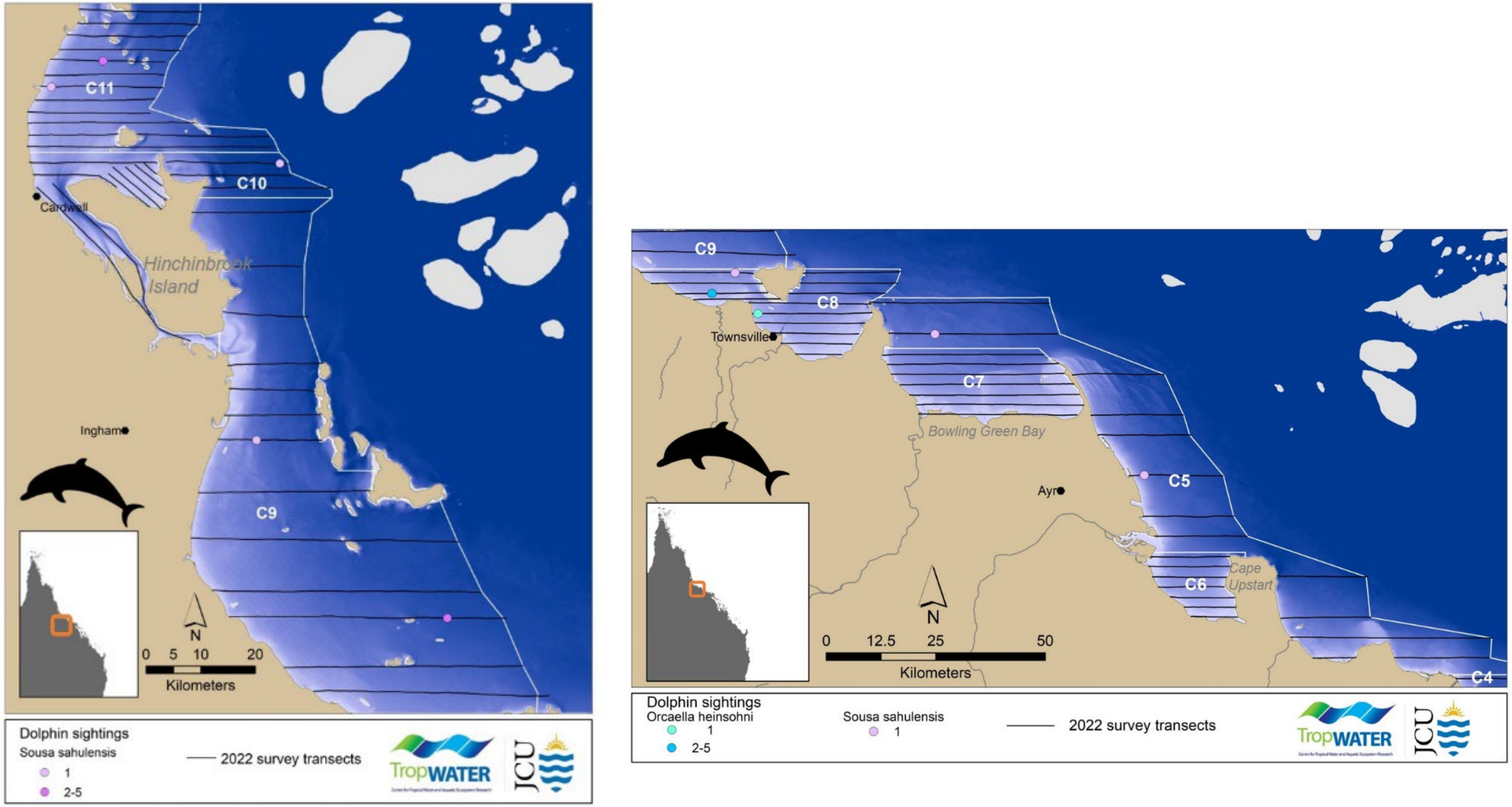


Figure 8.5. Distribution of dolphin sightings in the Cardwell (left panel) and Townsville-Ayr (right panel) regions in 2022. Only sightings with certain species identification are shown.

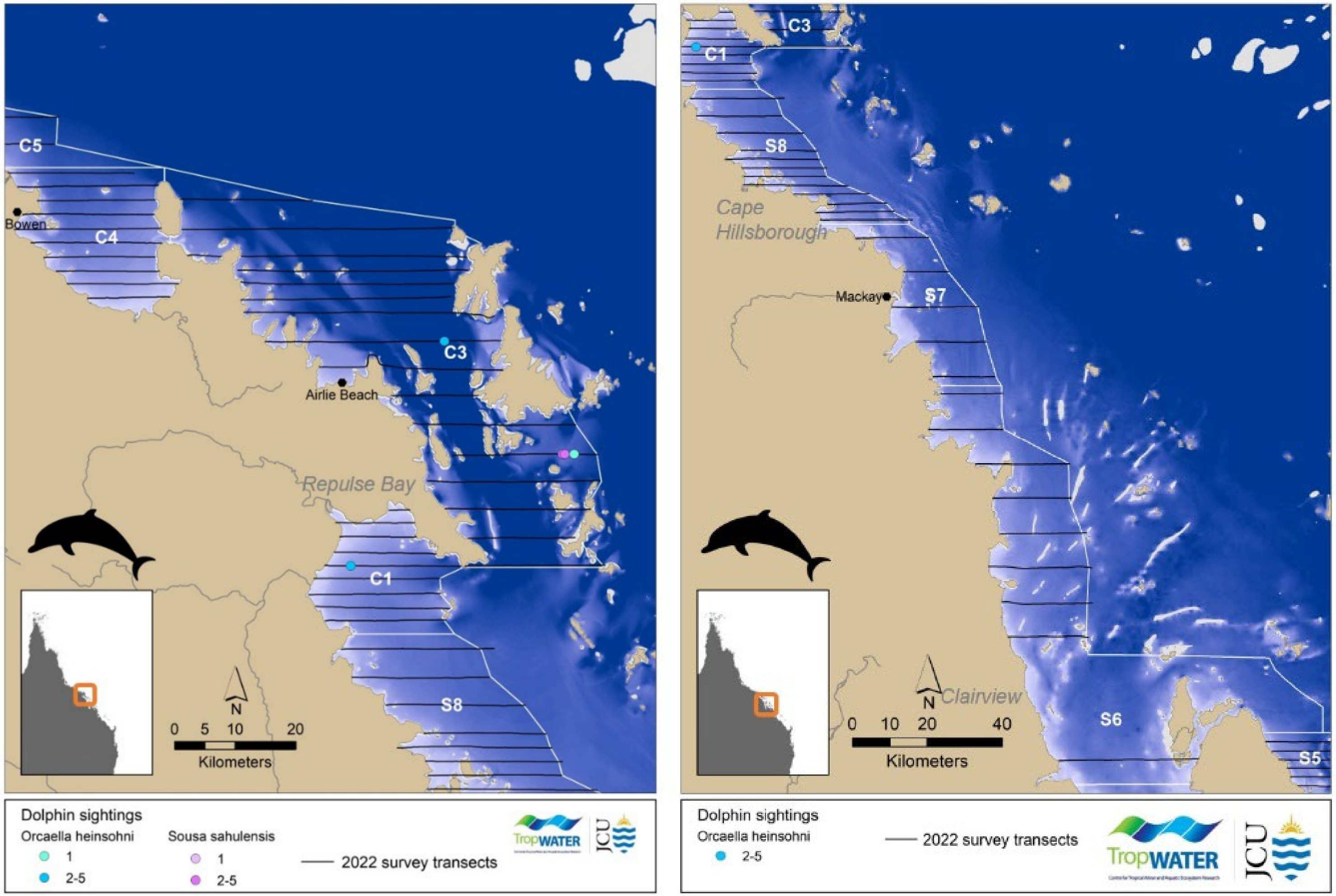


Figure 8.6. Distribution of dolphin sightings in the Whitsundays (left panel) and Mackay (right panel) regions in 2022. Only sightings with certain species identification are shown.

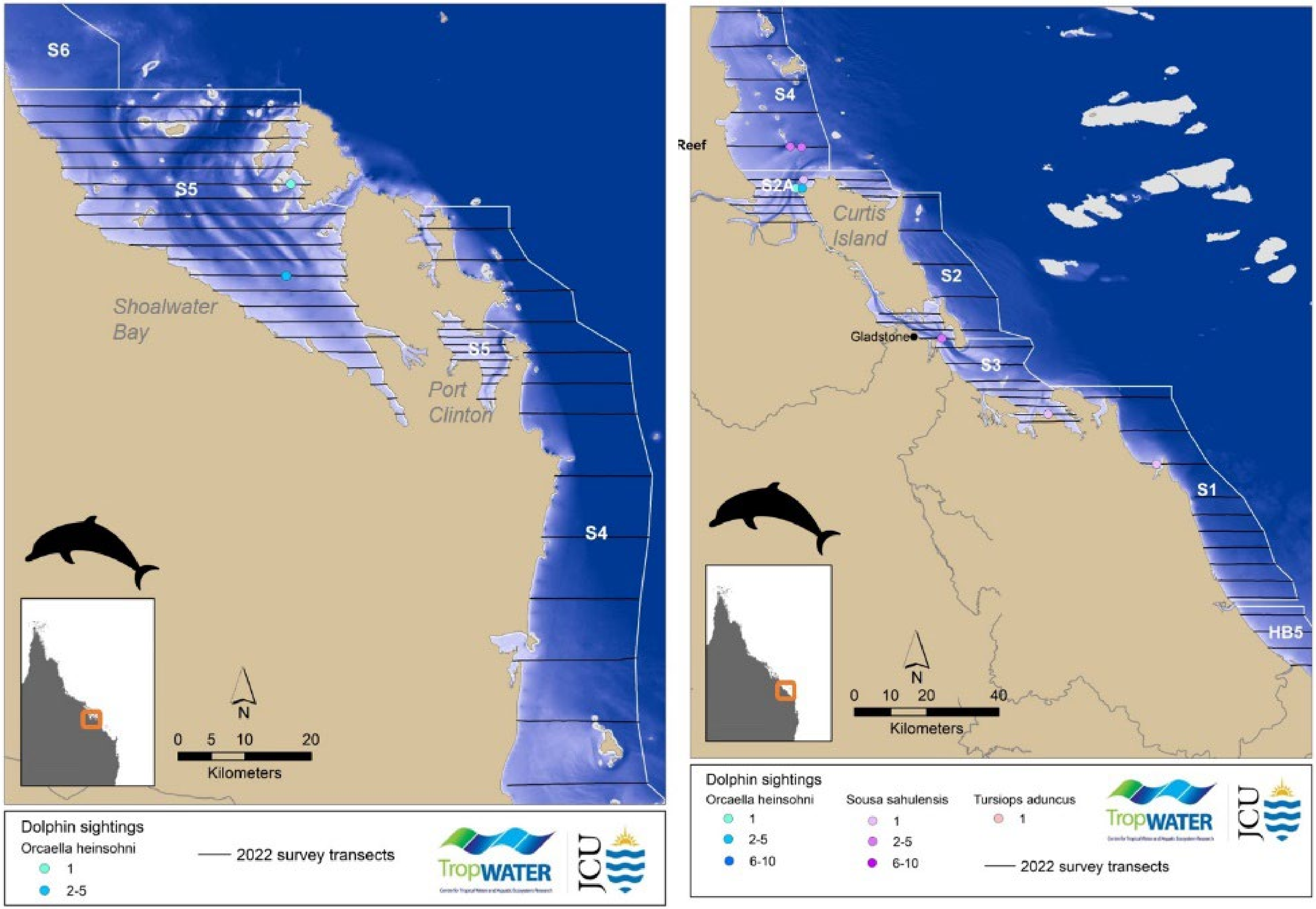


Figure 8.7. Distribution of sea turtle sightings in the Shoalwater Bay (left panel) and Gladstone (right panel) regions in 2022. Only sightings with certain species identification are shown.

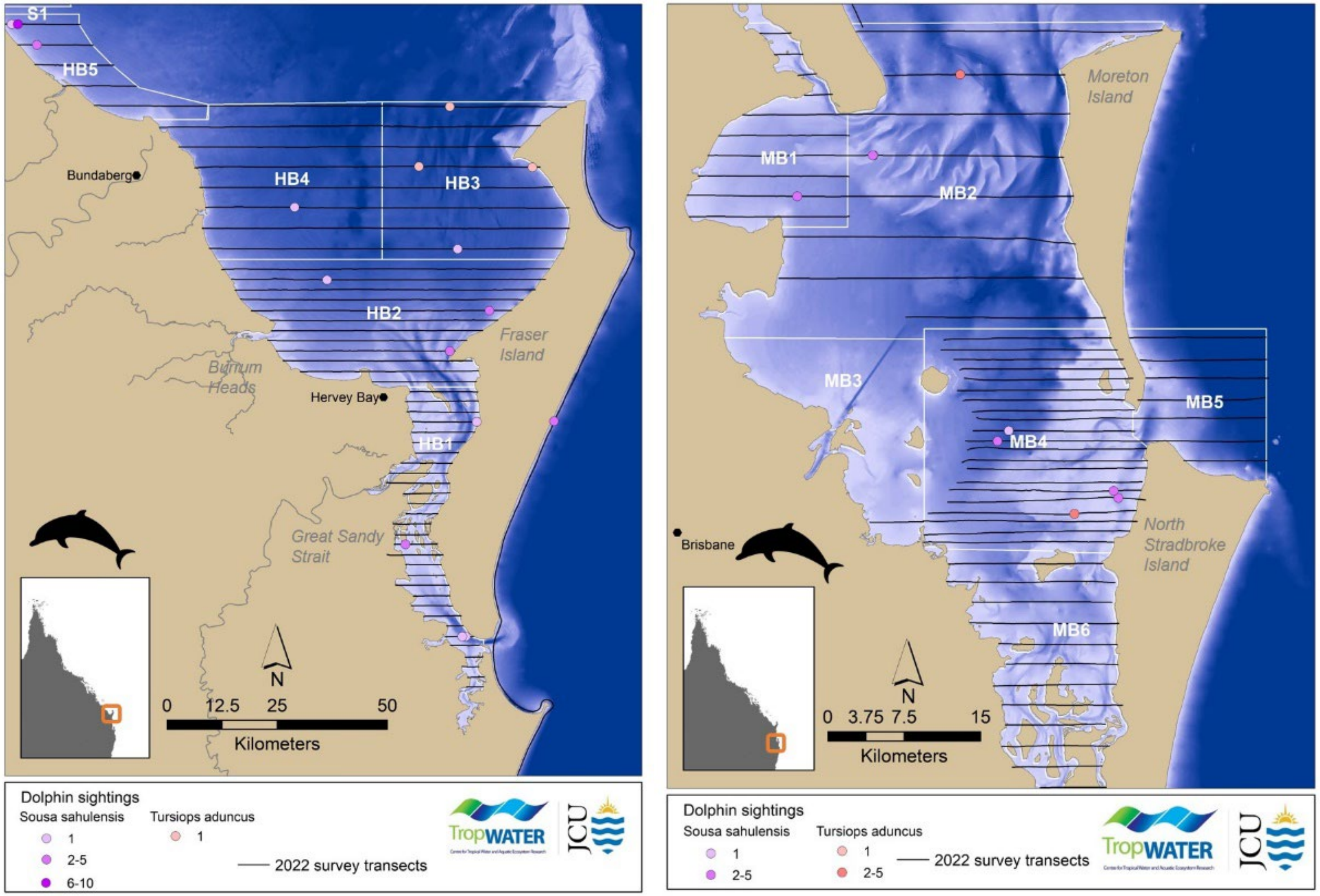


Figure 8.8. Distribution of dolphin sightings in the Hervey Bay (left panel) and Moreton Bay (right panel) regions in 2022. Only sightings with certain species identification are shown.

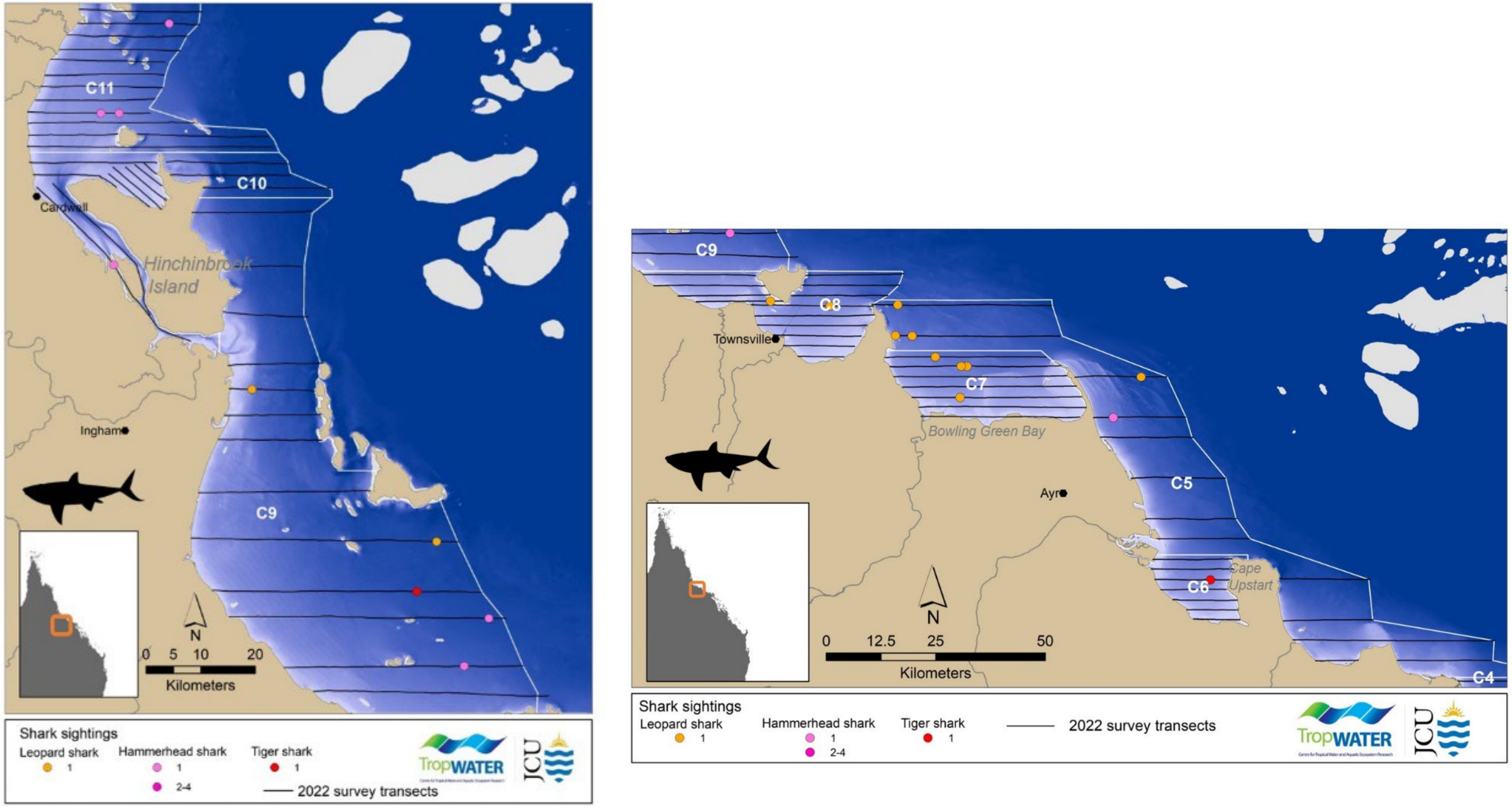


Figure 8.9. Distribution of shark sightings in the Cardwell (left panel) and Townsville-Ayr (right panel) regions in 2022. Only sightings with certain species identification are shown.

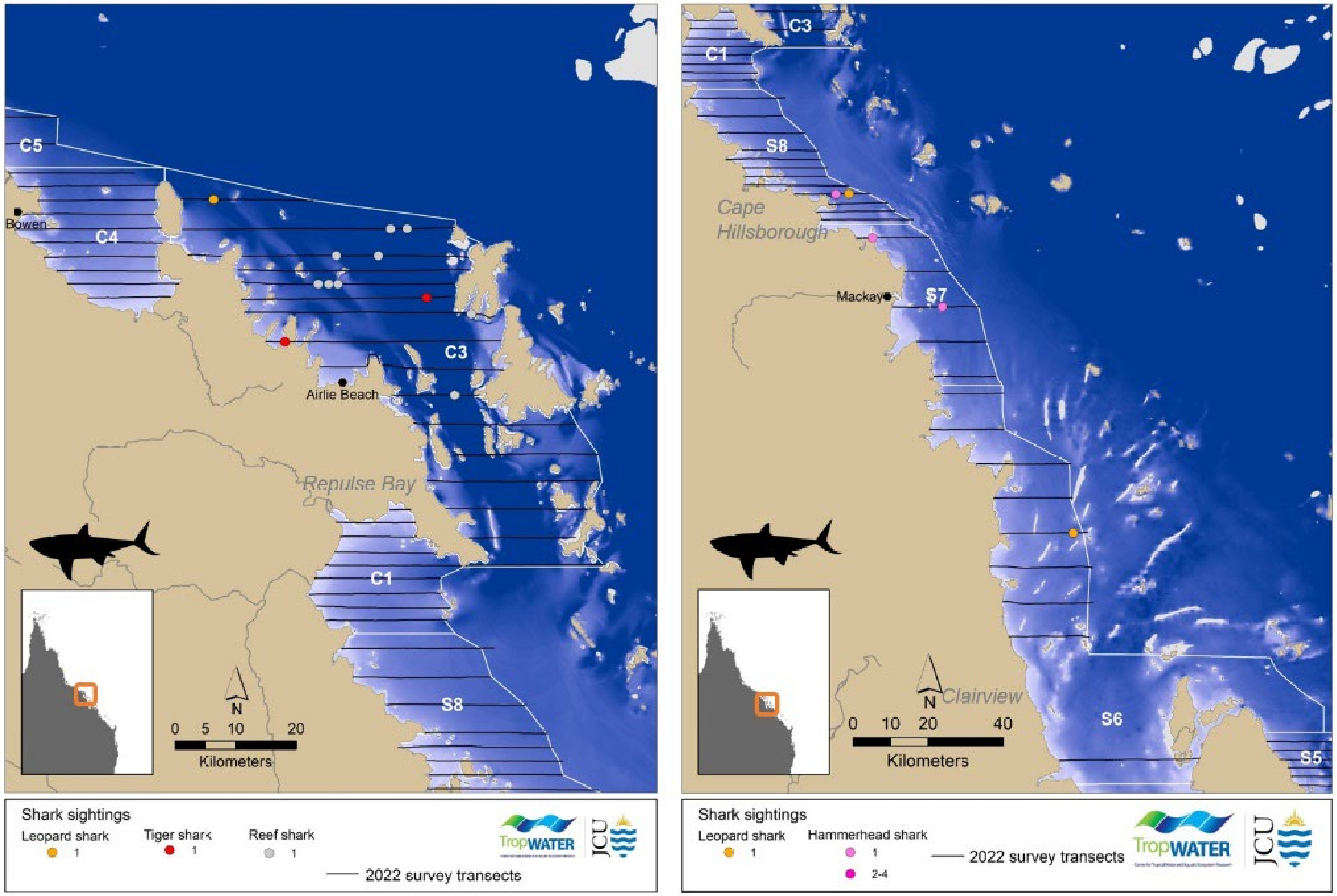


Figure 8.10. Distribution of shark sightings in the Whitsundays (left panel) and Mackay (right panel) regions in 2022. Only sightings with certain species identification are shown.

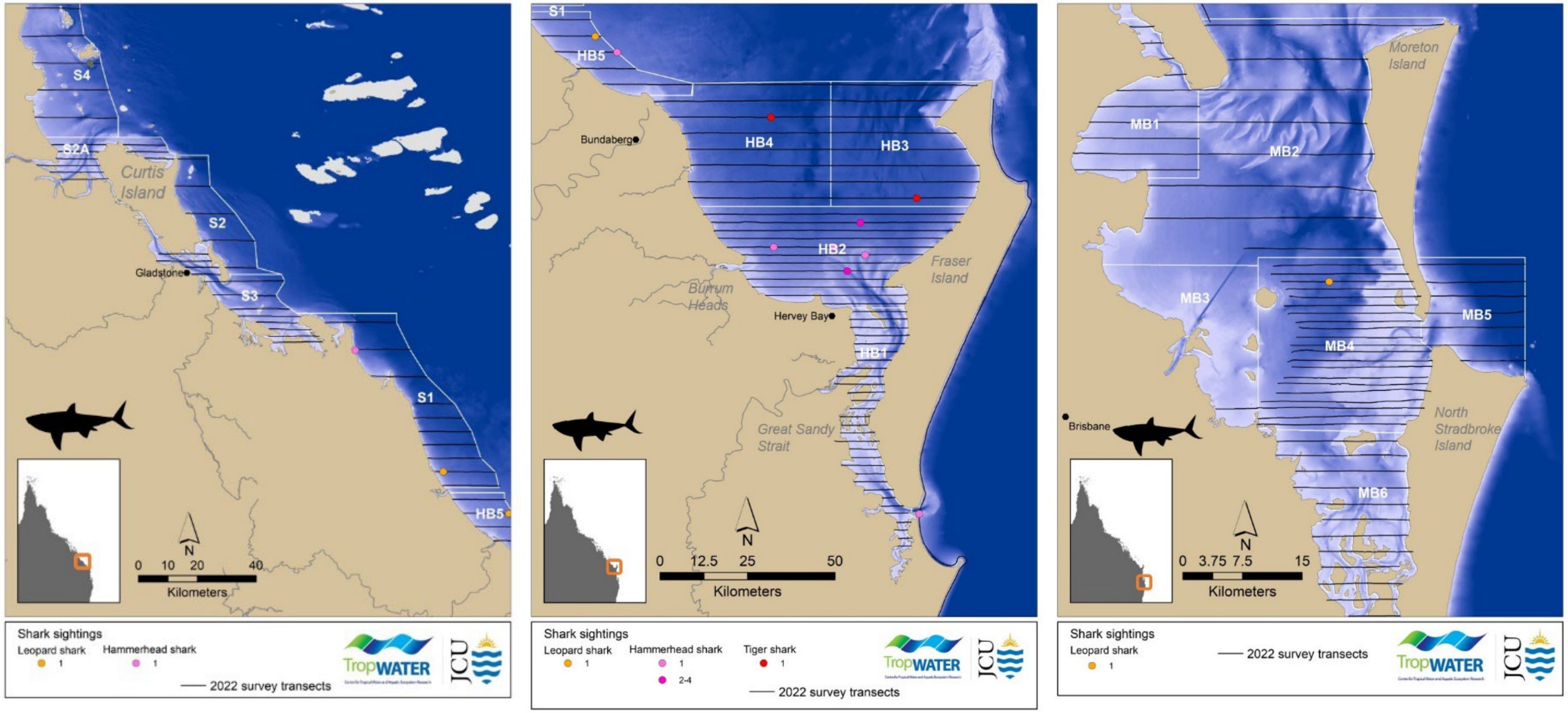


Figure 8.11. Distribution of shark sightings in the Gladstone (left panel) Hervey Bay (middle panel) and Moreton Bay (right panel) regions in 2022. Only sightings with certain species identification are shown.

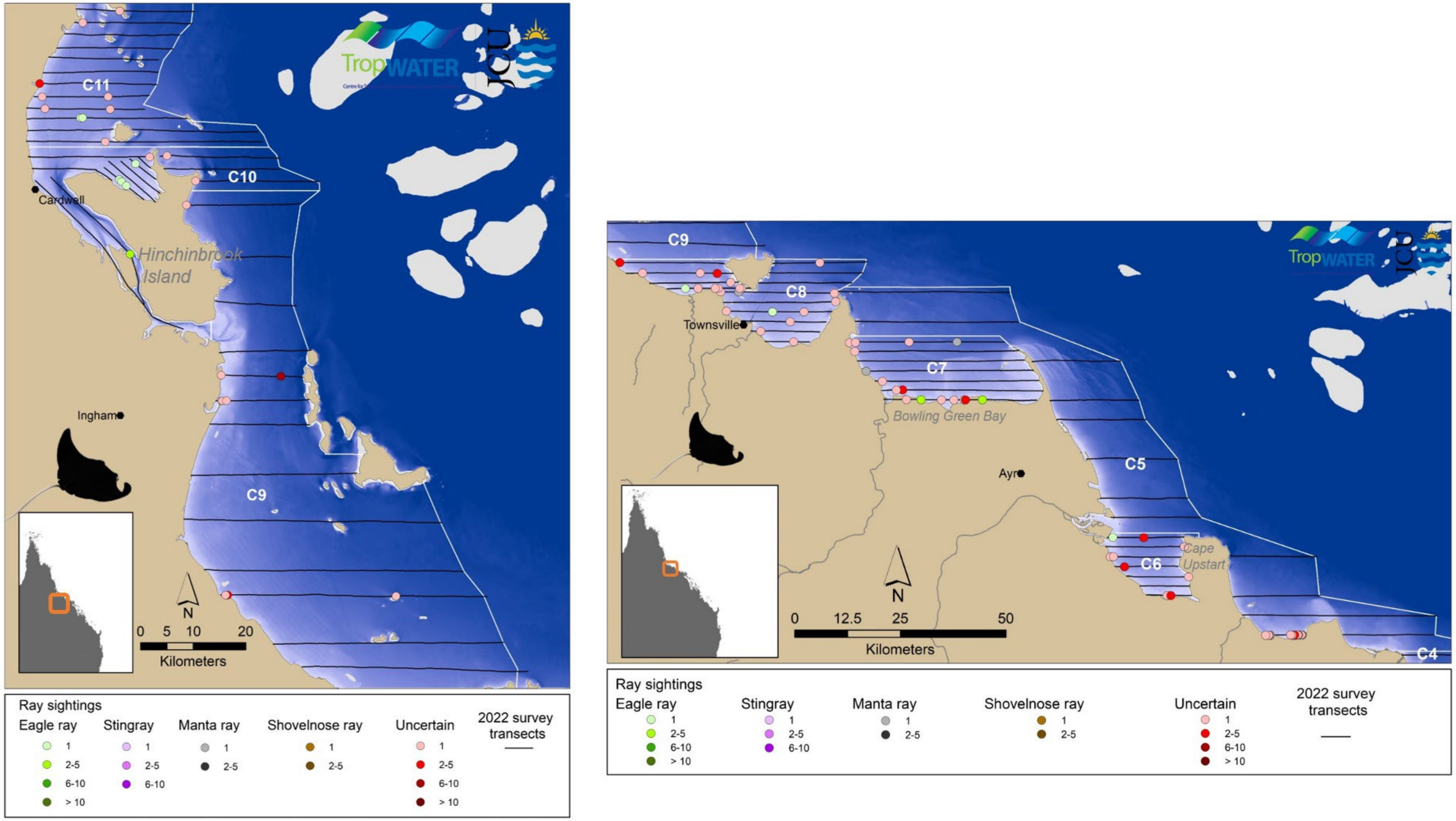


Figure 8.12. Distribution of ray sightings in the Cardwell (left panel) and Townsville-Ayr (right panel) regions in 2022. Only sightings with certain species identification are shown.

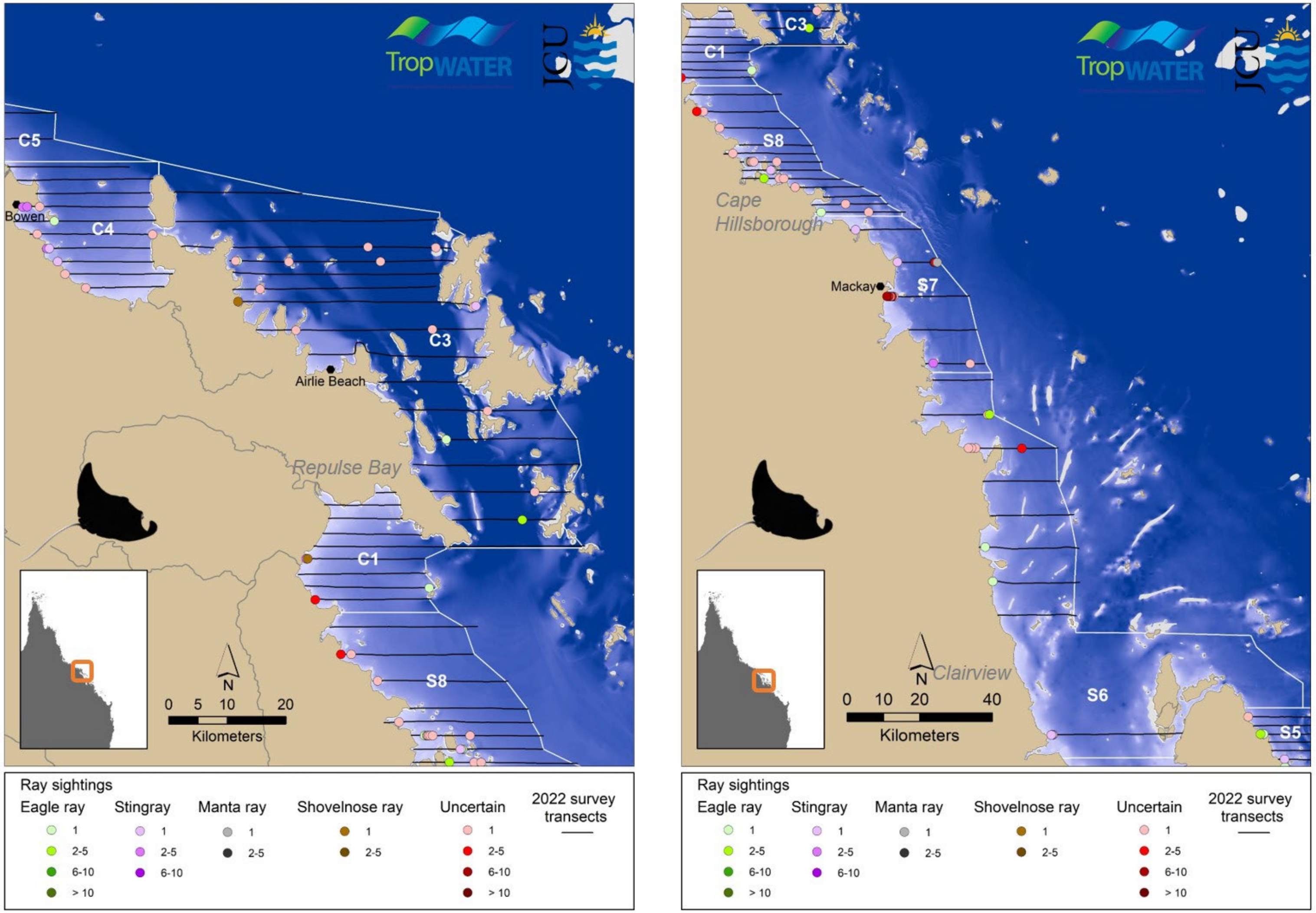


Figure 8.13. Distribution of ray sightings in the Whitsundays (left panel) and Mackay (right panel) regions in 2022. Only sightings with certain species identification are shown.

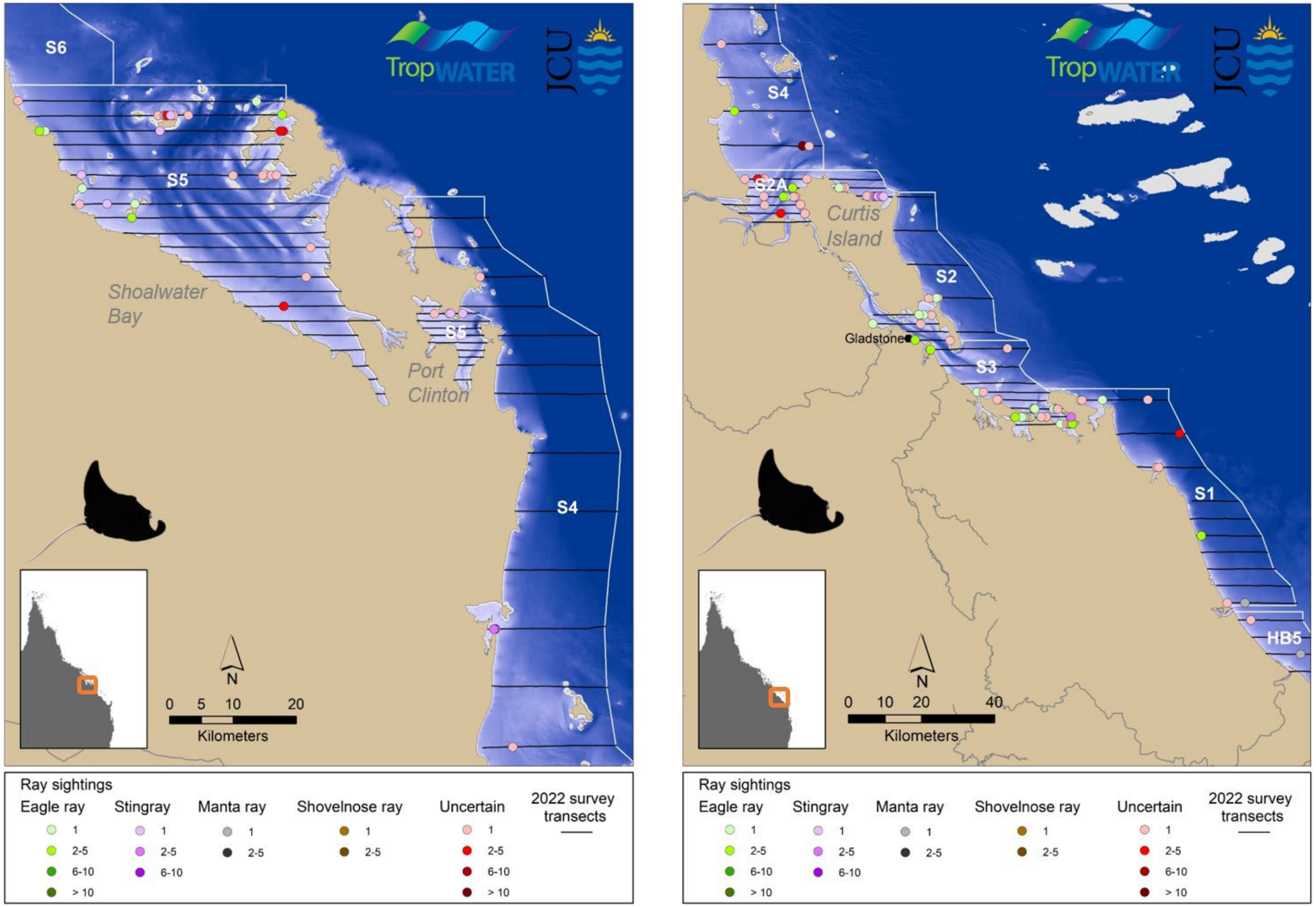


Figure 8.14. Distribution of ray sightings in the Shoalwater Bay (left panel) and Gladstone (right panel) regions in 2022. Only sightings with certain species identification are shown.

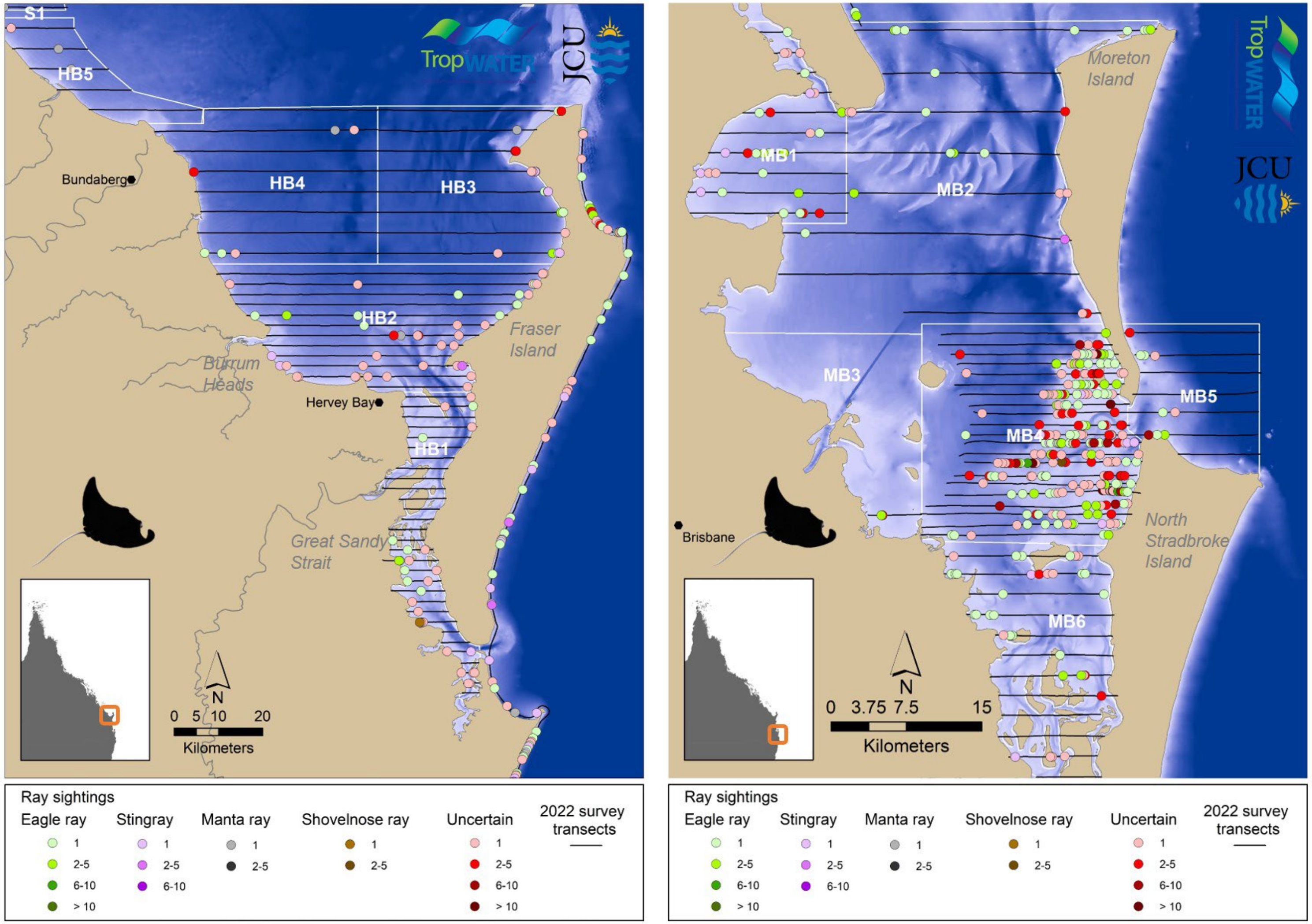
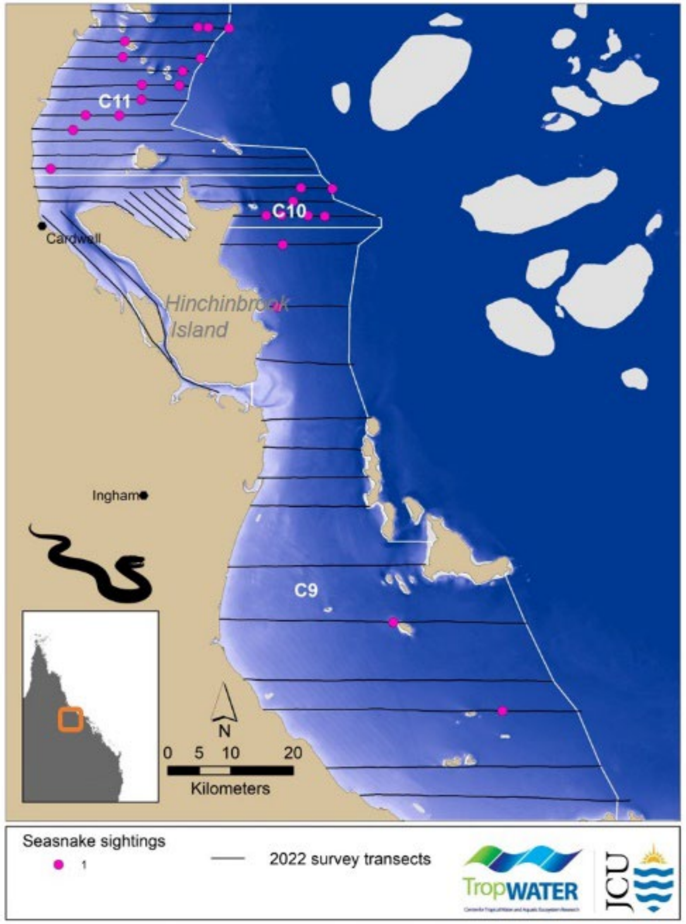


Figure 8.15. Distribution of ray sightings in the Hervey Bay (left panel) and Moreton Bay (right panel) regions in 2022. Only sightings with certain species identification are shown.



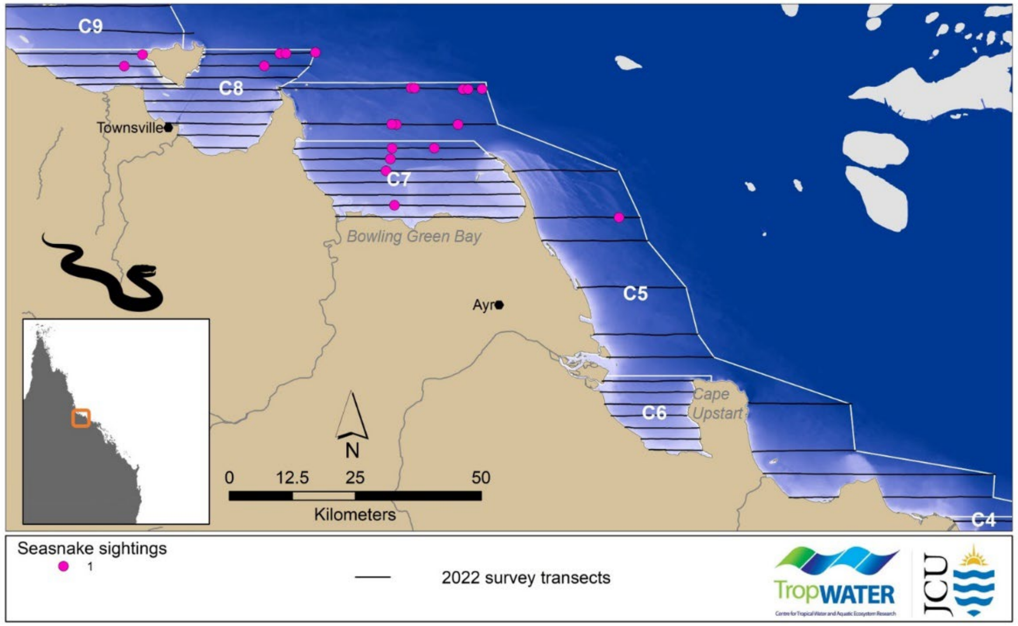


Figure 8.16. Distribution of seasnake sightings in the Cardwell (left panel) and Townsville-Ayr (right panel) regions in 2022. Only sightings with certain taxa identification are shown.

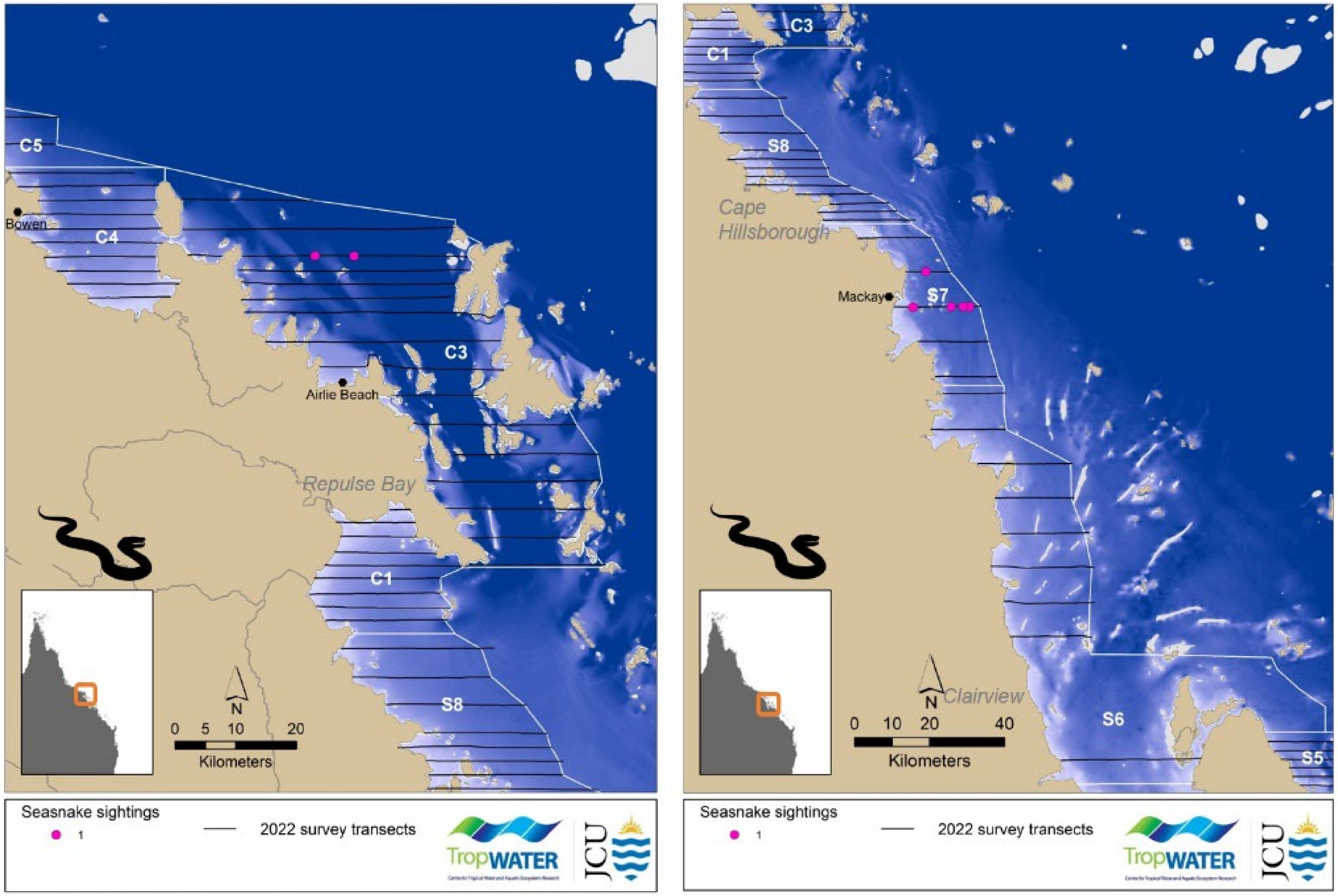


Figure 8.17. Distribution of seasnake sightings in the Whitsundays (left panel) and Mackay (right panel) regions in 2022. Only sightings with certain taxa identification are shown.

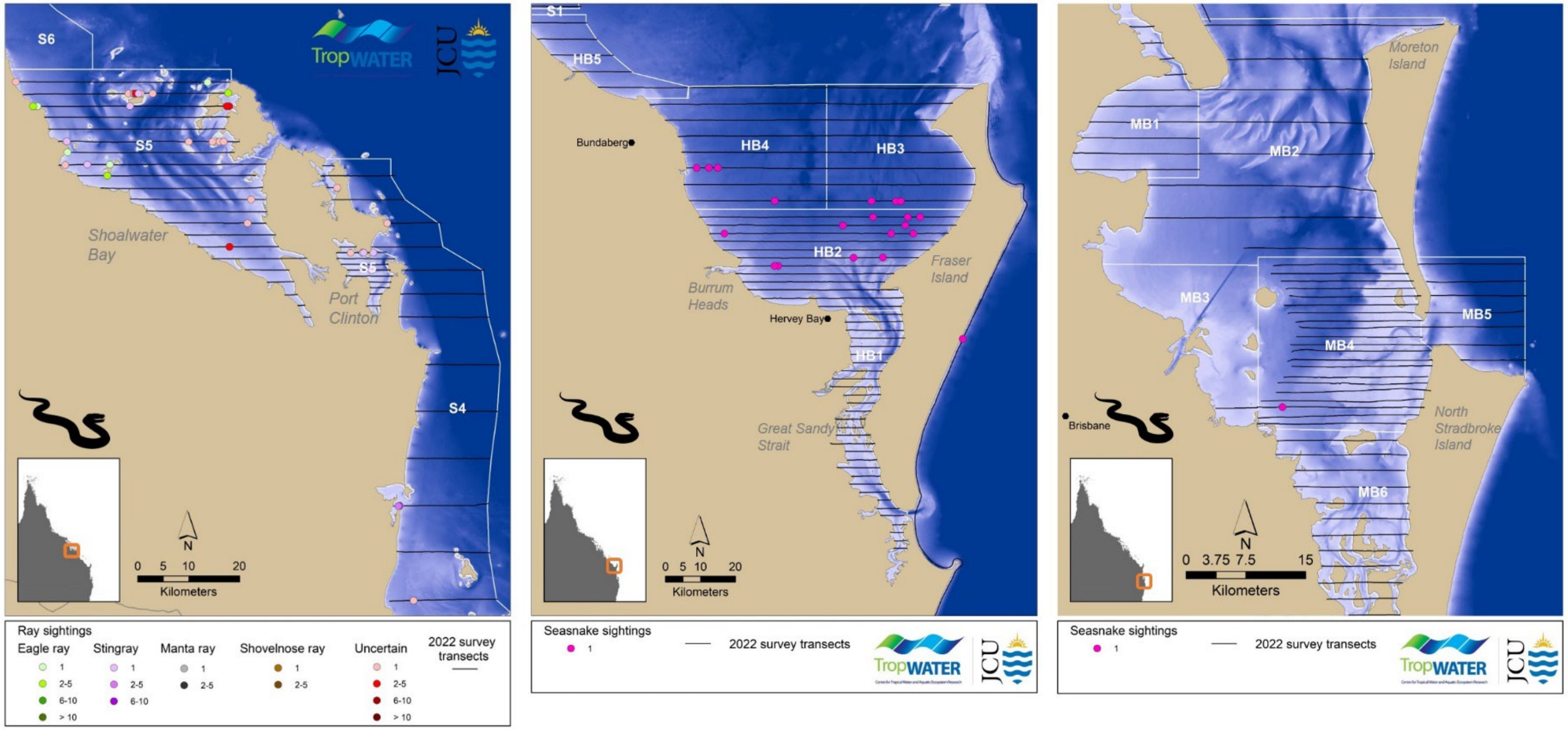


Figure 8.17. Distribution of seasnake sightings in the Shoalwater Bay (left panel) Hervey Bay (middle panel) and Moreton Bay (right panel) regions in 2022. Only sightings with certain taxa identification are shown.

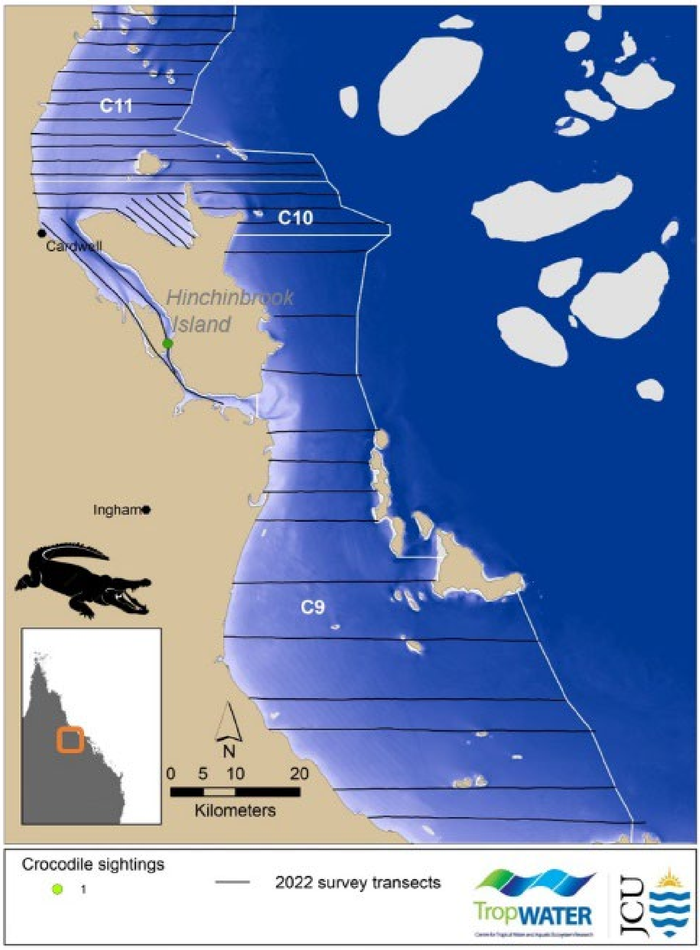


Figure 8.18. Distribution of crocodile sightings in the Cardwell region in 2022.

6.9 APPENDIX 9: RECORDS OF SIGHTINGS OF MARINE MEGAFAUNA SPECIES OTHER THAN DUGONGS AND SEA TURTLES DURING THE 2022 SURVEY OF THE URBAN COAST OF THE GBR, HERVEY BAY AND MORETON BAY.

Genus, species & survey region	Count of n_in_gp	Sum of n_in_gp
Crocodile	1	1
Urban coast of GBR	1	1
Dolphin	168	379
Urban coast of GBR	80	165
Moreton Bay	36	108
Sousa	11	21
Certain	8	16
Probable	3	5
Tursiops	17	75
Certain	7	27
Probable	10	48
Unknown	8	12
Hervey Bay	52	106
Sousa	22	55
Certain	14	42
Probable	8	13
Tursiops	1	3
Probable	1	3
Tursiops	20	37
Certain	3	3
Probable	17	34
Unknown	9	11
Ray	858	1426
Urban coast of GBR	285	418
Moreton Bay	416	820
Cownose Ray	3	14

Probable	3	14
Eagle Ray	205	366
Certain	196	346
NA	1	1
Probable	8	19
Manta Ray	1	1
Certain	1	1
NA	171	399
Shovelnose Ray	1	2
Certain	1	2
Sting Ray	5	5
Certain	5	5
Stingray	30	33
Certain	29	32
Probable	1	1
Hervey Bay	157	188
Eagle Ray	59	68
Certain	51	60
Guess	1	1
NA	1	1
Probable	6	6
Manta	1	1
Certain	1	1
Manta Ray	5	5
Certain	5	5
NA	71	87
Shovelnose Ray	1	1
Certain	1	1
Sting Ray	3	3
Certain	3	3

Stingray	17	23
Certain	17	23
Sea Snake	74	74
Urban coast of GBR	53	53
Moreton Bay	1	1
Hervey Bay	20	20
Shark	180	190
Urban coast of GBR	116	120
Moreton Bay	33	38
Leopard Shark	1	1
Certain	1	1
NA	32	37
Hervey Bay	31	32
Hammerhead	1	1
Certain	1	1
Hammerhead Shark	6	7
Certain	5	5
Probable	1	2
Leopard Shark	3	3
Certain	1	1
Probable	2	2
NA	19	19
Tiger Shark	2	2
Certain	2	2

NA: no record of genus or certainty on species ID.

6.10 APPENDIX 10: DUGONG POPULATION ESTIMATES IN THE URBAN COAST OF THE GBR, HERVEY BAY AND MORETON BAY USING THE HAGIHARA METHOD.

Southern Great Barrier Reef Region				
Block	2005	2011	2016	2022
S1	zzt	tfs	tfs	0
S2	tfs	0	tfs	0
S3 (inc S2A)	134 (± 82)	tfs	tfs	280 (± 129)
S4	zzt	dd	tfs	tfs
S5	611 (± 174)	345 (± 229)	583 (± 222)*	335 (± 231)
S6	dd	dd	tfs	tfs
S7	zzt	0	tfs	0
S8	tfs	tfs	122(± 88)	109 (± 90)
Total S-Blocks	745 (± 192)	345 (± 229)	705 (± 239)	724 (± 280)
C1	tfs	tfs	tfs	tfs
C3	tfs	tfs	tfs	tfs
C4	74 (± 41)	tfs	265 (± 160)	142 (± 85)
C5	ns	dd	tfs	tfs
C6	173 (± 82)	64 (± 52)	tfs	tfs
C7	tfs	tfs	tfs	161 (± 102)
C8	193 (± 101)	tfs	1171 (± 423)	228 (± 135)
C9	zzt	tfs	361 (± 252)	304 (± 220)
C10	266 (± 165)	116 (± 93)	320 (± 187)	447 (± 235)
C11	107 (± 85)	59 (± 53)	ns	118 (± 93)
C12	zzt	tfs	ns	ns
Total C-Blocks*	813 (± 230)	239 (± 119)	2117 (± 550)	1400 (± 385)
Total all blocks**	1558 (± 300)	537 (± 223)	2822 (± 600)	2124 (± 476)
Total 2016 blocks only	1451 (± 288)	478 (± 253)	2822 (± 600)	2006 (± 466)

* C2 (outside Witsundays) is no longer surveyed and thus was removed.

Hervey Bay				
Block	2005	2011	2016	2022
HB 1	319 (± 133)	365 (± 90)	583 (± 176)	0
HB 2	816 (± 238)*	898 (± 413)#	684 (± 173)~	184 (± 100)
HB 3	253 (± 173)	103 (± 66)	178 (± 106)	324 (± 203)
HB 4	tfs	72 (± 96)	610 (± 272)	1025 (± 592)
HB 5	0	0	0	0
Total all blocks	1388 (± 323)	1438 (± 438)	2055(± 382)	1533 (± 634)

Moreton Bay				
Block	2005	2011	2016	2022
MB 1	49 (± 24) *	tfs	tfs	tfs
MB 2	tfs	tfs	tfs	tfs
MB 3	0	tfs	tfs	Tfs*
MB 4	373 (± 71) **	552# (± 83)	447~ (± 75)	400 (± 116)
MB 5	0	tfs	tfs	tfs
MB 6	17 (± 14)	144 (± 66)	154 (± 27)	tfs
Total all blocks	453 (± 97)	696 (± 106)	601 (± 80)	400 (± 116)

* Only one of the five predefined transects could be flown in block MB3 in 2022 due to air traffic control restrictions.

6.11 APPENDIX 11: DUGONG POPULATION DENSITIES FROM 2005 TO 2022, POSTERIOR SUMMARY STATISTICS

Region	Year	Posterior Mean Density (Dugongs/km)	SE	95%CI
Hervey Bay	2005	0.309	0.084	0.184 - 0.504
Hervey Bay	2011	0.215	0.062	0.123 - 0.359
Hervey Bay	2016	0.304	0.088	0.173 - 0.514
Hervey Bay	2022	0.094	0.030	0.052 - 0.166
Moreton Bay	2005	0.330	0.090	0.201 - 0.540
Moreton Bay	2011	0.444	0.106	0.279 - 0.695
Moreton Bay	2016	0.393	0.102	0.244 - 0.644
Moreton Bay	2022	0.274	0.078	0.160 - 0.458
Southern Great Barrier Reef	2005	0.230	0.044	0.159 - 0.332
Southern Great Barrier Reef	2011	0.022	0.004	0.015 - 0.031
Southern Great Barrier Reef	2016	0.144	0.033	0.093 - 0.224
Southern Great Barrier Reef	2022	0.086	0.017	0.058 - 0.125

6.12 APPENDIX 12: ANNUALISED LOG-LINEAR CHANGE IN DUGONG POPULATION DENSITIES SINCE 2005

Region	Posterior Annualised Trend in Density	SE	95%CI	Probability of Decline
Hervey Bay	-0.057	0.021	-0.098 - -0.014	0.995
Moreton Bay	-0.012	0.021	-0.051 - 0.028	0.720
Southern Great Barrier Reef	-0.023	0.015	-0.052 - 0.006	0.938

6.13 APPENDIX 13: INTER-ANNUAL COMPARISON IN DUGONG POPULATION DENSITIES SINCE 2005

Year	**Hervey Bay**	**Moreton Bay**	**Urban coast of GBR**
2005	0.002	0.310	0.000
2011	0.022	0.084	1.000
2016	0.002	0.162	0.040

6.14 APPENDIX 14: COEFFICIENTS FROM THE LOGISTIC MODEL FOR MORETON BAY, HERVEY BAY, AND SOUTHERN GBR BETWEEN 1974 AND 2022.

Parameter	**Proportion**	**Std Error**	**95% CI**	**z-value**	**Pr(>|z|)**
(Intercept)	0.08	0.014	0.05, 0.11	–14.47	< 0.001
Year (base 1974)	0.99	0.017	0.95, 1.02	–0.85	0.396
$Year^2$	1.00	0.000	1.00, 1.00	1.29	0.196
Moreton Bay*	–	–	–	–	–
Hervey Bay	2.04	0.747	0.98, 4.13	1.96	0.050
Southern GBR	0.57	0.133	0.36, 0.91	–2.40	0.016
Year × Moreton Bay*	–	–	–	–	–
Year × Hervey Bay	1.00	0.032	0.94, 1.07	0.11	0.915
Year × Southern GBR	1.11	0.027	1.06, 1.16	4.28	< 0.001
$Year^2$ × Moreton Bay*	–	–	–	–	–
$Year^2$ × Hervey Bay	1.00	0.001	1.00, 1.00	–0.74	0.460
$Year^2$ × Southern GBR	1.00	0.001	1.00, 1.00	–3.99	< 0.001

* Moreton Bay was the baseline category therefore the coefficient is 0 (zero)

6.15 APPENDIX 15: NON-CLASSIFIED SPATIALLY EXPLICIT MODELS OF DUGONG DENSITY ACROSS THE URBAN COAST OF THE GREAT BARRIER REEF, HERVEY BAY AND MORETON BAY.

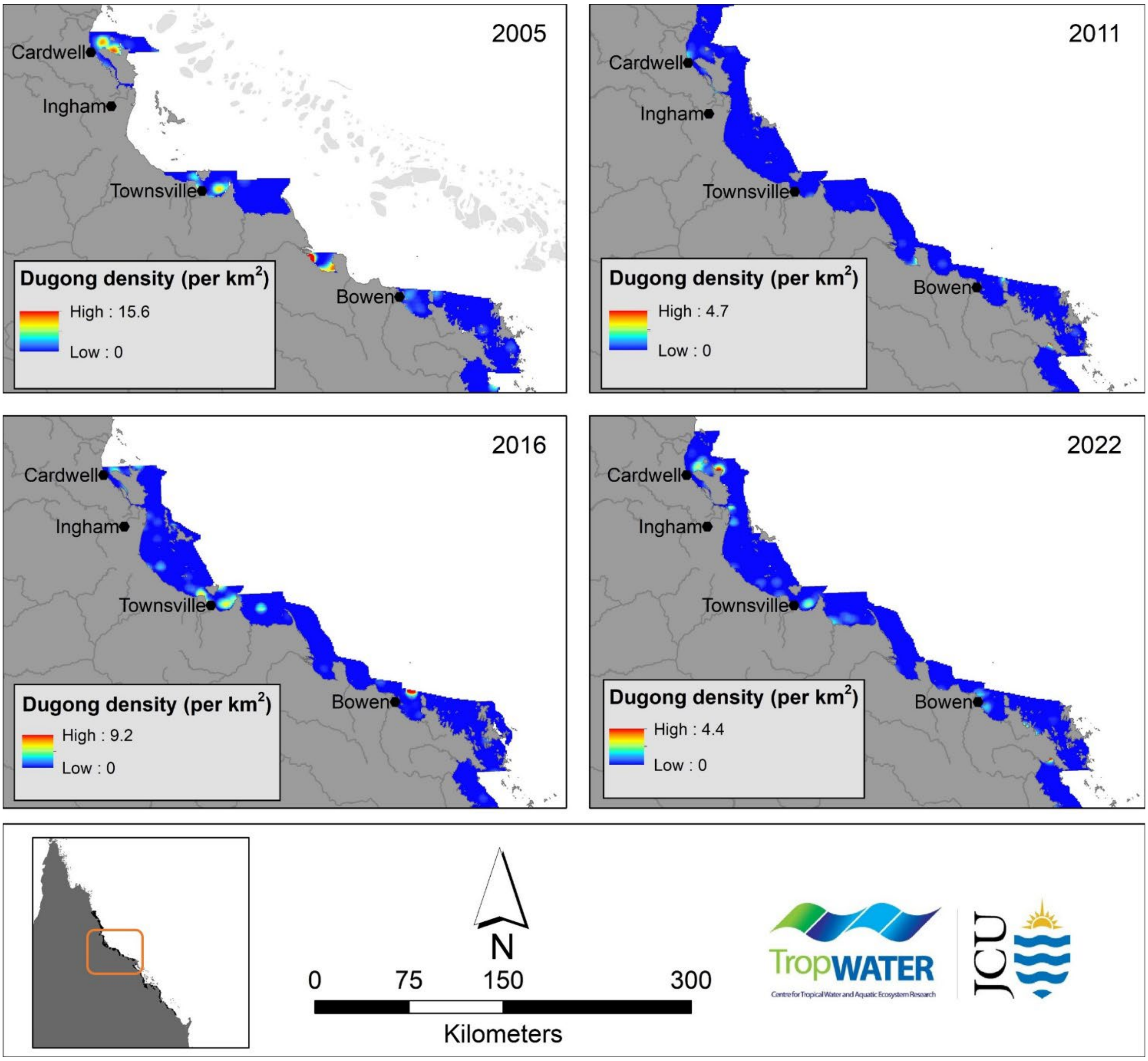


Figure 15.1. Non-classified spatially explicit models of dugong density in the central section of the Great Barrier Reef using data from aerial surveys conducted in 2005, 2011, 2016, and 2022.

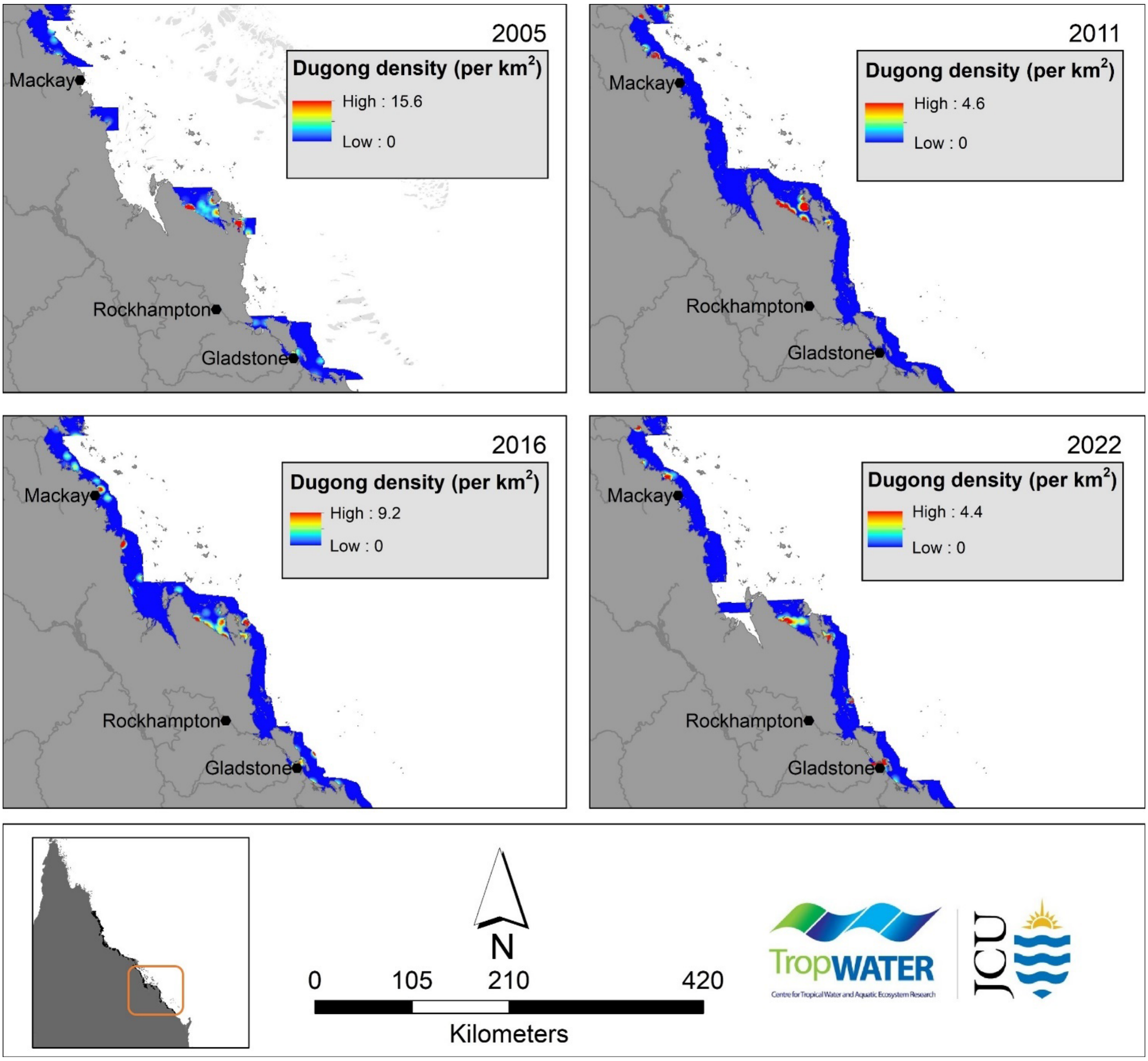


Figure 15.2. Non-classified spatially explicit models of dugong density in the southern section of the Great Barrier Reef using data from aerial surveys conducted in 2005, 2011, 2016, and 2022.

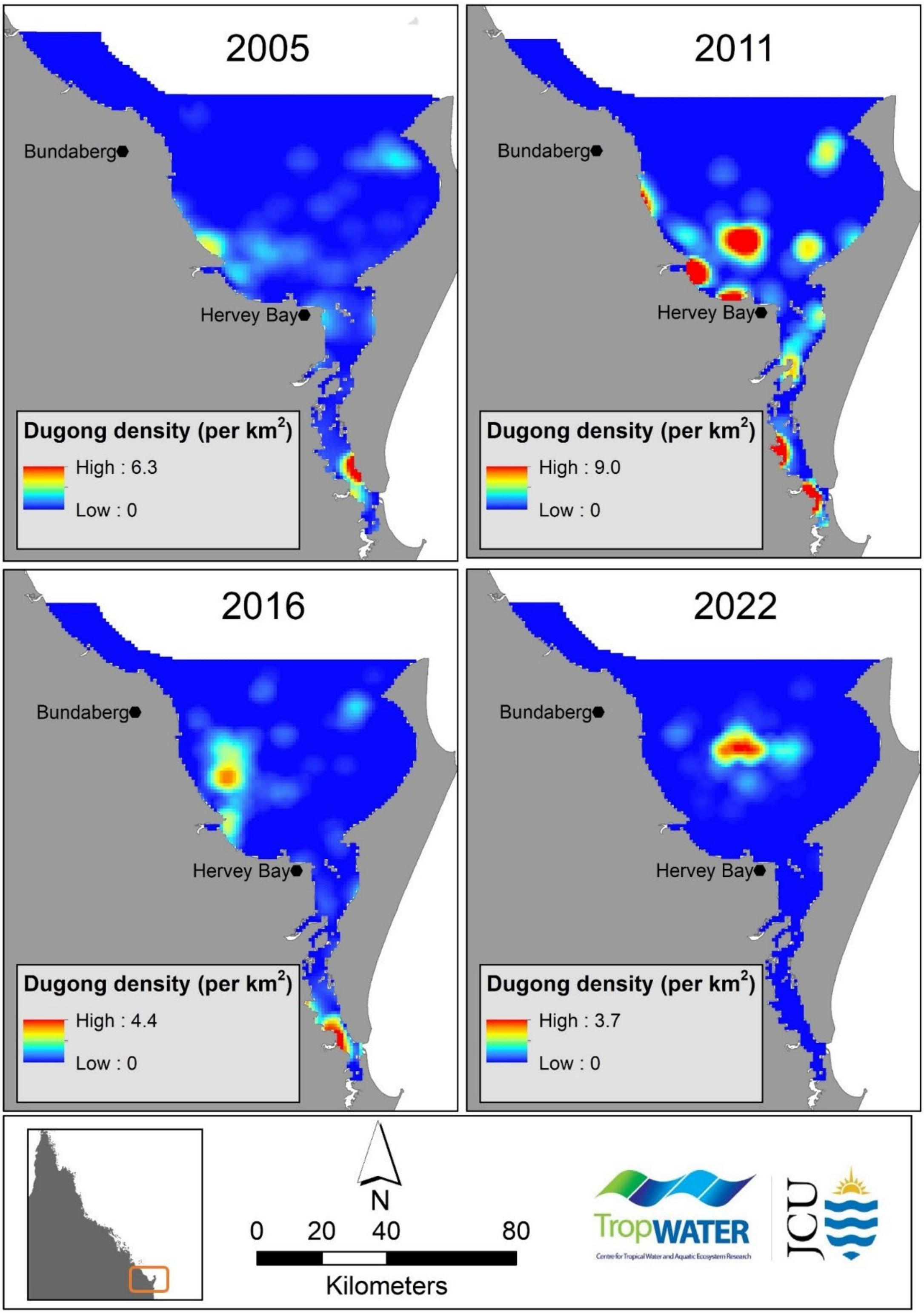


Figure 15.3. Non-classified spatially explicit models of dugong density in Hervey Bay using data from aerial surveys conducted in 2005, 2011, 2016, and 2022.

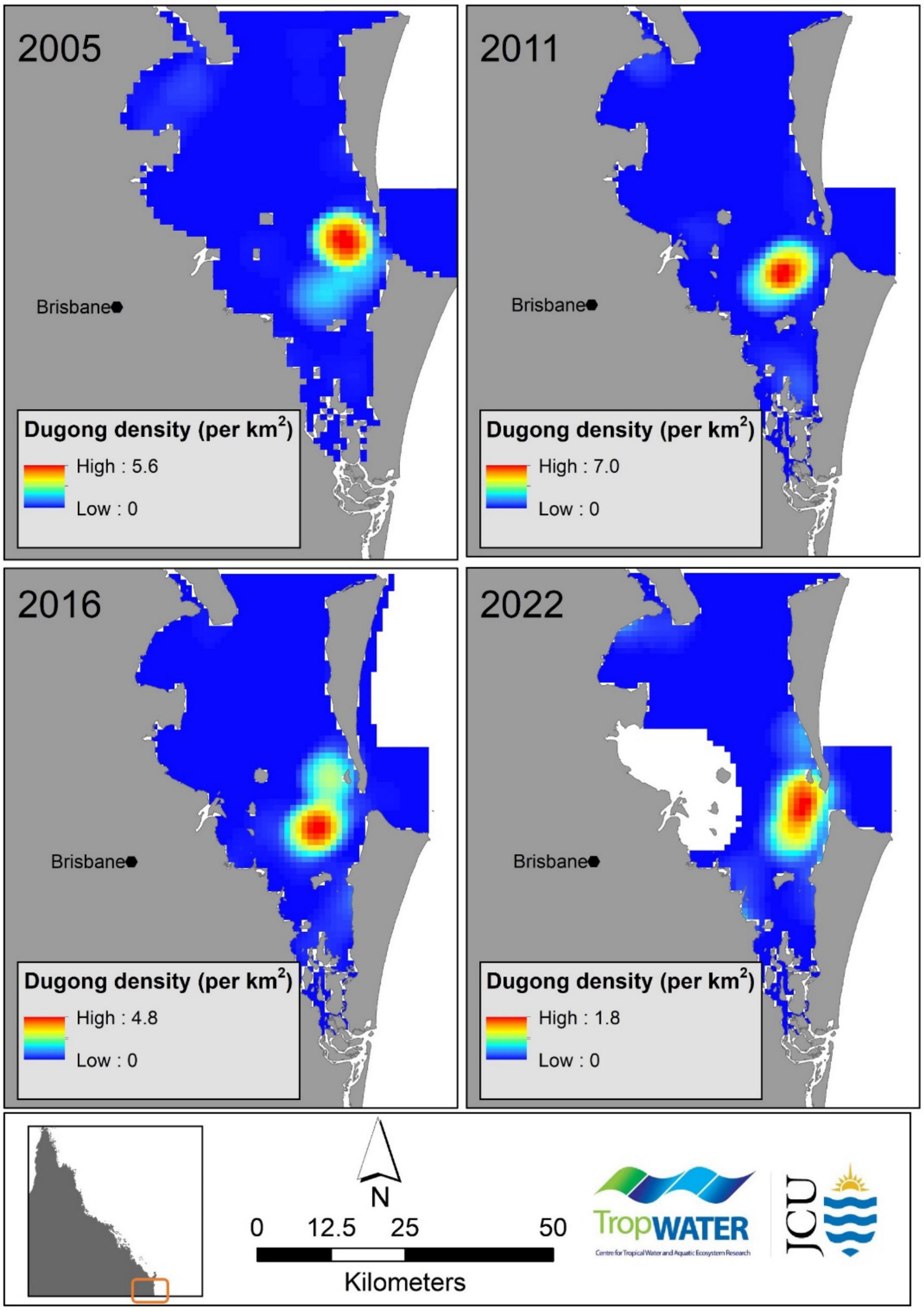


Figure 15.4. Non-classified spatially explicit models of dugong density in Moreton Bay using data from aerial surveys conducted in 2005, 2011, 2016, and 2022.

6.16 APPENDIX 16: REPORTS OF SEA TURTLE AND DUGONG STRANDINGS ACROSS THE URBAN COAST OF THE GBR, AND THE HERVEY BAY AND MORETON BAY REGIONS FOR THE PERIOD 2011-2022 (EXTRACTED FROM HTTPS://WWW.QLD.GOV.AU/ENVIRONMENT/PLANTS-ANIMALS/WILDLIFE/MARINE-STRANDINGS/STRANDING-DATA).

	Turtle Standings												
	Year												
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**Grand Total**
Region													
Palm Island												1	1
Townsville	397	392	147	80	68	49	46	38	49	40	43	41	1390
Groper Creek							1						1
Wunjunga	1												1
Bowen	30	30	20	37	19	4	3	7	6	4	4	8	172
Whitsundays	40	68	57	34	31	12	20	23	5	13	17	10	330
Mackay	98	45	57	35	30	21	16	12	13	31	40	31	429
Broad Sound		2											2
Wild Duck Island	1												1
Swain Reefs			1			1							2
Shoalwater Bay	36	48	4	4				1	14	12	3	5	127
Yeppoon	76	59	46	77	30	14	12	25	39	98	86	110	672
Peak Island		1		1									2
Capricornia	5	4	2	9	1	1	1	1	2		1	3	30
Gladstone	261	67	53	49	31	28	30	20	22	56	102	112	831
Agnes Waters	6	8	1	4	4	2	1	3	4	4	6	7	50
Red Rocks		1											1
Wreck Rock	2	1	2						1			2	8
Boaga				1		2						5	8
Bundaberg	11	8	12	12	5	5	6	9	6	12	19	12	117

Woongarra	15	4	6	4	4	2	3	2	2	3	2	1	48
Hervey Bay	145	142	172	164	69	62	58	38	28	103	198	418	1597
Sunshine Coast	150	101	131	114	43	45	17	9	1	5	1	9	626
Coral Sea	3												3
Wynnum				1					1				2
Gold Coast	24	25	15	24	9	5	7	3	1	3			116
Moreton Bay	434	379	341	469	330	325	322	347	250	299	418	410	4324
Grand Total	**1735**	**1385**	**1067**	**1119**	**674**	**578**	**543**	**538**	**444**	**683**	**940**	**1185**	**10891**

	Dugong Strandings												
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**Grand Total**
Region	178	45	36	25	20	24	15	24	22	32	33	44	498
Townsville	74	5	5	3	2	5	4	7	1	3	1		110
Burdekin	9							2	4				15
Bowen	12								2			1	15
Whitsundays	7	2				1			1	2			13
Mackay	12	2	2	1	4	2	1	1	1			2	28
Shoalwater Bay	4	6	4	2			1		1				18
Yeppoon	2	1		5	2							1	11
Gladstone	11	11	2				2	2	2	1	1	3	35
Bundaberg	1	1	4			2					1		9
Hervey Bay	21	4	8	5	7	4	4	7	4	17	18	19	118
Sunshine Coast	3	2	1							1	1	1	9
Moreton Bay	22	11	10	9	5	10	3	5	6	8	11	17	117
Grand Total	**178**	**45**	**36**	**25**	**20**	**24**	**15**	**24**	**22**	**32**	**33**	**44**	**498**