Distribution and abundance of dugong and large marine turtles in Moreton Bay, Hervey Bay and the southern Great Barrier Reef

A report to the Great Barrier Reef Marine Park Authority

March 2017

Prepared by Susan Sobtzick[1], Christophe Cleguer[2], Rie Hagihara[2], and Helene Marsh[2]

[1] Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), James Cook University, Townsville, QLD 4811
[2] College of Marine & Environmental Sciences, James Cook University, Townsville, QLD 4811

TropWater Report 17/21

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS USED IN THIS REPORT

AIC................ Akaike Information Criterion

EBK .... Empirical Bayesian Kriging

GBR.............. Great Barrier Reef

GBRMPA ...... Great Barrier Reef Marine Park Authority

GBRWHA...... Great Barrier Reef World Heritage Area

GPS.............. Global Positioning System

JCU............... James Cook University

km................. kilometre

m................... meter

MPA.............. Marine Protected Area

RIMReP .... Reef Integrated Monitoring and Reporting Program

s.e................. Standard Error

sGBR............ southern Great Barrier Reef

SOI .... Southern Oscillation El Niño Index

UAV .... unmanned aerial vehicle

ACKNOWLEDGEMENTS

We would like to thank the Great Barrier Reef Marine Park Authority and the Department of Defence for funding this research and the following dedicated aerial survey team members for their efforts in the field: Dr Jodie Haig, Genevieve Williams, Christian Jaehnichen, Dr Karen Chong Sen, Suzanne Hillcoat, Tiffany Sih, Laura Kamintzis, Dr Putu Liza Mustika, Alyssa Budd, as well as our ground support staff Brendan Cox and Omar Ramirez-Flores. Pilots Aaron Turkington, Jack Hart and Darryl Gosper showed exceptional skill and professionalism. We also would like to thank Fergus Molloy for his project management and for negotiating with the Department of Defence with regard to co-funding this project and providing access to the Shoalwater Bay Military Training Area. Research was conducted under James Cook University Animal Ethics A2362 and Great Barrier Reef Marine Park Authority Approval CMES67.

2016 aerial survey team members

EXECUTIVE SUMMARY

- This report presents the result of an aerial survey for dugongs and large juvenile and adult marine turtles that was conducted in October-November 2016 in the coastal waters of Queensland from just north of Hinchinbrook Island to the Queensland-New South Wales border. The survey is the latest in the time series of surveys conducted by James Cook University researchers since the 1980s and is a requirement of the Reef 2050 Long-Term Sustainability Plan.
- The results of this survey add to the evidence that dugongs in the survey region are in much better condition than at the time of the last such survey in 2011.
- The improvement is especially evident in the southern Great Barrier Reef (GBR) region (from the northern boundary of the survey region (18°12'S) to the southern boundary of the Great Barrier Reef Marine Park, 23°42'S) where the estimated numbers of dugongs have significantly increased, especially north of the Whitsundays. The percentage of calves also increased from zero in 2011 to >10% in 2016, which is above the averages for the historical survey data for this region.
- The magnitude of the increases in the southern GBR population estimates indicate that at least some of the differences between 2011 and 2016 must result from immigration into the survey area presumably from further north.
- These changes coincide with improvements in the condition of intertidal seagrass percentage cover which has increased in the southern GBR (except in the Wet Tropics) and a reduction in the number of dugong carcasses reported to the Queensland marine wildlife stranding program StrandNet.
- In contrast, the dugong population estimates for Moreton Bay and Hervey Bay have not significantly increased since 2005 and the percentages of calves have also remained relatively stable over this time period.
- The data collected by the 2016 survey add to the previous evidence indicating that climate and weather have profound influence on the abundance, distribution and fecundity of dugongs at sub-regional scales, mainly as a result of the impacts of climatic drivers on their seagrass habitats.
- Water quality is a major environmental driver of seagrass health. Thus, the management of water quality in the Great Barrier Reef World Heritage Area (GBRWHA) must continue to be an essential component of dugong conservation in the region along with the zonal management of activities that cause dugong mortality such as gill-netting, vessel strike and Indigenous hunting.
- The survey region also supports significant populations of in-water large juvenile and adult marine turtles. There are areas of very high turtle density in the southern GBR as well as in Moreton and Hervey Bays, in contrast to the dugong situation where the densities are much higher in Moreton Bay and Hervey Bay than anywhere in the southern GBR.
- This report makes a series of recommendations relevant to the megafauna component of the Reef Integrated Monitoring and Reporting Program (RIMReP) including:

(1) the bridging studies required to transition the aerial monitoring of dugongs and large marine turtles from manned to unmanned aircraft;

(2) the desirability of considering the deep genetic break in dugong stocks along the eastern coast of Queensland at the Whitsundays in the design of future dugong surveys;

(3) the importance of aligning the timing and scope of future monitoring of seagrasses in the GBRWHA and the aerial monitoring of dugongs and large marine turtles; and

(4) the desirability of StrandNet giving higher priority to the monitoring of the body condition (as opposed to the carcass condition) of stranded dugongs and marine turtles irrespective of whether the cause of death can be identified.

1 INTRODUCTION

The Great Barrier Reef World Heritage Area supports globally significant populations of the dugong (*Dugong dugon*), a coastal marine mammal that feeds mainly on seagrasses (Marsh et al. 2011) and five species of marine turtles, the green (*Chelonia mydas*), loggerhead (*Caretta caretta*), olive ridley (*Lepidochelys olivacea*), flatback (*Natator depressus*) and hawksbill (*Eretmochelys imbricata*) turtles. In addition, leatherback turtles (*Dermochelys coriacea*) are occasionally sighted in the region.

The significance of the Great Barrier Reef (GBR) region for dugongs and green and loggerhead turtles was among the reasons for its World Heritage listing (GBRMPA, 1981). Thus, the status and trends in the distribution and abundance of these species is critical information for the management of the World Heritage Area (GBRMPA 2005).

The urbanized coast of Queensland Australia extends from about Port Douglas (16° 48’S, 145° 47’E) to the Queensland-New South Wales border (28º 10’S; 145 44’E) and most of the adjacent coastal water and islands north of 23°42'S are in the Great Barrier Reef World Heritage Area. Over the last 30 years or so, the coastal waters of the entire region south to the state border have been protected by the progressive establishment and upgrading of one of the world’s most extensive network of ecosystem-scale Marine Protected Areas (MPAs) including part of the Cairns Section and the Southern and Central Sections of the Great Barrier Reef Marine Park (e.g., Fernandes et al. 2005), the associated sections of the Great Barrier Reef Coast Marine Park (NPSR 2015), the Great Sandy Marine Park (incorporating Hervey Bay; NPSR 2016) and the Moreton Bay Marine Park (NPSA 2017). These MPAs were developed in conjunction with other management initiatives such as fisheries management plans, Dugong Protection Areas (Marsh 2000), arrangements to manage Indigenous hunting (Marsh et al. 1996; Havemann et al. 2005) and arrangements to minimize the impact of terrestrial runoff on the seagrass communities on which dugongs and green turtles depend (Reef Water Quality Protection Plan http://www.reefplan.qld.gov.au/).

As the only surviving member of the family Dugongidae (Marsh et al. 2011), the dugong is a species of high biodiversity value. The dugong is listed as vulnerable to extinction by the International Union for Conservation of Nature (Marsh and Sobtzick 2015). Anecdotal evidence suggests that dugong numbers have decreased throughout most of their range (Marsh et al. 2002, 2011). Significant populations persist in Australian waters, which are now believed to support most of the world's dugongs. Dugongs are listed in Appendix 1 of the Convention of Migratory Species. As a signatory to that Convention and the associated Dugong Memorandum of Understanding, Australia has international obligations to conserve dugongs in its waters and the species is listed as a Matter of National Environmental Significance under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act).

All the species of marine turtles occurring in Australasian waters are also Matters of National Environmental Significance by virtue of their listing as threatened, migratory and marine species under the EPBC Act. Loggerhead, olive ridley and leatherback turtles are listed as 'Endangered'; green, flatback and hawksbill turtles as 'Vulnerable'. As with the dugong, Australia has international obligations to conserve the marine turtles in its waters.

Since the 1980s, aerial surveys have provided information on dugong distribution and abundance for many parts of their distribution in Australia (Marsh et al. 2011). These surveys have been a cost-effective means of assessing the distribution and abundance of dugongs at vast spatial scales (>tens of thousands of km^2).

As part of this series of surveys, dugongs have been surveyed along the east coast of Queensland using standardised techniques since the mid-1980s. This aerial survey monitoring of dugong distribution and abundance has been coordinated across jurisdictions in this region at the same time of year over two years at approximately five-year intervals. The entire Queensland coast south from 16.5ºS has generally been surveyed in one year; the remote Great Barrier Reef region north of 16.5ºS has been surveyed in the same year as Torres Strait in another year, ideally the year after the southern survey. These surveys have provided long-term information on the distribution and abundance of dugongs and the Reef Long-Term Sustainability Plan (Commonwealth of Australia 2015) commits to continue to survey the dugong population every five years.

The boundary between the northern and southern survey series was set at 16.5ºS in the 1980s for logistical reasons. Recent unpublished research on dugong genetics by Alexandra McGowan, David Blair et al., indicates that there is a deep genetic break between dugong populations on the east cost of Queensland at about 20.65ºS. Satellite tracking suggests limited dugong movements across this region (Marsh and Rathbun 1990; Preen 1999 and unpublished; Sheppard et al. 2006; Gredzens et al. 2014; Cleguer et al. 2015a and b, 2016; Zeh et al. 2016). Taken together, these results suggest that there are two dugong stocks along the east coast of Queensland, one north and one south of the genetic break. This stock structure has not been reflected in the design of the aerial surveys conducted to date including the 2016 survey, but is reflected in some of the analyses in this report.

Large juvenile and adult marine turtles have been recorded on the dugong surveys. Several species of marine turtles co-occur in the survey regions and the turtles have not been identified to species because it is impossible to do such identification using the standard dugong aerial survey technique and the results have generally not been formally reported (but see Marsh and Saalfeld 1989; Fuentes et al. 2015). Given the relevance of information on marine turtles to the Reef 2050 Long-Term Sustainability Plan (Commonwealth 2015), it is important to maximise the information obtained from the dugong surveys. The stock structure of Australian marine turtles is complex (Commonwealth 2017) and this complexity is reflected in the marine turtles using the coastal in-water habitats of our survey region. As our survey did not identify marine turtles to species, we did not consider marine turtle stock structure in this report.

Thus, the objective of this study was to help the Great Barrier Reef Marine Park Authority and the Queensland government fulfil the requirements of the Reef 2050 Long-Term Sustainability Plan (Commonwealth 2015) by:

1. Continuing the time series of surveys for dugongs and large marine turtles using the latest advances in distribution and abundance analysis.
2. Advising GBRMPA about the implications of the findings for the conservation and management of dugongs and large marine turtles in the southern GBR.

2 METHODS

2.1 Survey design

The design for the aerial survey conducted in 2016 was based on that used in previous aerial surveys in the survey area conducted by researchers at James Cook University. Figures 1 and 2 show the locations of the survey blocks and the orientation and spacing of the transects flown in October and November 2016 in the three survey areas: Moreton Bay, Hervey Bay and the southern Great Barrier Reef (sGBR). The references for the historical surveys with which the 2016 survey results are mostly compared in this report are detailed in Table 1.

We had a fixed budget for the survey. As anticipated in discussions with GBRMPA prior to the survey, we were unable to survey Blocks C11 and C12 in 2016 because of the extra costs resulting from: (1) numerous weather-related down days for the southern team; (2) the northern team conducting more (but shorter) flights than anticipated; and (3) the need to re-survey a section of Moreton Bay (as detailed below).[1]

Two survey teams (northern and southern team), each consisting of four observers and one team leader, were assembled to work in the three areas. Some observers already had extensive dugong aerial survey experience. Observers in both teams were trained prior to the survey.

1 We propose to include Blocks C11 and C12 in the upcoming survey of the northern GBR and Torres Strait, planned for 2018.

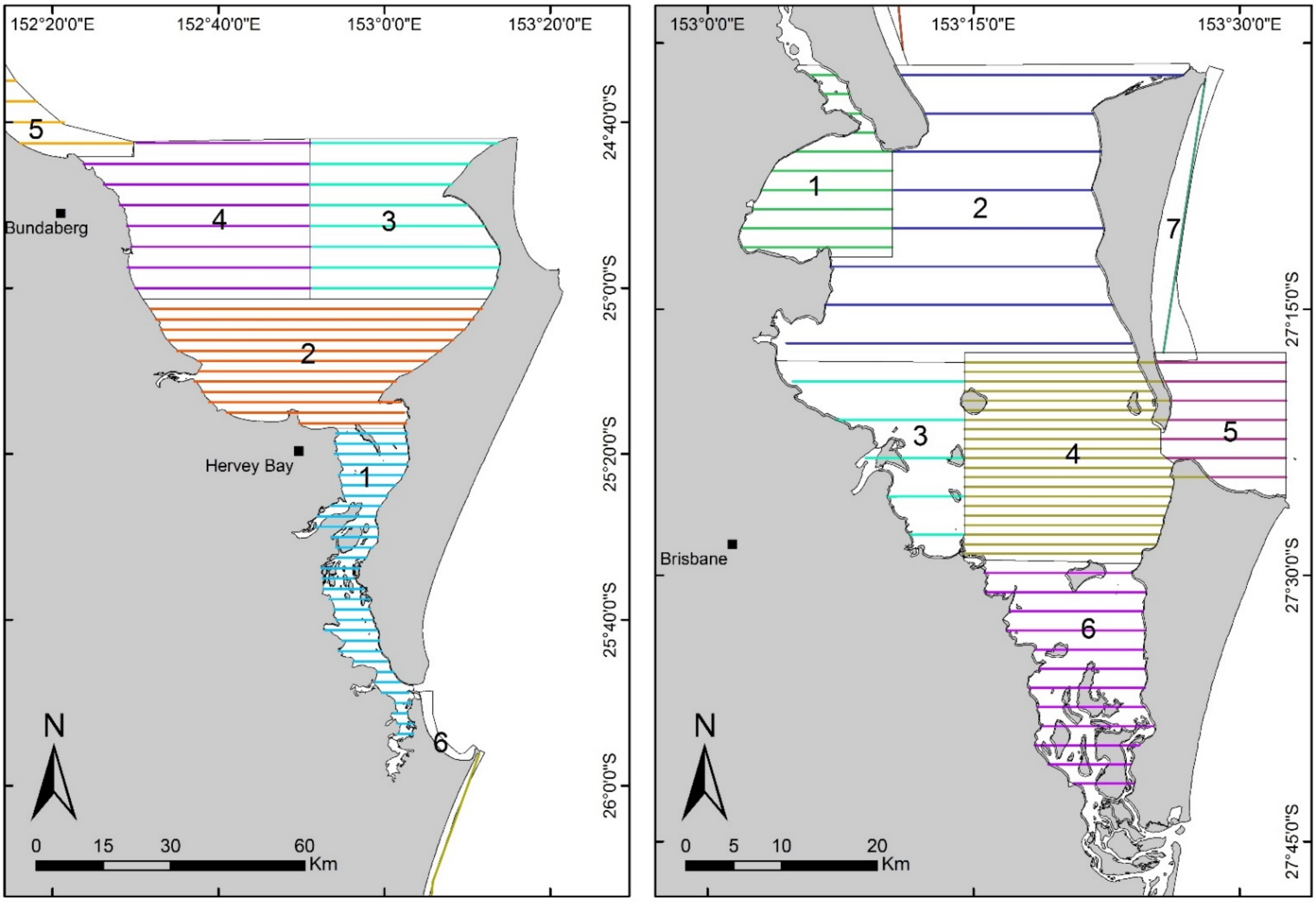


Figure 1. Blocks and transects surveyed in Hervey Bay Region (left) and Moreton Bay Region (right) during the dugong and marine turtle aerial survey in October-November 2016.

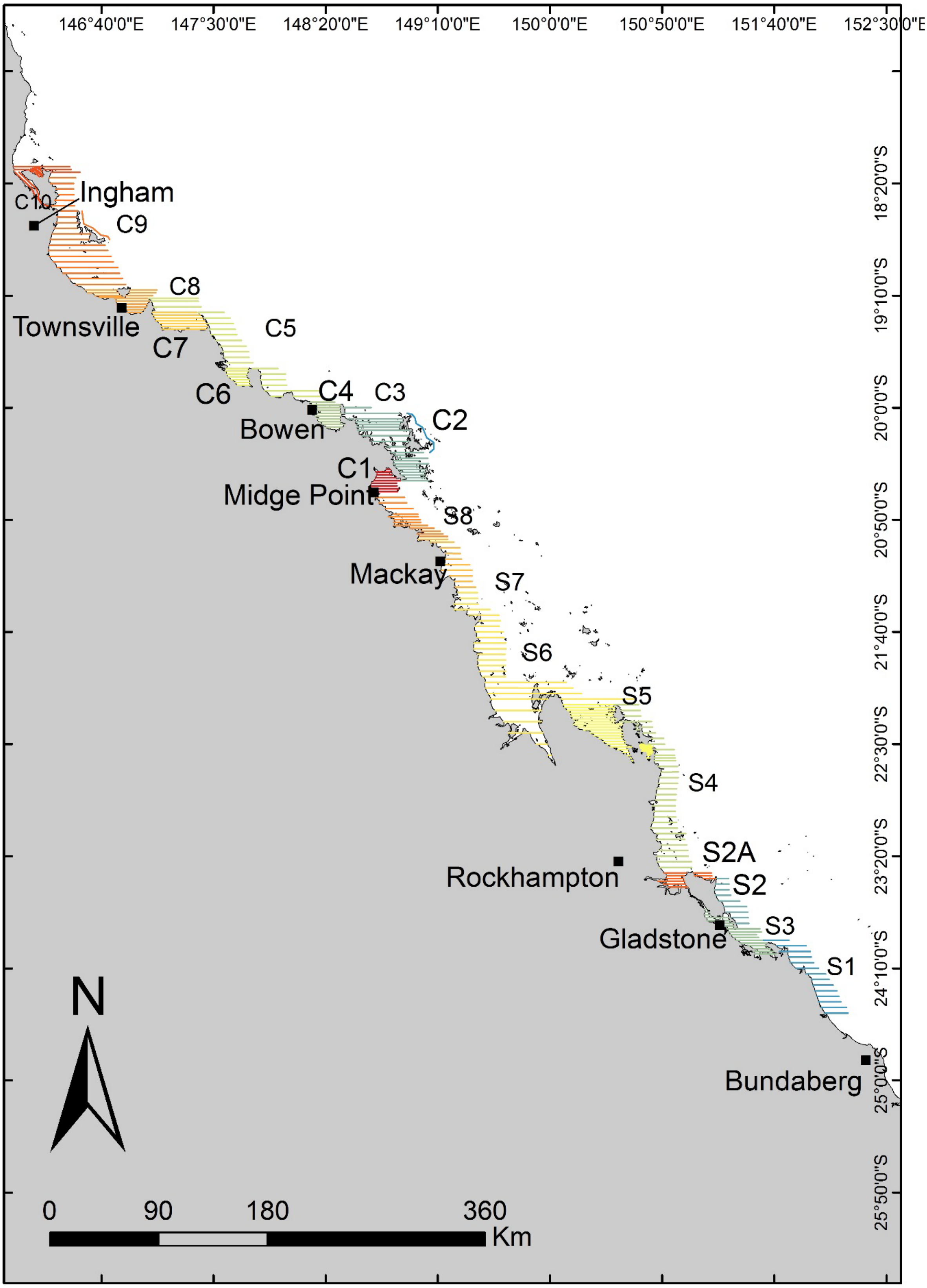


Figure 2. Blocks and transects surveyed in the southern Great Barrier Reef Region during the dugong and marine turtle aerial survey in October-November 2016. The deep genetic break in the dugong population occurring on the east coast of Australia is in the vicinity of Midge Point (Alexandra McGowan, David Blair et al. unpublished data). Note the single zig-zag offshore transect flown in Block C2.

Table 1. References for the historical aerial surveys conducted in Moreton Bay, Hervey Bay and the southern Great Barrier Reef with which the 2016 dugong population results are mostly compared in this report.

Date of survey	Reference
Moreton Bay	
November 2005	Marsh & Lawler, 2007
November 2011	Sobtzick et al., 2012
Hervey Bay	
November 2005	Marsh & Lawler, 2007
November 2011	Sobtzick et al., 2012
Southern GBR	
November 1994	Marsh et al., 1996
October-December 1999	Marsh & Lawler, 2000
November 2005	Marsh & Lawler, 2007
November 2011	Sobtzick et al., 2012

2.2 Survey methodology

The aerial survey methodology followed the strip transect aerial survey technique detailed in Marsh and Sinclair (1989a) and used in earlier surveys along the Queensland coast (Table 1). A 6-seat, high-wing, twin-engine Partenavia 68B was flown along predetermined transects as close as possible to a ground speed of 100 knots. To comply with the requirements of the Civil Aviation Safety Authority, the survey was conducted at a height of 500 feet (152 m) above sea level as opposed to 450 feet (137 m) flown in surveys conducted prior to 2011. The experimental work of Marsh and Sinclair (1989b) indicates that there should be no difference in dugong sightability between survey heights of 152 and 137 m.

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. 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. 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. However, as explained by Pollock et al. (2006), although we found no decline in detection with distance across the strip, there was a large amount of measurement error in the assignment of dugong sightings to distance classes within the transect strip because: (1) dugongs surface cryptically and for only 1–2 seconds (Chilvers et al. 2004); of (2) the inherent limitations of using colour bands on the wing struts (as approved by the Civil Aviation Safety Authority) to define distance categories, and (3) the shape of the aircraft. The cryptic nature of dugong surfacing and the often high sighting rate also meant that observers could not afford to take their eyes off the water to read an inclinometer. Thus, following Pollock et al. (2006), we decided not to use distance category as a co-variate in the analyses. 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 1989a, Pollock et al. 2006).

The surveys were conducted in passing mode with dugongs and large marine turtles as the main focus. For each animal sighting, observers recorded the type of animal (e.g., dugong or 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. Calves were defined as being less than 2/3 of the size of the cow and swimming in close proximity to her. On the relatively rare occasions (see Table 4 and footnotes to Tables 10, 12, and 14) when groups of dugongs were sighted that were too large to accurately count in passing mode (generally more than 10 animals), the aircraft abandoned the transect and went into circling mode in an effort to obtain a total count of the group before resuming the transect.

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) and each transect (cloud cover). Every few minutes during each transect, and whenever conditions changed, the survey leader recorded sea state, visibility, and glare on each side (assessed by the mid-seat observers).

2.3 Population and density estimates

2.3.1 Dugong population estimates

Since the start of the dugong surveys in the 1980s three methods have been used to estimate dugong relative abundance and density: Marsh and Sinclair 1989a (Marsh and Sinclair method), Pollock et al. 2006 (Pollock method) and Hagihara et al. 2014 and in review (Hagihara method). All these methods attempt 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). The Pollock and Hagihara methods require data that were not collected prior to 2000 limiting inter-survey comparisons. The revised availability probabilities developed by Hagihara et al. (2014) consider the heterogeneity of dugong diving behaviour with water depth and therefore the different likelihoods of dugongs being available to observers in different depth strata. We consider that the Hagihara method is superior to the former methods as it makes fewer assumptions. Thus, the information in the Results section of this report is based on the Hagihara method. The results from the earlier methods are presented in Appendices 9 and 10 for completeness and to enable historical comparisons where the data allow.

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 1989a; 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 those provided by the model that best fit the data according to Akaike's Information Criterion (AIC), which corrects for small sample bias. The probability that a dugong would be detected by at least one observer for each side of the aircraft was:

$$\hat{p}_d = 1 - (1 - \hat{p}_1)(1 - \hat{p}_2)$$

where $\hat{p}_1$ is the perception probability obtained for the primary and $\hat{p}_2$ the secondary observers (i = 1,2). As outlined in Pollock et al. (2006), the Horvitz-Thompson population estimator was also applied for each survey block to obtain a corrected population estimate ($\hat{N}$)

$$\hat{N} = \sum_{j=1}^{n} [1/\hat{p}_j]$$

where n is the number of dugongs counted within the survey and $\hat{p}_j$ is:

$$\hat{p}_j = p_b \hat{p}_{aj} \hat{p}_{dj}$$

The above formula corrects each sighting for the proportion of the survey area sampled (p_b), the probability of that group of dugongs (j) being available given the conditions at the sighting location ($\hat{p}_{aj}$) and the probability of that group of dugong being detected given that it was available ($\hat{p}_{dj}$).

Relative abundance estimates were calculated for individual blocks with at least five individual dugong sightings and are presented ± standard error.

2.3.2 Turtle population estimates

Estimates of the size of the population of all large juvenile and adult marine turtles (not identified to species) were calculated using the methodology developed by Fuentes et al. (2015). This methodology is based on the same principles as the Pollock method but considers green turtle diving behaviour rather than dugong diving behaviour when calculating the availability bias correction factor, which has not been depth-corrected. Fuentes et al. (2015) used green turtle diving data obtained by four research projects from widely dispersed locations. Depth corrected diving data are available for green turtles in Torres Strait (Hagihara et al. 2016a) but the bathymetry of Torres Strait is very different from the east coast of Australia thus we decided that it would be inappropriate to use these data to adjust the results from this survey for availability bias.

2.4 Statistical analyses

2.4.1 Dugong calf counts

The proportions of calves were compared between years and the three survey regions (Moreton Bay, Hervey Bay and the southern Great Barrier Reef) using logistic regression and survey data collected by James Cook University (JCU) research teams to ensure that the survey methodology was consistent. For Moreton Bay, the surveys were those conducted in 1976, 1977, 1979, 2000, 2001, 2005, 2011 and 2016; for Hervey Bay - 1979, 1988, 1992, 1993, 1994, 2001, 2005, 2011 and 2016 and for the southern GBR - 1974, 1975, 1976, 1977, 1978, 1979, 1986, 1992, 1994, 1999, 2005, 2011 and 2016. The data for all these surveys are in the dugong survey database in the JCU Tropical Data Hub (DOI: 10.4225/28/557F7B61ED8E1). Year was treated as a continuous independent variable; survey region as a categorical variable. The results from two surveys were removed because not all blocks were surveyed (1999 Moreton Bay; 2006 Hervey Bay).

2.4.2 Dugong distribution across bathymetric ranges

To examine the distribution of dugong sightings (uncorrected dugong counts) across water depth and survey years, log-linear models were used for the following major dugong habitats: Moreton Bay, Hervey Bay, Shoalwater Bay, Cleveland Bay and the Hinchinbrook area. The water depth (not corrected for tide) for each dugong sighting was estimated from bathymetric models by Beaman (2010). The relative area of each depth category differed and this difference may have influenced the number of dugongs. Thus, the surveyed area was used as an offset in separate log-linear models for each location.

2.4.3 Temporal and spatial variation in dugong population density

As explained in the Introduction, Alexandra McGowan and David Blair et al. (unpublished data) have detected a deep genetic break in the dugong population occurring on the east coast of Australia in the vicinity of Midge Point (20.65^{o}S; 148.72^{o}E) and satellite-tracked dugongs have not been observed moving across this break.[2] Thus to evaluate temporal patterns of dugong density over the distribution range for each putative stock, the total area covered by the 2016 survey was split into two regions around the region of the genetic break. The putative southern stock was assumed to consist of the dugongs sighted in Moreton Bay, Hervey Bay and all of the southern (S) blocks in the southern GBR region, while the northern stock was represented in this survey by the dugongs sighted in the central (C) Blocks in the southern GBR region.

To examine the temporal and spatial variation in the number of dugongs sighted in the survey regions where population abundance estimates using the Hagihara method were available, we used negative binomial models for: (1) Moreton Bay, (2) Hervey Bay, (3) the entire southern stock and (4) the northern stock within the survey region; and a zero-inflated negative binomial model for the southern Great Barrier Reef region. In each case, the appropriate model was chosen based on examining over-

[2] Given the sample size of tracked dugongs, these results do not prove that dugongs never move across the genetic break but suggest that dugongs do not move across the break and breed.

dispersion statistics and Akaike Information Criterion. The effects of year, block and the interaction between year and block were determined, and the best parsimonious model was selected based on over-dispersion statistics and AIC. The response variable was the number of dugongs per transect corrected for availability and perception biases. Log transformed transect length (km) was used as an offset in all models so that the models were testing for changes in dugong density rather than population size *per se*. The statistical analyses were performed in R (R Core Team 2015).

The analysis for Moreton Bay was based on three surveys (2005, 2011, and 2016). All Blocks inside the bay except Block MB3 were included in the analysis. Block MB3 had too many transects with zero sightings in all years to be legitimately included in the model.

Dugong densities in Hervey Bay were compared among the 2005, 2011 and 2016 surveys. Block HB5 was removed from the analysis because no dugongs were sighted there in any of the three survey years.

Several blocks were removed from the statistical analysis of the southern GBR for the following reasons: 1) a single zig-zag transect was flown in C2, precluding the analytical approach used for the other blocks; 2) there were too many transects with no dugong sightings in Block C3; and 3) inconsistent survey intensity among survey years in block C5 where in 2005 (one zig-zag transect was flown in 2005). Blocks C11 and C12 were also removed as these blocks were not surveyed in 2016.

For the southern stock, the 2005, 2011 and 2016 aerial surveys were comparable and the adjusted dugong counts from these survey data were analysed using both the Hagihara and Pollock methods as well as Marsh and Sinclair method.

For the northern stock, dugong counts for five surveys were comparable (1994, 1999, 2005, 2011 and 2016) using the Marsh and Sinclair method while the data from the 2005, 2011 and 2016 aerial surveys were comparable using the Hagihara and Pollock methods. Table 2 provides an overview of these analyses.

Table 2. Summary of the methods used to compare the spatial and temporal patterns in dugong densities for various geographic regions. Year and Block were treated as categorical variables in all the analyses.

Method	Moreton Bay	Hervey Bay	southern GBR	southern genetic stock	northern genetic stock
Hagihara method*	2005, 2011, 2016	2005, 2011, 2016	2005, 2011, 2016	2005, 2011, 2016	2005, 2011, 2016
Pollock method**				2011, 2016	2011, 2016
Marsh and Sinclair method**				2005, 2011, 2016	1994,1999, 2005, 2011, 2016

*in Results
** in Appendices 12 and 13

2.4.4 Distribution of large juvenile and adult turtles (all species combined) across bathymetric ranges

To examine the distribution of sightings of large juvenile and adult marine turtles of all species combined (uncorrected counts) across water depth and survey years, a log-linear model was used for turtle sightings in the following major habitats: Moreton Bay, Hervey Bay, Shoalwater Bay, Cleveland Bay and the Hinchinbrook area. The water depth for each turtle sighting was identified from bathymetric models by Beaman (2010). Depths were not tide-corrected. The relative area of each depth category differed and this difference may have influenced the number of turtles sighted (e.g., the larger the area, more likely to sight a turtle). Thus, the transect length (km) was used as an offset in the models.

We did not attempt to analyse temporal and spatial variation in the density of large juvenile and adult marine turtles because: (1) the animals were not identified to species and (2) the absence of comparable processed historical data.

2.5 Spatial modelling

We developed spatially-explicit models of dugong and marine turtle density and distribution using the method of Grech and Marsh (2007) and Grech et al. (2011) with the following improvements:

a. Input data (see Table 3):
    i. Dugong counts corrected for perception and depth-specific availability probabilities as per the Hagihara method.
    ii. Marine turtle counts corrected for perception and turtle dive-specific availability probabilities as per Fuentes et al. (2015).
b. The spatial autocorrelation of the data was investigated by a variogram analysis using the geostatistical interpolation method Empirical Bayesian Kriging (EBK) in ArcGIS 10.2. Empirical Bayesian Kriging creates multiple simulations of the semivariogram by sequentially changing input parameters to find the best fit parameters for the input data. The search neighbourhood for the dugong data was set to a radius of 5000 m. This corresponds with the home range of dugongs at Burrum Heads, Hervey Bay (Sheppard et al. 2006). For the turtle data, the search neighbourhood was set to a radius of 5600 m, which corresponds with the median home range of green turtles in the southern Great Barrier Reef (Shimada et al. 2016).
c. Relative densities were calculated at a grid size of 1km^2 for both species, a scale enabled by the recent improvements in recording the accuracy of aircraft altitude and the GPS locations of dugong observations.

Grid cells were classified into four categories, based on the relative density of dugongs estimated from the spatially explicit dugong population models and the frequency analysis of Grech and Marsh (2007) and Grech et al. (2011): 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) relative dugong density.

Several classification methods were tested in ArcGIS to categorise marine turtle densities based on their frequency distribution. After testing and interpreting the ecological/behavioral relevance of several classification methods for marine turtle densities (i.e., natural breaks (jenks), geometric intervals, standard deviation), the classification developed by Grech and Marsh (2007) and Grech et al. (2011) was found to produce the most ecologically appropriate categories for marine turtles as well as dugongs.
Grid cells with 0 dugongs and 0 turtle per km^2 were included: (1) to ensure that the spatial layers of dugong and turtle density extended across the entire survey area; (2) because dugongs and turtles are likely to move across units where they were not detected during the surveys and (3) because we have not attempted to estimate abundance for areas where dugongs and turtles were not sighted (which is theoretically possible but very difficult; see Martin et al. 2014).

The spatially-explicit models were developed for individual survey years and as composite of multiple survey years when deemed ecologically relevant (see Table 3).

Table 3. Data used to develop the spatially explicit models of dugong and marine turtle density and distribution.

Taxa	Input data	Region	Survey year - Model
Dugong	Adjusted number of dugongs, following the Hagihara method	Moreton Bay	2005, 2011, 2013*, 2016, composite all years
		Hervey Bay	2005, 2006, 2011, 2016 composite (2005-2011-2016)**
		Southern GBR	2005, 2011, 2016
Turtle	Adjusted number of turtles, following method from Fuentes et al. (2015)	Moreton Bay	2016
		Hervey Bay	2016
		Southern GBR	2016

* included in spatial models only as conducted at a different time of the year from the other surveys
** the composite model excluded the data collected in 2006 because not all the blocks were surveyed that year

3 RESULTS

3.1 Survey flight summary

The southern GBR region was surveyed from 28th October – 25th November; Hervey Bay from 14th November – 26th November and Moreton Bay from 6th – 27th November 2016. Appendix 2 summarizes the details of the daily activities and survey flights for both teams.

In Moreton Bay, Block MB4 was surveyed twice as the first survey flight was conducted during sub-optimal tides and in marginal weather conditions. The second survey flight was completed in better conditions in terms of tidal states and Beaufort Sea State. Thus, we analysed the data from the second survey flight only (including population size estimations and statistical analysis), with the exception of the observation summary presented in Table 4.

Sampling intensities varied between individual blocks resulting in 4.19-37.6% survey intensities across the entire study area (see Appendix 3).

3.2 Conditions

The southern survey team was forced to spend considerable periods on the ground as a result of the unsuitable weather conditions, which made this survey challenging to complete in a short timeframe (Appendices 2 and 4).

Glare varied throughout the survey areas as a result of changing sun angles and sea state. In 2016, overall mean glare (i.e., mean of modes for each transect) was higher than in previous surveys. Otherwise, weather conditions in 2016 were comparable to previous surveys Appendix 4).

3.3 Observations

We only report animals sighted on transect. Details of dugong and turtle sightings are provided in Tables 4 and 5 and the locations of sightings are shown in Appendices 5, 6 and 7.

3.3.1 Dugong sightings

During the October-November 2016 aerial survey, a total of 85 dugongs were sighted in Moreton Bay including the first survey of Block MB4; 110 dugongs in Moreton Bay when the data from the second survey of Block MB4 were included; 168 dugongs in Hervey Bay and 217 dugongs including the southern GBR (all excluding herds, Table 4 and Appendices 5, 6 and 7). The mean group size (excluding herds) did not differ significantly among the Moreton Bay, Hervey Bay and southern GBR regions ($F = 0.86$, $df = 2$, $p = 0.43$).

Eight herds were sighted during the aerial survey: one in the southern GBR (8 animals in Shoalwater Bay); one in Hervey Bay (15 dugongs) and six in Moreton Bay (one group of 68 dugongs during the first survey of MB4; and five groups during the second survey of MB4: 14, 33, 36, 45, and 49 dugongs).

3.3.2 Sightings of large juvenile and adult marine turtles

Large numbers of marine turtles were sighted in all regions: 377 sightings of 548 turtles in Moreton Bay including the first survey of Block MB4; 447 sightings of a total of 556 turtles in Moreton Bay that included the second survey of Block MB4; 410 sightings of 467 turtles in Hervey Bay and 670 sightings of 863 turtles in the southern GBR (Table 5). The mean group size did not differ significantly between the regions ($F = 2.44$, $df = 2$, $p = 0.09$).

Table 4. Number sightings of dugongs, calves, and herds encountered on transect and group sizes excluding herds for the three regions surveyed in October-November 2016.

Region	# dugong sightings[1]	#dugongs*	# calves sighted[1]	% calves*	Group size (excluding herds)			Number of herds (# dugongs)
					Mode	Mean	Range	
Moreton Bay ***1st survey Block MB4***	65	85	10	10 (11.8%)	1	1.45	1-5	1 (68)
Moreton Bay ***2nd survey Block MB4***	82	110	9	11 (10.0%)	1	1.33	1-4	5 (14, 33, 36, 45, 49)
Hervey Bay	126	168	21	22 (13.1%)	1	1.32	1-4	1 (15)
southern GBR	150	217	21	22 (10.1%)	1	1.33	1-9	1 (8)

* calves as percentage of total number of dugongs sighted.

Table 5. Number of turtle sightings and group sizes for the three regions surveyed in October-November 2016.

Region	Number of turtle sightings	Number of turtles	Group size		
			Mode	Mean	Range
Moreton Bay ***Including 1st survey Block MB4***	377	548	1	1.45	1-47[1]
Moreton Bay ***Including 2nd survey Block MB4***	447	556	1	1.24	1-26
Hervey Bay	410	467	1	1.14	1-7
Southern GBR	670	863	1	1.29	1-11

[1]Records of large groups of turtles represent a large number of turtles seen in quick succession rather than social groups

3.3.3 Dugong calf counts

The proportion of calves differed significantly among years and survey regions (Moreton Bay, Hervey Bay and the southern GBR) (Table 6, Figure 3). From the 1980s, the proportion of calves in Moreton Bay increased at a slow rate but plateaued after 2000 and was 10% in 2016. The proportions of calves in Hervey Bay fluctuated between 1.5% in 1994 and 22.1% in 1988 with 2016 in the mid-range at 13.1%. The percentage of calves in the southern GBR peaked between 1990 and 2000. No calves were sighted in 2011 in the southern GBR but the percentage of calves recovered to 10.1% in 2016.

Contingency analysis to compare the percentage of calves sighted in 2011 and 2016 for these three regions showed significant combined yearly and regional differences (Chi=797, df=11, $p<0.01$). However, Moreton Bay and Hervey Bay Regions had relatively similar proportions of calves in 2011 and 2016, and the pattern was very different in the southern GBR where no calves were sighted in 2011. The number of calves in the southern GBR however recovered in 2016 (Figures 3 and 4).

Table 6. Analysis of deviance table examining the variation in the proportion of calves sighted in Moreton Bay*, Hervey Bay** and the southern GBR region*** between the 1970s and 2016.

	DF	Deviance	Residual DF	Residual Deviance	Pr (Chi)
Null			30	157.81	
Year	1	19.46	29	138.35	<0.001
I(year^2)	1	18.44	28	119.92	<0.001
Region	2	1.14	26	118.77	0.56
Year * Region	2	6.33	24	112.44	<0.05
I(Year^2) * Region	2	7.73	22	104.71	<0.05

*1976, 1977, 1979, 2000, 2001, 2005, 2011 and 2016
**1979, 1988, 1992, 1993, 1994, 2001, 2005, 2011 and 2016
***1974, 1975, 1976, 1977, 1978, 1979, 1986, 1992, 1994, 1999, 2005, 2011 and 2016

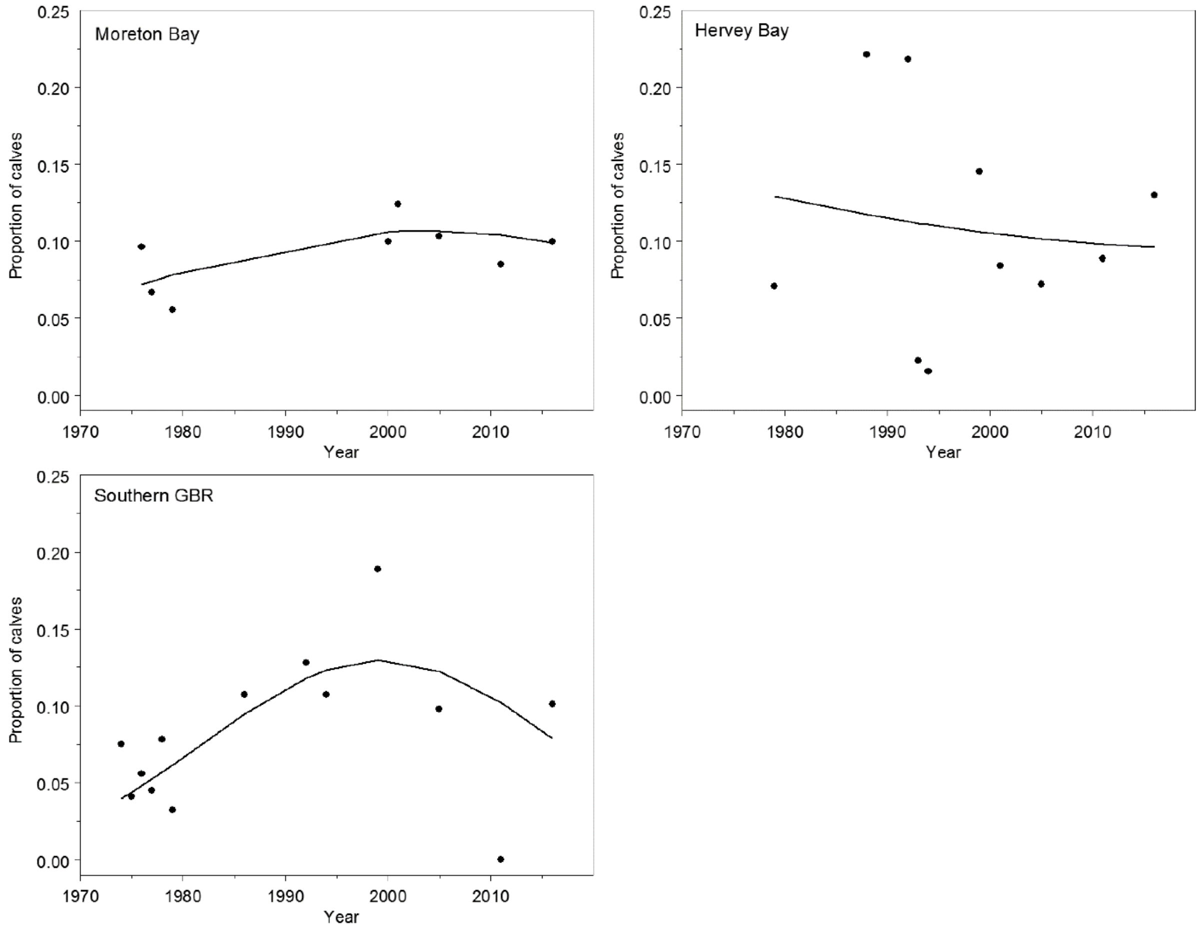


Figure 3. Proportion of calves plotted against survey year in Moreton Bay, Hervey Bay and southern Great Barrier Reef Region. Each line represents the proportion of calves predicted by the logistic regression.

Figure 4. Mosaic plot depicting the proportion of calves and adult dugongs sighted in the survey regions Moreton Bay (MB), Hervey Bay (HB) and the southern GBR (sGBR) in 2011 and 2016. Adult dugongs are in grey; calves in green. The size of each tile in the mosaic is proportional to the sample size. Although the proportion was highest in Hervey Bay in both 2011 and 2016, the proportion of calves was relatively similar across regions in 2016. The greatest temporal difference was in the southern GBR where no calves were recorded in the 2011 survey, but the number recovered in 2016 to the level observed in 2005 (Figure 3).

3.3.4 Dugong sightings with respect to bathymetry

Dugongs were sighted in waters up to 42 m deep (not corrected for tides). Over the entire survey area (Moreton Bay, Hervey Bay, southern GBR), 96% of dugongs were sighted in waters less than 20 m deep (89% in waters less than 15m deep; 83% in waters less than 10 m deep). In five areas with high dugong density: Moreton Bay (Moreton Bay Region, blocks 1-6); Hervey Bay (Hervey Bay Region, blocks 1-4); Shoalwater Bay (southern GBR Region, blocks S4 and S5), Cleveland Bay (southern GBR Region, Block C8) and the Hinchinbrook area (southern GBR Region, block C10), dugong sightings varied between different depth strata (Figure 5). Similar to our observations in 2011, relatively more dugongs were seen in deeper water (>15m) in Hervey Bay and Hinchinbrook Island in 2016 than in surveys before 2011, a result consistent with the low intertidal seagrass biomass in these areas (Table 19).

The number of dugongs sighted in water <5 m deep was significantly higher than in the remainder of the depth categories in three southern locations (Moreton Bay, Hervey Bay and Shoalwater Bay). However, dugong numbers were significantly lower in that depth category in 2005 than in any other year (Table 7). That year, dugong numbers were higher in 5 to < 10 m deep waters in these locations and 15 to < 20 m for Shoalwater Bay. These results indicate the dugongs moved to slightly deeper water in 2005. The number of dugongs in Hervey Bay also significantly differed among years and depth categories. The distribution patterns across years and depth categories were variable as in Moreton Bay, indicating dugongs’ movement across depth categories across years (Figure 5), but the bay showed more variability among years (26% of variance explained by year, Table 7).

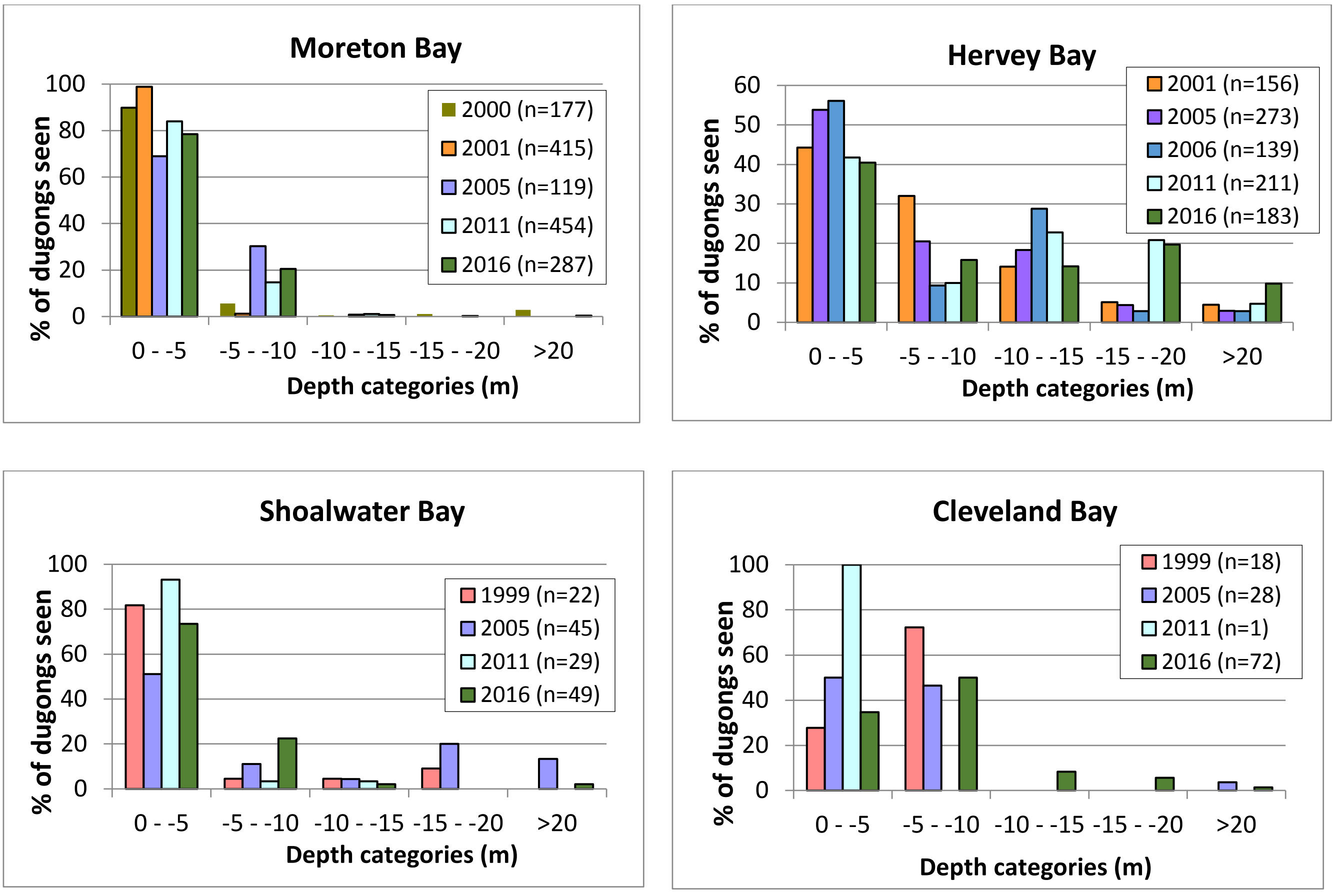
In Shoalwater Bay, although all effects (year, depth category and interaction of year and depth category) were significant, the depth category explained 75% of variability in the data, and significantly larger numbers of dugongs were sighted in the shallowest depth category. The effects of year and the interaction term were comparably smaller (Figure 5, Table 7), indicating lesser variability in movements across depths between years.

In contrast to other three locations above, in Cleveland Bay and the Hinchinbrook area, higher or similar number of dugongs were sighted in water 5-<10 m deep as water <5 m deep across years. In Cleveland Bay, the effects of year were strongest with 60% of variance explained by year, much greater than the effects of depth (30% of variance). There was no significant effect of interaction of year and depth. This large yearly effect is exacerbated by the very low number of dugong sightings in Cleveland Bay in 2011. Around Hinchinbrook Island, depth category explained the largest amount of variation (74% of variation explained by depth category, Table 7), indicating dugongs sighting patterns differ less across years. A significant effect of interaction between year and depth category is largely due to more dugong sightings in water exceeding 15 m in 2011 and 2016 than other two years. Model outputs are found in Appendix 8.

3.3.5 Turtle sightings with respect to bathymetry

Turtles were sighted in waters up to 56 m deep (not corrected for tides). Over the entire survey area (all three regions), 96% of all turtles were sighted in waters less than 20m deep; 91% in waters less than 15m deep; and 82% in waters less than 10m deep (Figure 6).

The distribution of depth use by the large juvenile and adult turtles differed significantly among locations (Moreton Bay, Hervey Bay, Shoalwater Bay, Cleveland Bay and the Hinchinbrook area) and depth categories, as demonstrated by the significant interaction between location and depth category (Table 8). Water depth alone explained 63% of the variance. In all locations, a large proportion of turtles occur in water <5 m deep, but in Shoalwater Bay and Cleveland Bay relatively large number of turtles were also sighted in water 5 to < 10 m deep in comparison to the situation in both Moreton Bay and Hervey Bay turtles. In Hervey Bay and the Hinchinbrook area to a lesser extent more turtles were also sighted in water >10 m deep compared to all other locations. The model outputs are in Appendix 8.



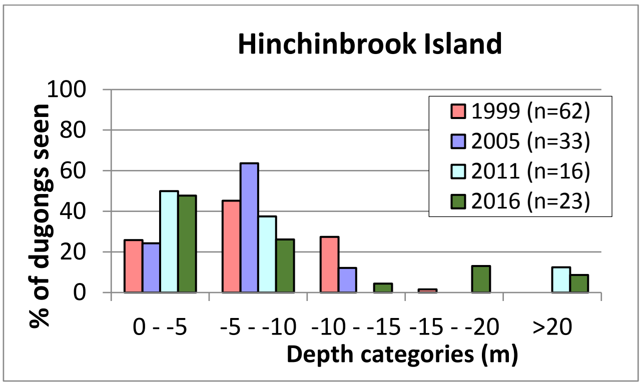


Figure 5. Frequency distribution of dugongs sighted with respect to bathymetry in five areas of the 2016 surveys: Moreton Bay (Moreton Bay Region, blocks 1-6); Hervey Bay (Hervey Bay Region, blocks 1-4); Shoalwater Bay (Southern GBR Region, blocks S4 and S5), Cleveland Bay (Southern GBR Region, block C8) and Hinchinbrook Island (Southern GBR Region, block C10). Note that the percentages have not been weighted for the area of each depth category in contrast to the analysis in Table 7 below.

Table 7. Analysis of deviance table from the log-linear models used to explore temporal changes in the dugongs' use of habitats of different depth in Moreton Bay, Hervey Bay, Shoalwater Bay, Cleveland Bay and the Hinchinbrook area.

(a) Moreton Bay					
	DF	Deviance	Residual DF	Residual Deviance	Pr(Chi)
Null			24	2955.75	
Year	4	307.70	20	2648.05	<0.0001
Depth category	4	2487.07	16	160.98	<0.0001
Year * Depth category	16	160.98	0	0.00	<0.0001
(b) Hervey Bay					
	DF	Deviance	Residual DF	Residual Deviance	Pr(Chi)
Null			24	211.75	
Year	4	55.84	20	155.91	<0.0001
Depth category	4	36.58	16	199.33	<0.0001
Year * Depth category	16	119.34	0	0.00	<0.0001
(c) Shoalwater Bay					
	DF	Deviance	Residual DF	Residual Deviance	Pr(Chi)
Null			19	220.56	
Year	3	14.08	16	206.48	<0.01
Depth category	4	164.99	12	41.49	<0.001
Year * Depth category	12	41.49	0	0.00	<0.001
(d) Cleveland Bay					
	DF	Deviance	Residual DF	Residual Deviance	Pr(Chi)
Null			19	164.02	
Year	3	99.00	16	65.02	<0.001
Depth category	4	48.90	12	16.12	<0.001
Year * Depth category	12	16.12	0	0.00	0.19
(e) Hinchinbrook area					
	DF	Deviance	Residual DF	Residual Deviance	Pr(Chi)
Null			19	280.86	
Year	3	34.40	16	246.47	<0.001
Depth category	4	207.46	12	39.01	<0.001
Year * Depth category	12	39.00	0	0.00	<0.001

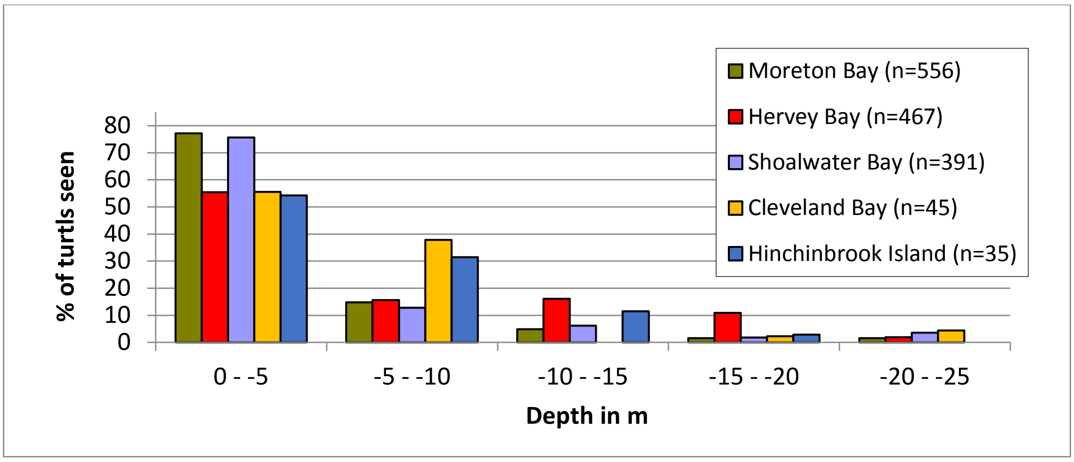


Figure 6. Frequency distribution of turtles sighted with respect to bathymetry in Moreton Bay, Hervey Bay, and the southern GBR Region combined. Note that the percentages have not been weighted for the area of each depth category in contrast to the analysis in Table 8 below.

Table 8. Analysis of deviance table for the log-linear model used to explore the pattern of the turtles' use of habitats of different water depth in Moreton Bay, Hervey Bay, Shoalwater Bay, Cleveland Bay and Hinchinbrook Island in 2016.

	DF	Deviance	Residual DF	Residual Deviance	Pr(Chi)
Null			21	1507.33	
Location	4	211.35	17	1295.98	<0.001
Depth category	4	994.60	13	301.38	<0.001
Location * Depth category	13	301.38	0	0.00	<0.001

3.4 Population size estimates and trends

3.4.1 Dugong population size estimates

Dugong population size estimates are presented here for the Hagihara method and in Appendix 9 for the Pollock method. These methods are superior to the Marsh and Sinclair method because the more recent methods consider the spatial heterogeneity in the availability correction factors. However, since our pre-2000 surveys provide results for the Marsh and Sinclair method only, the density estimates using this method is presented in Appendix 10 to compare dugong densities over longer time periods where the data permit.

The raw data for sightings of dugong groups for each transect in each block surveyed in October-November 2016 used to estimate population size are have been added to the on-line dugong data set at https://dugongs.tropicaldatahub.org.

The probability of observers sighting dugongs, given they were available for detection, was high in both teams. The perception probability estimates, based on the generalised Lincoln-Petersen models fitted using the MARK program, suggest that the double-observer teams sighted 81-97% of dugongs that were available (Table 9).

Table 9. Details of models and perception probabilities for dugong population estimations for each team.

Team	Model [1]	Probability estimates [2] (± s.e.)	Perception probability of each tandem team
1 (north)	All observers different	Port Primary 0.65 (± 0.06) Port Secondary 0.47 (± 0.05) Starboard Primary 0.79 (± 0.05) Starboard Secondary 0.74 (± 0.05)	Port 0.81 Starboard 0.95
2 (south)	Prim/Sec observers different	Both Primary 0.87 (± 0.02) Both Secondary 0.76 (± 0.02)	Port 0.97 Starboard 0.97

[1] The generalised Lincoln-Petersen model of best fit according to Akaike's Information Criterion using the MARK program (White and Burnham 1999), where the perception probability was either the same for all observers, varied according to experience (primary or secondary observers), varied according to side of the aircraft (port or starboard), or was different for every observer.
[2] Probability estimate provided by the model

3.4.1.1 Dugongs in Moreton Bay

In 2016, the dugong population estimate for Moreton Bay was 601 ± 80 using the Hagihara method (Table 10 and Figure 7). In general, Block MB4 (Eastern Banks) had higher dugong densities than any other block in the Moreton Bay Region. There was a significant interaction between year and block (Table 11). Dugong densities in 2016 were the highest for all blocks except Block MB1 (Deception Bay) where the density was lowest in 2016. Block MB4 had very similar numbers among all three years, suggesting that the Eastern Banks are a stable habitat for dugongs in Moreton Bay (Figure 8 and Appendix 11). The numbers sighted in Block MB6 were much higher in 2011 and 2016 than in 2005.

Table 10. Relative dugong abundance (± standard errors) in Moreton Bay for 2005, 2011, and 2016 based on the Hagihara method.

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

Herds sighted 2005: *10 dugongs; **31, 21 and 146 dugongs
2011: [#]44, 117 and 170 dugongs
2016: [~]14, 33, 36, 45, and 49 dugongs
tfs – too few sightings for population estimations

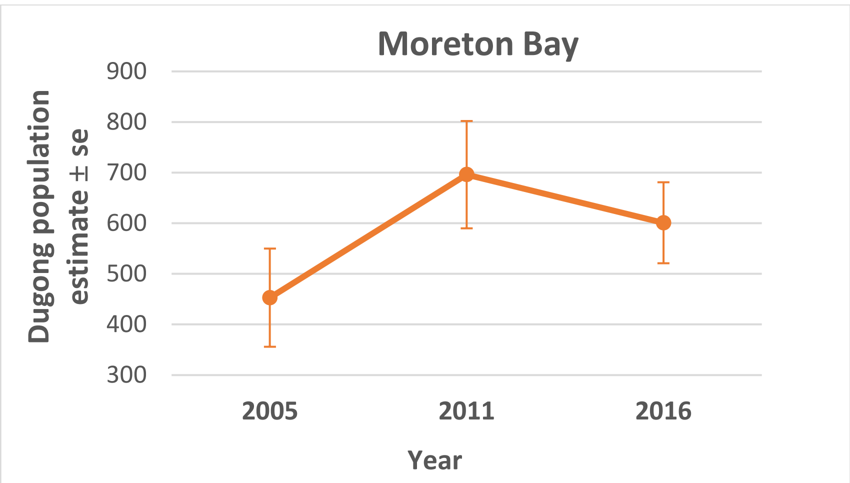


Figure 7. Dugong population size estimates ± se for the Hagihara method in 2005, 2011, and 2016 in Moreton Bay. For the locations of the survey blocks refer to Figure 1.

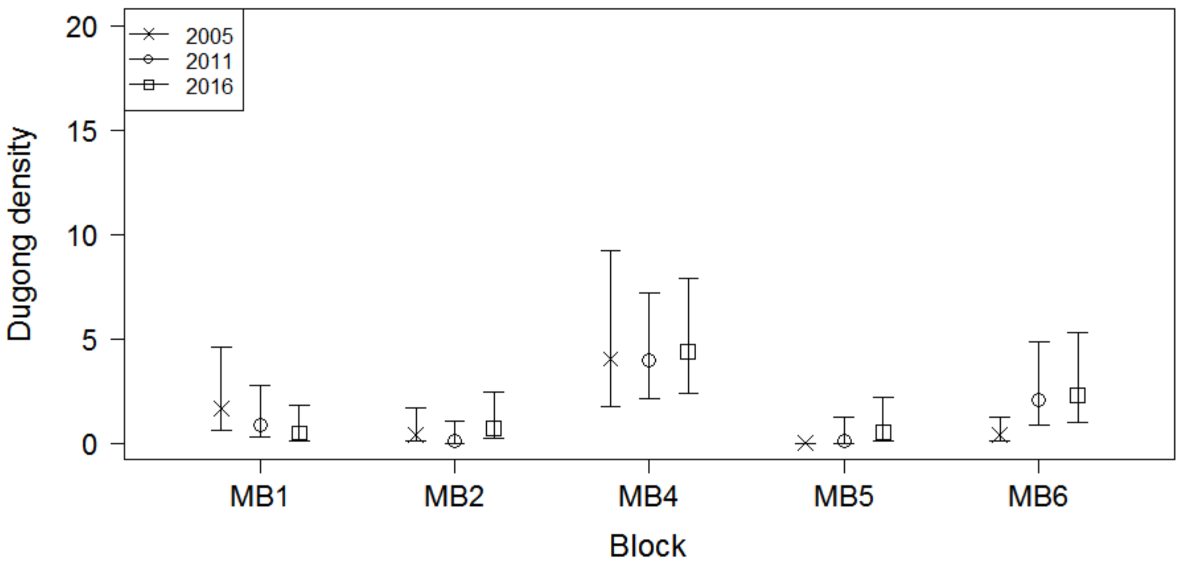


Figure 8. Estimated number of dugongs per km^2 (dugong densities) per transect predicted from the negative model based on dugong adjusted counts using the Hagihara method for the aerial surveys in 2005, 2011 and 2016 of Moreton Bay. Lines represent 95% confidence intervals. The location of each block is shown in Figure 1.

Table 11. Analysis of deviance table for the negative binomial model of adjusted dugong density in Moreton Bay for the surveys conducted in 2005, 2011 and 2016.

	DF	Deviance	Residual DF	Residual Deviance	Pr(Chi)
Null			163	201.74	
Year	2	2.87	161	198.87	0.23
Block	4	46.54	157	152.33	<0.001
Year * Block	8	16.45	149	135.88	<0.05

3.4.1.2 Dugongs in Hervey Bay

In 2016, the dugong population size in Hervey Bay was estimated to be 2055 ± 382 animals using the Hagihara method (Table 12 and Figure 9), the highest estimate since 2005. Most of this increase in dugong numbers occurred in Block HB4 (Figure 10). There was a significant difference in dugong densities among blocks in Hervey Bay Region; in all three years Block HB2 had the highest densities. The effect of year was present only in the interaction term, as a result of Block HB4 having a significantly higher density in 2016 than in the other two years (Figure 10, Table 13 and Appendix 11). In all three years, Blocks HB1 and HB3 had lower densities than Blocks HB2 and HB4.

Table 12. Relative dugong abundance (± standard errors) in Hervey Bay for 2005, 2011 and 2016 based on the Hagihara method.

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

Herds sighted: 2005: *13, 24, and 47 dugongs
2011: #25 dugongs
2016: ~15 dugongs

tfs – too few sightings for population estimations

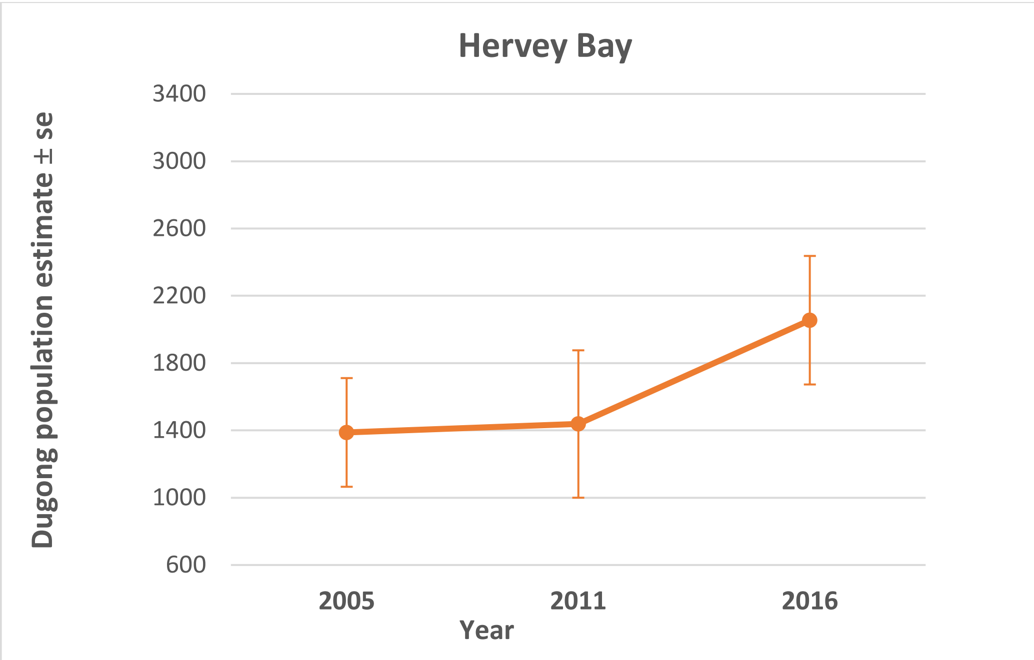


Figure 9. Estimated population sizes (± s.e.) for individual blocks in Hervey Bay in 2005, 2011, and 2016 based on the Hagihara method. For locations of blocks refer to Figure 1. No estimates were obtained for Block HB5 because of the low number of sightings.

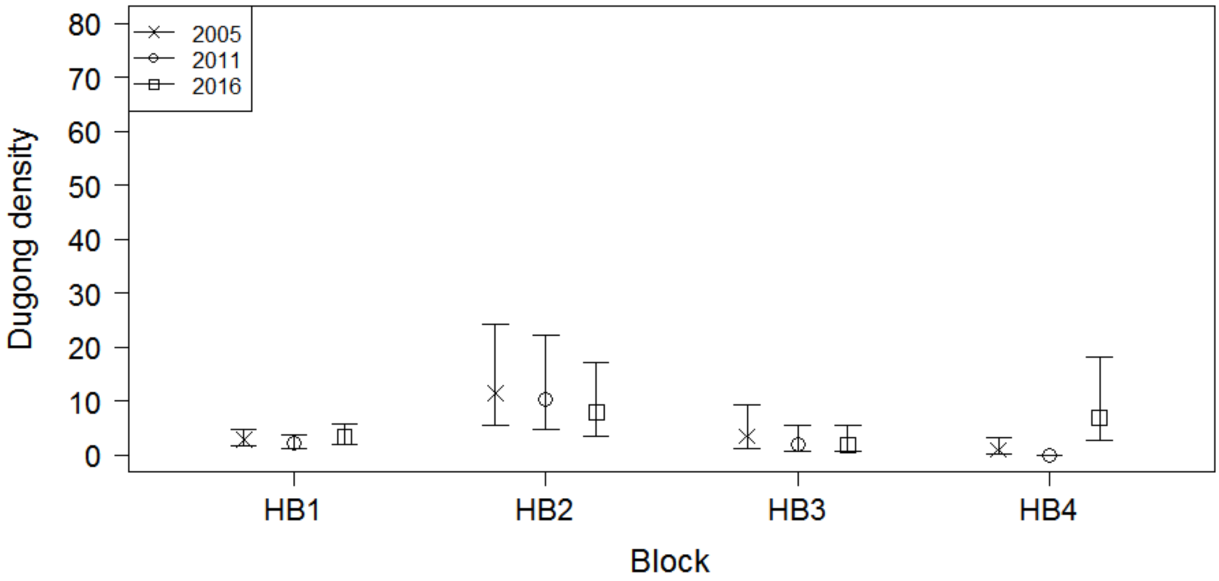


Figure 10. Estimated number of dugongs per km^2 (dugong densities) per transect predicted from the negative model based on adjusted dugong counts using the Hagihara method for the aerial surveys of the Hervey Bay region conducted in 2005, 2011 and 2016. Lines represent 95% confidence intervals. Blocks HB5, HB6 and HB7 were removed for the reasons explained in the text. The location of each block is shown in Figure 1.

Table 13. Analysis of deviance table from the negative binomial model of adjusted dugong density for Hervey Bay in 2005, 2011, and 2016.

	DF	Deviance	Residual DF	Residual Deviance	Pr(Chi)
Null			173	235.17	
Year	2	2.45	171	232.72	0.29
Block	3	34.86	168	197.86	<0.001
Year * Block	6	22.49	162	175.37	<0.001

3.4.1.3 Dugongs in the southern Great Barrier Reef

The estimated size of the dugong population in the southern GBR region in 2016 was 2822 ± 600 using the Hagihara method (Table 14 and Figure 11). This estimate represents a more than fivefold increase in numbers from the 2011 estimate. Most of the increase in population size estimates in 2016 results from the blocks north of the Whitsundays (C-Blocks), with Block C8 (Cleveland Bay) contributing most to the increase (Table 14 and Figure 12).

The best-fitting zero-inflated negative binomial model indicated that dugong density in the southern GBR was significantly higher than in 2011 but similar to that in 2005 (Figure 12). The densities among blocks also differed significantly, and higher densities were found in Block S5 (Shoalwater Bay), C8 (Cleveland Bay) and C10 (the Hinchinbrook area) in both 2005 and 2016 (Appendix 11). The model without the year x block interaction was significantly better ($z = -10.77$, $p<0.001$, AIC = 1456) than the model with the interaction term (AIC = 1461), indicating that the pattern of distribution of dugong density was similar across blocks over the three surveys. An analysis of deviance table cannot be generated for a zero-inflated negative binomial model.

Table 14. Relative dugong abundance (± standard errors) in the southern Great Barrier Reef for 2005, 2011, and 2016 based on the Hagihara method.

Southern Great Barrier Reef Region			
Block	**2005**	**2011**	**2016**
S1	zzt	tfs	tfs
S2	tfs	0	tfs
S3	134 (± 82)	tfs	tfs
S4	zzt	dd	tfs
S5	611 (± 174)	345 (± 229)	583 (± 222)*
S6	dd	dd	tfs
S7	zzt	0	tfs
S8	tfs	tfs	122(± 88)
Total S-Blocks	**745 (± 192)**	**345 (± 229)**	**705 (± 239)**
C1	tfs	tfs	tfs
C2	ns	dd	0
C3	tfs	tfs	tfs
C4	74 (± 41)	tfs	265 (± 160)
C5	ns	dd	tfs
C6	173 (± 82)	64 (± 52)	tfs
C7	tfs	tfs	tfs
C8	193 (± 101)	tfs	1171 (± 423)
C9	zzt	tfs	361 (± 252)
C10	266 (± 165)	116 (± 93)	320 (± 187)
C11	107 (± 85)	59 (± 53)	ns
C12	zzt	tfs	ns
Total C-Blocks	**813 (± 230)**	**239 (± 119)**	**2117 (± 550)**
Total all blocks	**1558 (± 300)**	**537 (± 223)**	**2822 (± 600)**
Total 2016 blocks only	**1451 (± 288)**	**478 (± 253)**	**2822 (± 600)**

dd – different design; ns – not surveyed; tfs – too few sightings for population estimations;
zzt – zig zag transects flown which do not allow population estimates
* one herd of 8 animals seen

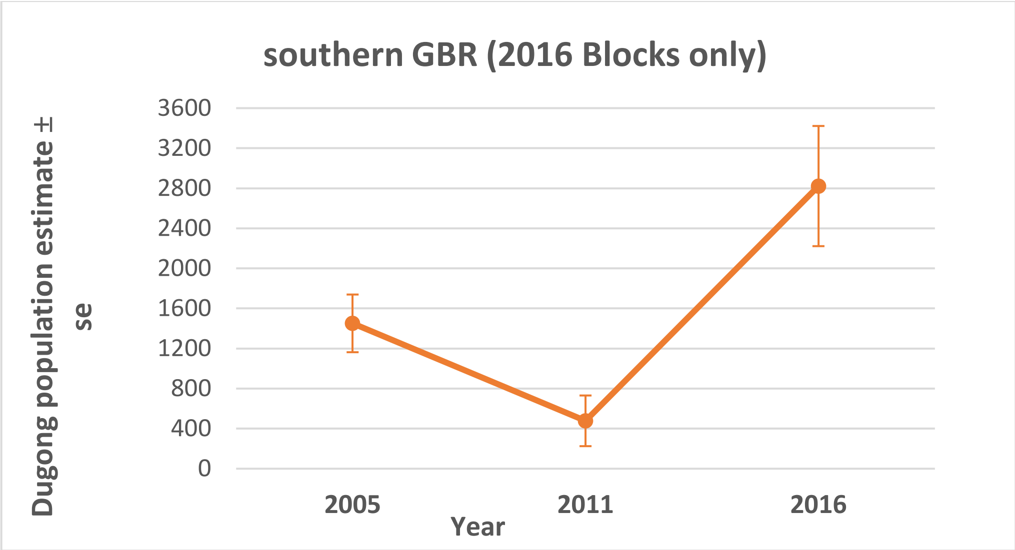


Figure 11. Dugong population size estimates ± se for the Hagihara method in 2005, 2011, and 2016 in the southern Great Barrier Reef (Blocks that were not surveyed in 2016 were omitted from the 2005 and 2011 totals).

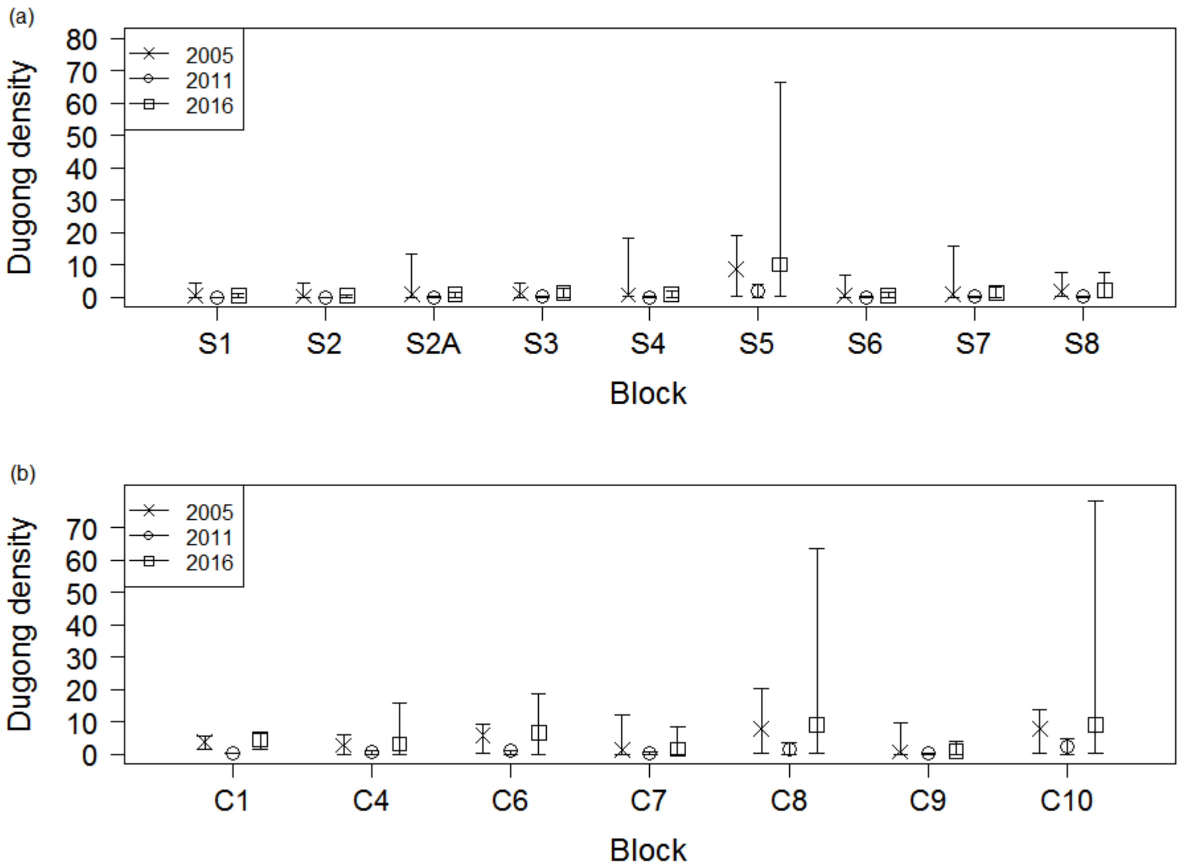


Figure 12. Estimated number of dugongs per km^2 (dugong densities) per transect predicted from the zero-inflated negative binomial model based on adjusted dugong counts using the Hagihara method for the aerial surveys of the southern GBR conducted in 2005, 2011 and 2016 for (a) southern (S) blocks and (b) central (C) blocks. The lines represent 95% confidence intervals. Blocks C2, C3, C5, C11 and C12 were removed due to reasons explained in the text. The location of each block is shown in Figure 1.

3.4.1.4 Southern and northern dugong stocks

For both southern and northern stocks, dugong densities were significantly different among years (Tables 15 and 16). For the southern stock, the densities for the 2016 survey was the highest of the three surveys (Figures 13 and 14) and significantly higher than for 2011 but there was no significant difference between 2016 and 2005 for all blocks, whereas the densities in 2011 were the lowest (Appendix 13). There was also a significant block effect. Blocks MB4 (Eastern Banks, Moreton Bay) and HB2 (Hervey Bay) had the highest densities in all years, followed by Blocks S5 and S6 in the Shoalwater Bay. The effect of the interaction between year and block could not be examined due to there being too many blocks with zero sightings especially in the southern GBR.

The effects of both year and block were also significant in the northern genetic stock, with the highest dugong densities recorded in 2016, followed by 2005, and the significant difference between 2016 and 2005 was at the borderline (p=0.05) for all blocks. Again, the lowest densities were recorded in 2011, and the densities were significantly higher in 2016than 2011 for all blocks (Figures 13 and 14 and Appendix 14). As shown above, Blocks C8 (Cleveland Bay near Townsville) had the highest densities followed by Blocks C10 (Hinchinbrook Island), C6 (Upstart Bay) and C4 (Bowen) (Figure 14). The other blocks had very low dugong densities. As for the southern stock, the interaction between year and block could not be examined due to there being too many blocks without dugong sightings. Comparable results were found in dugong densities estimated from Marsh and Sinclair and Pollock methods for both southern and northern stocks (Appendices 12 and 13).

Table 15. Relative dugong abundance (± standard errors) for the southern and northern dugong stocks for 2005, 2011, and 2016 based on the Hagihara method.

	Hagihara method		
Region	**2005**	**2011**	**2016**
Moreton Bay	453 (± 97)	696 (± 106)	601 (± 80)
Hervey Bay	1388 (± 323)	1438 (± 438)	2055 (± 382)
S-Blocks	745 (± 192)	345 (± 229)	705 (± 239)
Total southern stock	**2,586 (± 384)**	**2,479 (± 506)**	**3,361 (± 458)**
Total northern stock (only sGBR blocks C1-C10)	**706 (± 214)**	**180 (± 107)**	**2117 (± 550)**

Figure 13. Dugong population size estimate ± se for the Hagihara method in 2005, 2011, and 2016 for the southern and northern dugong stocks.

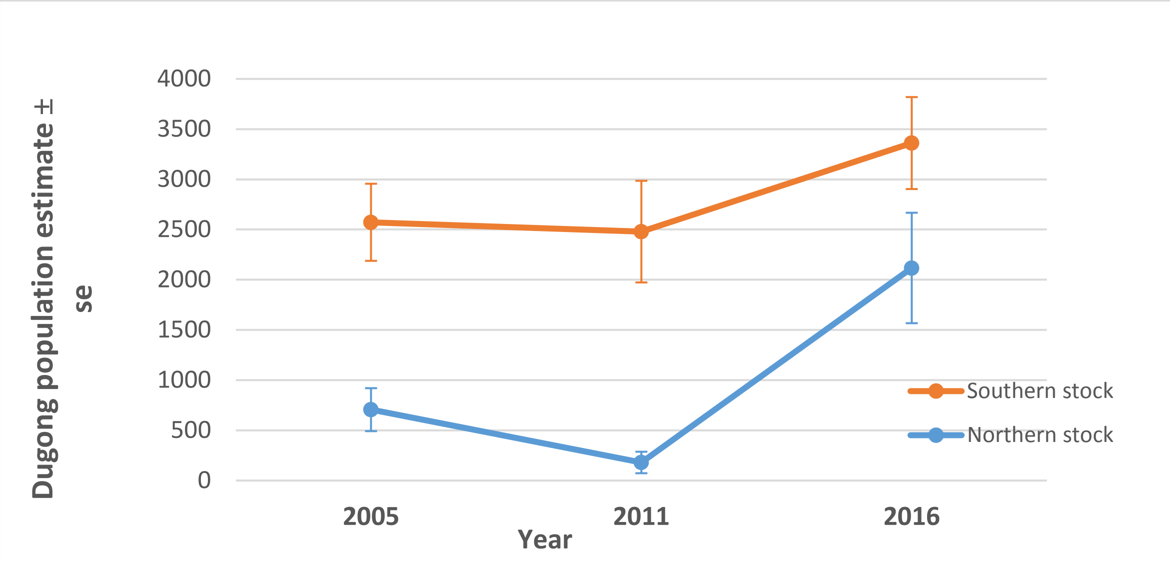


Table 16. Analysis of deviance table from the negative binomial model based on the surveys in 2005, 2011 and 2016 of: (a) the southern, and (b) the northern stocks of dugongs along the east coast of Queensland from Hinchinbrook Island to the New South Wales border.

(a) Southern stock					
	DF	**Deviance**	**Residual DF**	**Residual Deviance**	**Pr(Chi)**
Null			777	860.81	
Year	2	7.67	775	853.15	<0.05
Block	19	325.14	756	528.01	<0.001
(b) Northern stock					
	DF	**Deviance**	**Residual DF**	**Residual Deviance**	**Pr(Chi)**
Null			324	322.40	
Year	2	42.84	322	279.55	<0.001
Block	8	67.49	314	212.06	<0.001

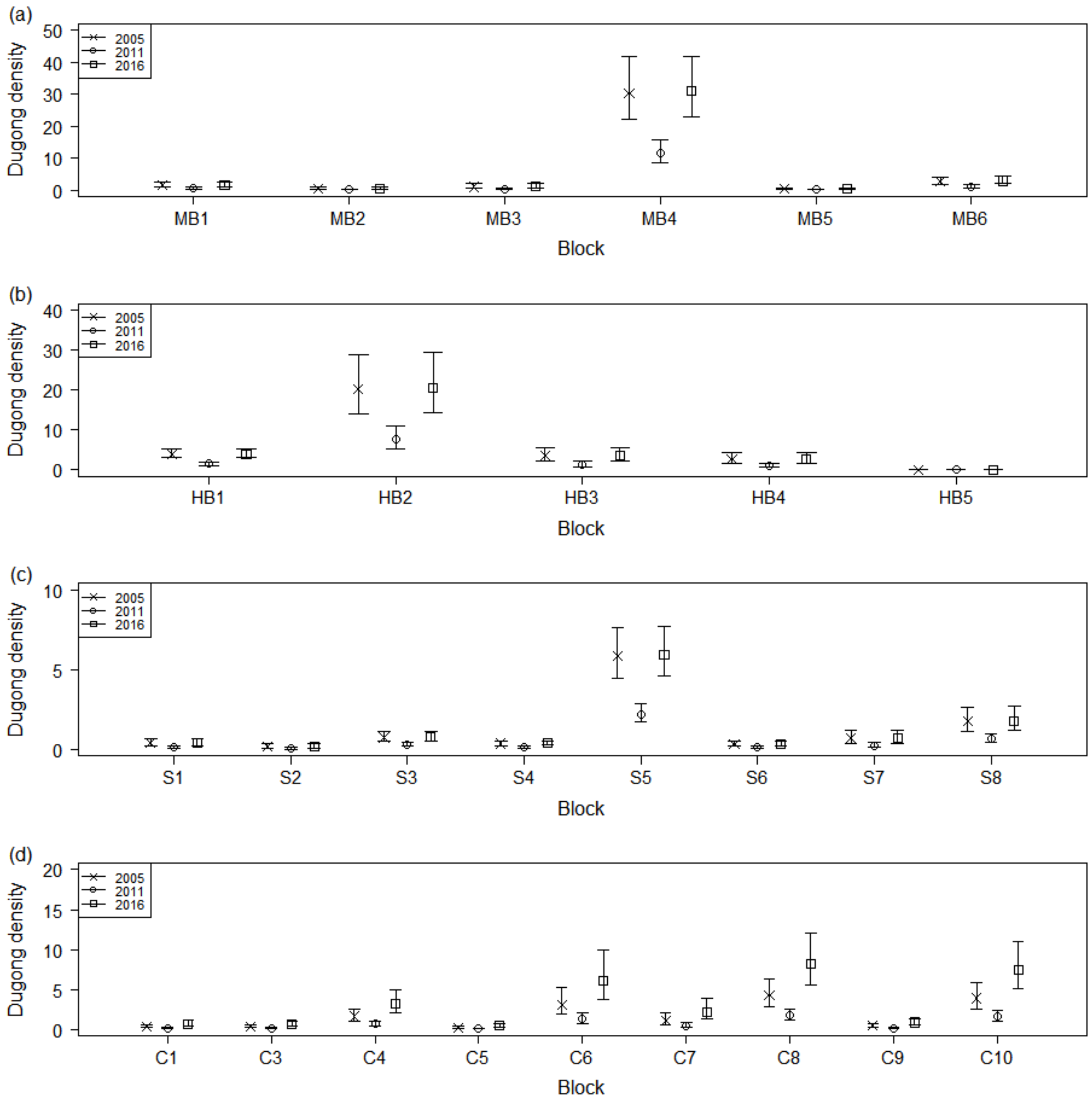


Figure 14. Estimated number of dugongs per km^2 (dugong densities) per transect predicted from the negative binomial model based on adjusted counts using the Hagihara method for the aerial surveys conducted in 2005, 2011 and 2016 for the southern stock (a, b and c) and the northern stock (d). Lines represent 95% confidence intervals. Blocks HB6 and HB7 were removed as explained in the text. The location of each block is shown in Figure 1.

3.4.2 Turtle population size estimates

The probability of observers sighting large juvenile and adult marine turtles of all species, that were available for detection, was high for both teams. The perception probability estimates, based on the generalised Lincoln-Petersen models fitted using program MARK, suggest that the double-observer teams sighted 83-91% of the large juvenile and adult turtles that were available (Table 17).

Table 17. Details of models used to calculate the perception bias and the resultant perception probabilities for large juvenile and adult turtles for each team.

Team	Model [1]	Probability estimates [2] (± s.e.)	Perception probability of each tandem team
1 (north)	All observers different	Port Primary 0.37 (± 0.02) Port Secondary 0.73 (± 0.03) Starboard Primary 0.71 (± 0.03) Starboard Secondary 0.58 (± 0.03)	Port 0.83 Starboard 0.88
2 (south)	All observers different	Port Primary 0.75 (± 0.02) Port Secondary 0.64 (± 0.02) Starboard Primary 0.75 (± 0.02) Starboard Secondary 0.51 (± 0.02)	Port 0.91 Starboard 0.88

[1] The generalised Lincoln-Petersen model of best fit according to Akaike's Information Criterion using the MARK program (White and Burnham 1999), where the perception probability was either the same for all observers, varied according to experience (primary or secondary observers), varied according to side of the aircraft (port or starboard), or was different for every observer.
[2] Probability estimate provided by the model

The turtle population size estimates presented here are based on the Fuentes et al. (2015) method.

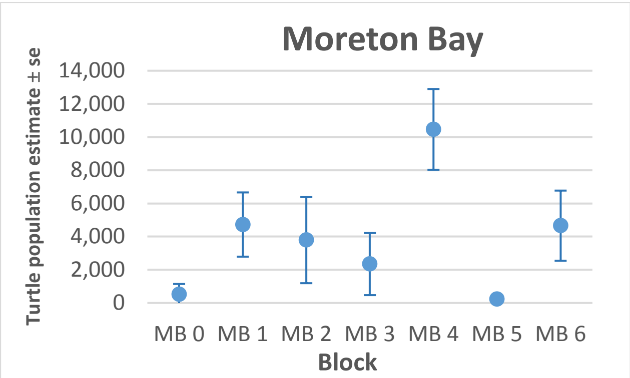
In Moreton Bay, the population of large juvenile and adult marine turtles of all species was estimated to be 26229 (± 4946) in November 2016 with around 40% in Block MB4 (Eastern Banks) (Table 18 and Figure 15). The corresponding population for Hervey Bay was estimated to be 49853 ± 8664 large juvenile and adult marine turtles, more than 60% of which occurred in block HB1 (Table 18 and Figure 15). Turtle abundance in the southern GBR varied greatly between survey blocks. The overall population estimate was 135471 ± 19802 with more than half of these animals recorded in Blocks S5 and S6 (Shoalwater Bay region) (Table 18 and Figure 15).

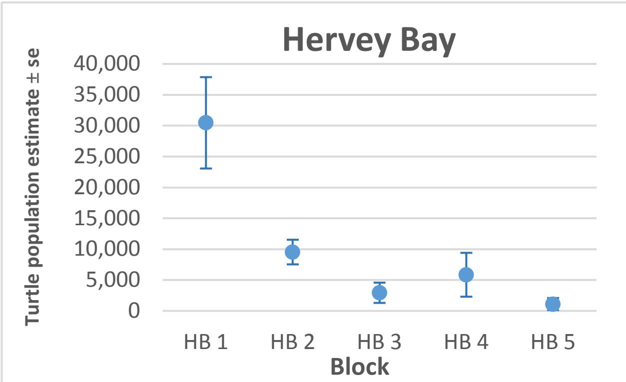
Table 18: Relative abundance of large juvenile and adult marine turtles of all species (± standard errors) in Moreton Bay, Hervey Bay and the southern Great Barrier Reef in 2016. Population size estimates were based on the Fuentes method.

Moreton Bay	
Block	**Population Estimate**
MB 1	4728 (± 1935)
MB 2	3792 (± 2600)
MB 3	2344 (± 1872)
MB 4	10466 (± 2434)
MB 5	239 (± 238)
MB 6	4660 (± 2115)
TOTAL	**26229 (± 4946)**

Hervey Bay	
Block	**Population Estimate**
HB 1	30462 (± 7399)
HB 2	9533 (± 1994)
HB 3	2936 (± 1640)
HB 4	5855 (± 3552)
HB 5	1067 (± 1019)
TOTAL	**49853 (± 8664)**

Southern GBR	
Block	**Population Estimate**
C1	1821 (± 1397)
C3	9162 (± 2500)
C4	3206 (± 1132)
C5	1719 (± 1637)
C6	1265 (± 1399)
C8	5706 (± 2551)
C9	5859 (± 3273)
C10	4503 (± 2660)
S2	2125 (± 2010)
S3	1775 (± 1165)
S4	11769 (± 5250)
S5	44063 (± 9277)
S6	25640 (± 14148)
S7	6327 (± 3550)
S8	10531 (± 4679)
TOTAL	**135471 (± 19802)**





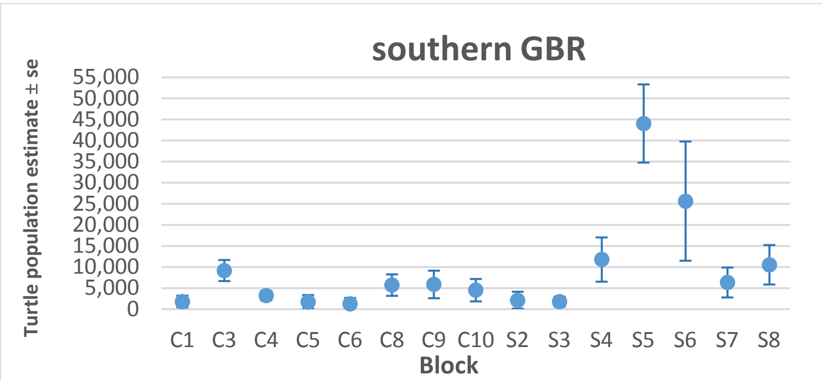


Figure 15. Turtle population size estimates ± standard errors for blocks in Moreton Bay, Hervey Bay and the southern Great Barrier Reef in 2016 generated using the Fuentes method. Note the different y-axes.

3.5 Spatially-explicit models of dugong and marine turtle distribution and density

3.5.1 Dugongs in Moreton Bay

The spatially-explicit models of dugong distribution and density developed using the time series of aerial surveys conducted in Moreton Bay confirms that Moreton Bay supports a significant population of dugongs especially in Block MB4 (Eastern Banks) where dugong densities are consistently high (Figure 16). The dugongs' use of Deception Bay (Block MB1) and the most southerly Block (MB6) fluctuated over time. The dugongs' use of Block MB5 was greatest on the only winter survey, which was conducted in 2013.

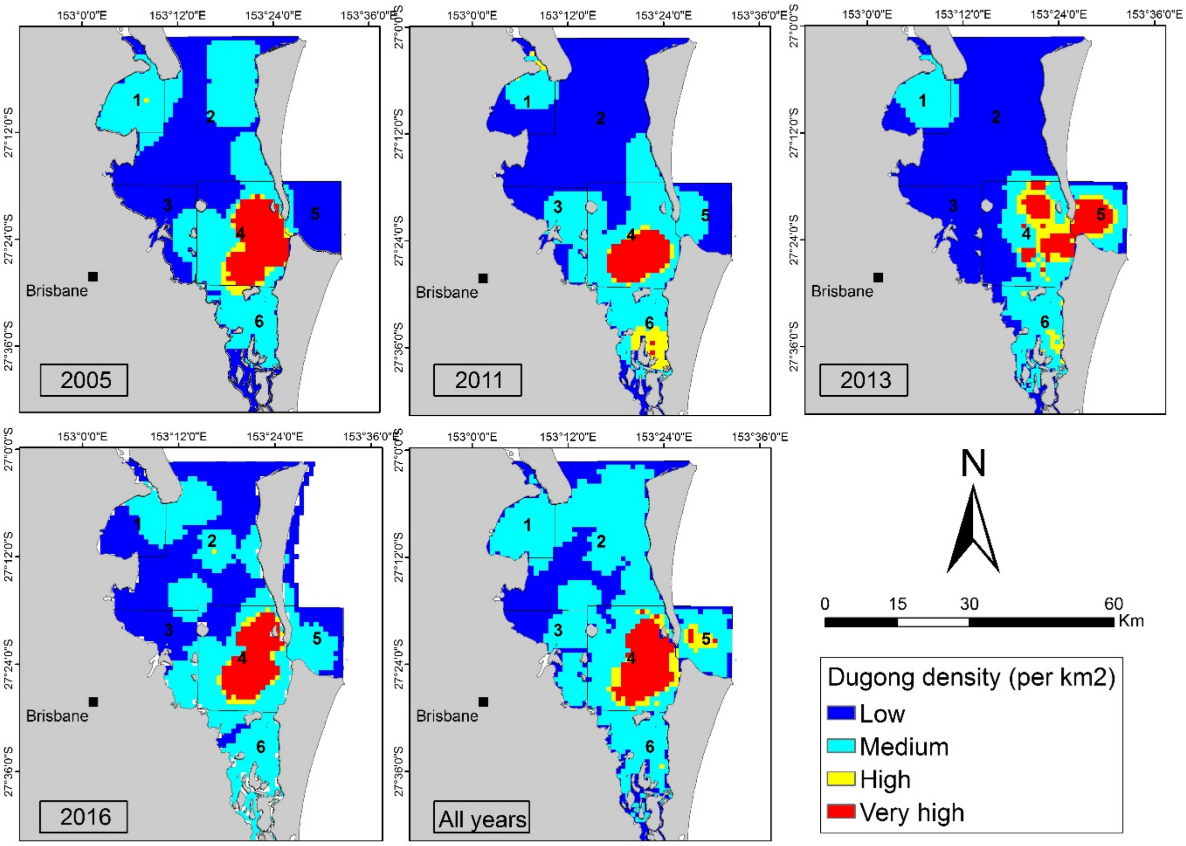


Figure 16. Spatially-explicit models of dugong density in Moreton Bay using data from the aerial surveys conducted in 2005, 2011, 2013, and 2016, and all years combined. Dugong density estimates were generated using the Hagihara method. Dugong densities were classified as Low (0 dugongs per km^2); Medium (0-0.5 dugongs per km^2); High (0.5-1 dugongs per km^2), and Very high (>1 dugongs per km^2). Survey block numbers are indicated in the middle of each block. Note the importance of Block MB6 is understated in the 2016 model because the animals were dispersed in that region.

3.5.2 Dugongs in Hervey Bay

The spatially-explicit model of dugong distribution and density shows a generally consistent pattern across the surveys of Hervey Bay analysed here (Figure 17). The increase in dugong density in Block HB4 described in Section 3.1.4.2 can clearly be seen in Figure 17. Areas of very high dugong density (i.e. red areas) are less apparent in 2016 than in the other years because dugongs were spread throughout the Bay. The composite spatially-explicit model of dugong distribution and density shows that the southern part of Hervey Bay consistently supports large numbers of dugongs.

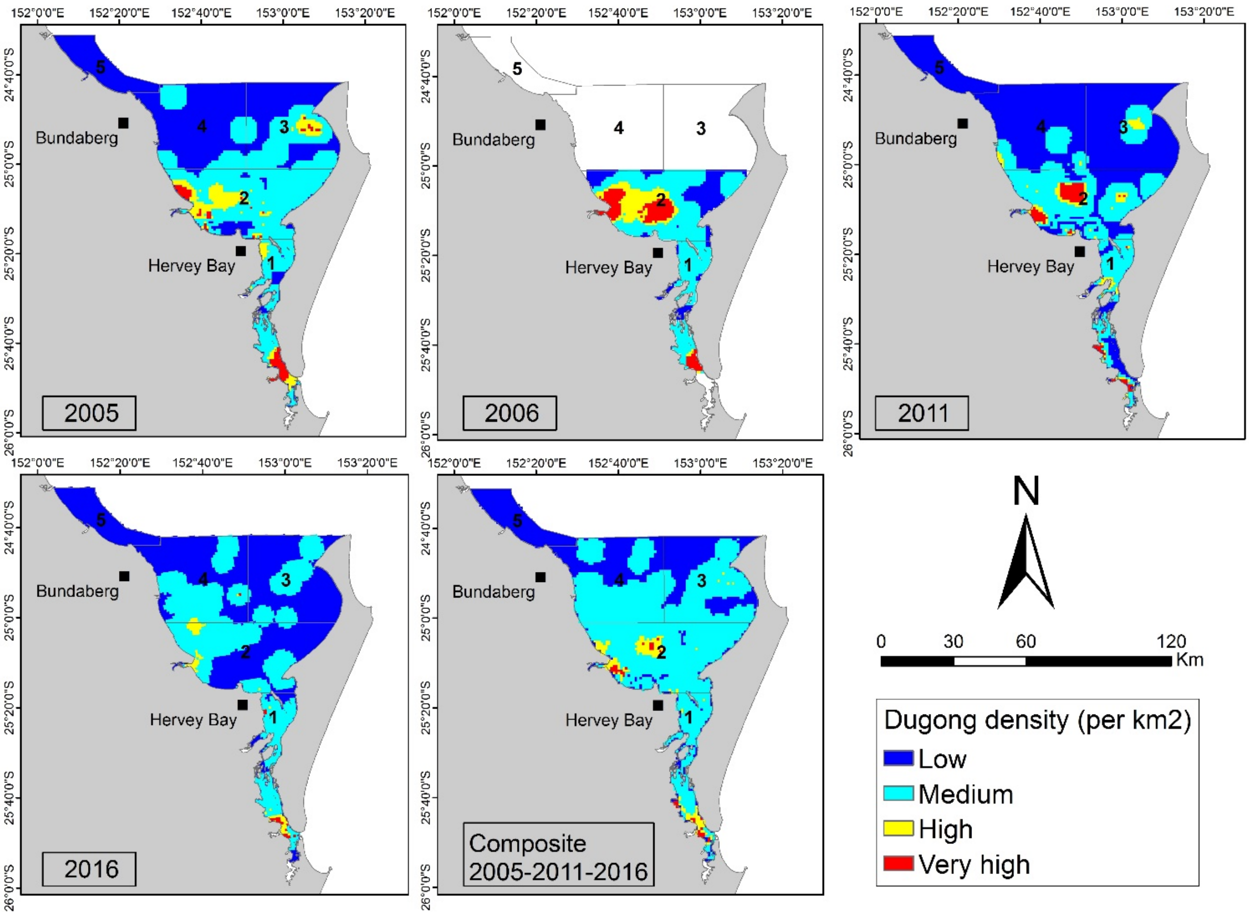


Figure 17. Spatially-explicit models of dugong density in Hervey Bay using data from aerial surveys conducted in 2005, 2006, 2011, and 2016, and a composite model for survey years 2005, 2011 and 2016. Dugong density estimations were generated used the Hagihara method. Dugong densities were classified 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 km2). Survey block numbers are indicated in the middle of each block. Note that the composite model excluded the data collected in 2006 because not all the blocks were surveyed that year.

3.5.3 Dugongs in the southern Great Barrier Reef

The spatially-explicit model of dugong distribution and density in the southern GBR in 2016 reflects the results described in Section 3.1.4.3 and demonstrates increased dugong density north of the Whitsundays (C-Blocks), especially the Townsville area (Block C8) compared with 2011 (Figure 18). The areas of higher dugong density also include the region between Bowen and Mackay and the Shoalwater Bay region. The models show that the Hinchinbrook, Townsville and Shoalwater Bay regions consistently support higher densities of dugongs than most of the remaining southern GBR region but that no-where in the region are there areas of dugong density comparable to the 'hotspots' in Moreton and Hervey Bays.

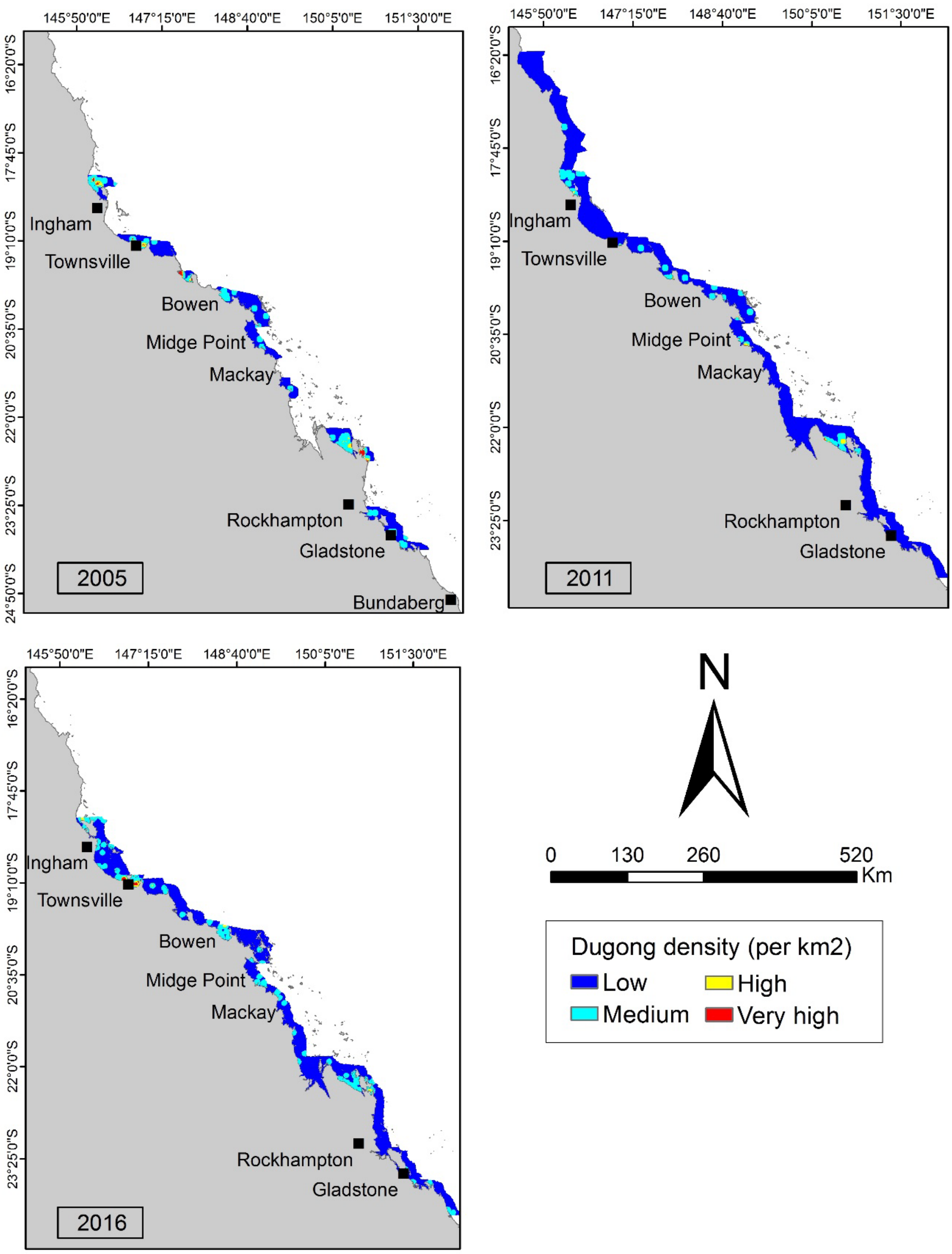


Figure18. Spatially-explicit models of dugong density in the southern GBR using data from aerial surveys conducted in 2005, 2011, and 2016. Dugong density estimations were based on the Hagihara method. Dugong densities were classified as Low (0 dugongs per km^2); Medium (0-0.5 dugongs per km^2); High (0.5-1 dugongs per km^2), and Very high (>1 dugongs per km^2).

3.5.4 Marine turtles

This is the first time the improved spatially explicit modelling method developed by Grech and Marsh (2007) and Grech et al. (2011) has been used to investigate the distribution and density of marine turtles in the southern GBR, Moreton Bay and Hervey Bay. At the scale of the southern GBR, our analysis shows that marine turtles occur in very high densities throughout most of the area surveyed in 2016 (Figure 19) with hotspots in the areas of Hinchinbrook Island, Townsville, between Bowen and Mackay, South of Mackay, Shoalwater Bay and Gladstone. The highest turtle densities are located in Block MB4 in Moreton Bay and in the northern section of Block HB1 near the city of Hervey Bay.

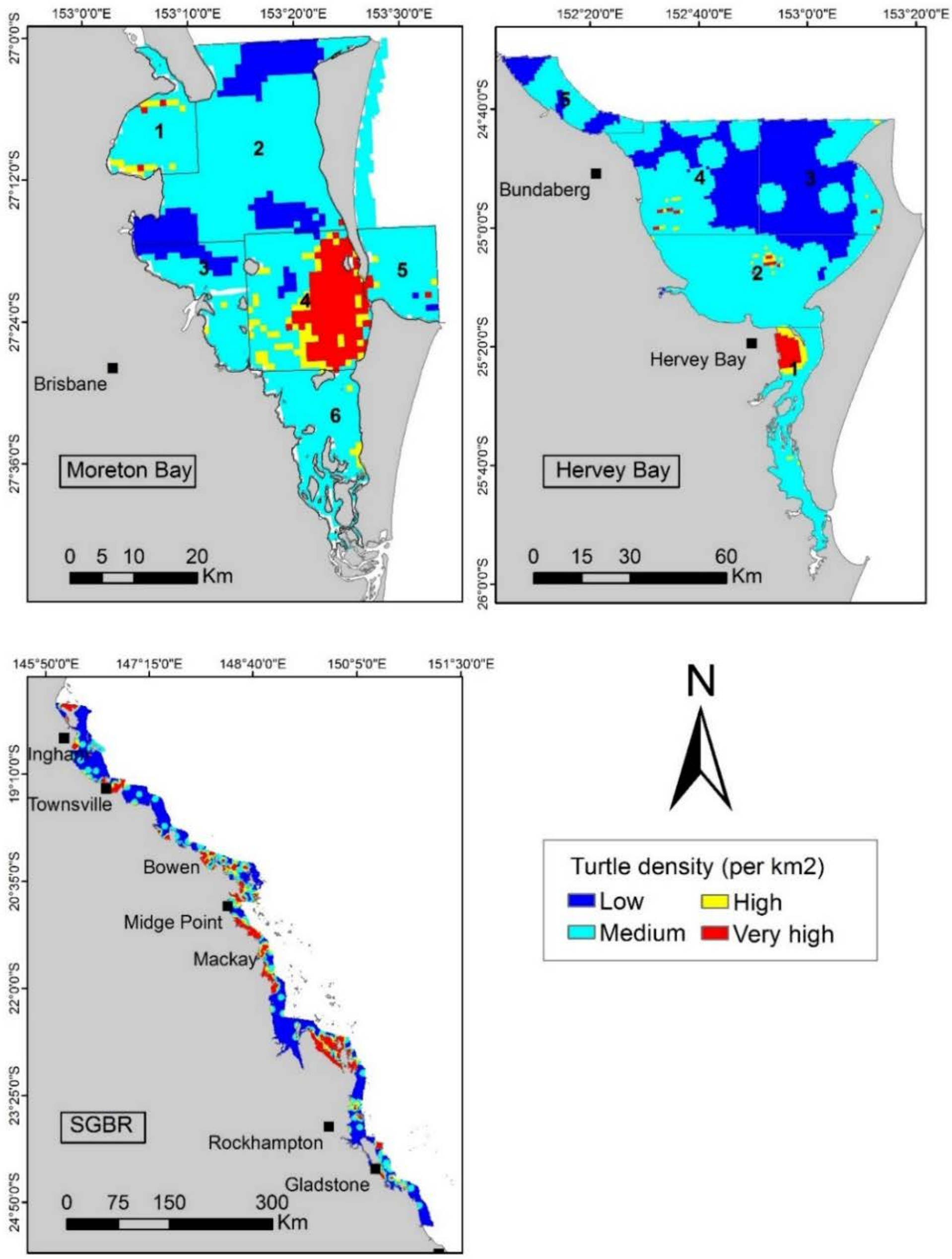


Figure 19. Spatially-explicit models of turtle density in Moreton Bay (top left), Hervey Bay (top right) and the southern Great Barrier Reef (bottom left) using the 2016 aerial survey data. Corrected density estimates were generated using the Fuentes method. Turtle densities were classified as Low (0 turtles per km^2); Medium (0-0.5 turtles per km^2); High (0.5-1 turtles per km^2), and Very high (>1 turtles per km^2).

4 DISCUSSION

4.1 Overview of results

The results of this survey add to the evidence from StrandNet and seagrass monitoring to indicate that the dugongs and their habitats in the survey region from north of Hinchinbrook Island to the Queensland–New South Wales border are in much better condition than at the time of the last such survey in 2011.

The improvement is especially evident in the southern GBR region where the estimated numbers of dugongs have significantly increased, especially north of the Whitsundays (Table 14). The percentage of calves has increased from zero in 2011 to 10.1% in 2016, a percentage above the averages for the historical survey data to 2011 for all regions except Hervey Bay (Fuentes et al. 2016). Intertidal seagrass percentage cover has increased except in the Wet Tropics (McKenzie et al. 2016 and Table 19) and the number of dugong carcasses reported to the Queensland marine wildlife stranding program StrandNet has declined (https://www.ehp.qld.gov.au/wildlife/caring-for-wildlife/strandnet-reports.html#document_availability and Table 20).

The magnitude of the increase in the southern GBR population estimates is too high to be explained by natural increase (the maximum rate of increase for a dugong population is likely to be only about 5% p.a. see Marsh et al. 2011). Thus, at least some of the differences between 2011 and 2016 must result from immigration into the survey area presumably from further north (Table 14).

In contrast, the dugong population estimates for Moreton Bay and Hervey Bay have not significantly increased over the 2011 values (Tables 10 and 12) and the percentages of calves have also remained relatively stable over this time period (Figure 3).

Table 19. Temporal changes in the abundance (% cover) of coastal intertidal seagrass (McKenzie et al. 2016). Comparable data are not available for Moreton Bay.

Area	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15
Burnett-Mary										38
Fitzroy	81	81	100	75	81	31	25	25	8	25
Mackay-Whitsundays	63	88	54	63	63	8	13	13	33	67
Burdekin	88	31	34	25	11	6	5	29	44	49
Wet Topics	38	30	55	70	54	46	7	13	21	19
Cape York							63	81	63	75

Code: ■ = *very good (81-100)*, ■ = *good (61 - 80)*, ■ = *moderate (41 - 60)*, ■ = *poor (21 - 40)*, ■ = *very poor (0 - 20).*

Table 20. Regional distribution of dugong strandings for the period January 1 to September 30 each year from 2011 to 2016 from StrandNet data. (see https://www.qld.gov.au/environment/library/). Years with aerial survey data are shaded.

Location	2011	2012	2013	2014	2015	2016
Moreton Bay	15	6	8	6	3	6
Hervey Bay	18	6	6	2	5	1
Rockhampton	10	8	2	1	2	0
Mackay	3	1	0	1	0	2
Townsville	49	4	3	2	0	4
Cairns	11	5	3	30	4	2

The results of the survey also reinforce other evidence that the survey region supports large populations of in-water large juvenile and adult marine turtles (Table 18). There are areas of very high turtle density in the southern GBR as well as in Moreton and Hervey Bays (Figure 19) in contrast to the dugong situation where the densities are much higher in Moreton Bay and Hervey Bay than anywhere in the southern GBR (Figures 16, 17 and 18).

Although historical data are not (yet) available from the surveys for marine turtles, the StrandNet data suggest that the marine turtle populations are also in much better condition than in 2011 (https://www.ehp.qld.gov.au/wildlife/caring-for-wildlife/strandnet-reports.html#document_availability and Table 21).

Table 21. Regional distribution of marine turtle strandings for the period January 1 to September 30 each year from 2009 to 2016 from StrandNet data (see https://www.qld.gov.au/environment/library/). Years with aerial survey data are shaded.

Location	2011	2012	2013	2014	2015	2016
Moreton Bay	301	278	253	241	137	166
Hervey Bay	95	81	125	45	4	12
Rockhampton	250	75	68	82	37	22
Mackay	61	29	37	23	13	7
Townsville	127	261	101	50	37	20
Cairns	27	60	40	15	19	10

4.2 Methods for adjusting for availability bias

The use of the Hagihara method that corrects for the heterogeneity in dugong diving behavior with depth was indicated by our log-linear analysis of dugong depth-use across surveys because the year by depth interaction was significant for all five locations investigated (Table 7) and there were clear differences in dugong depth use between locations (Figure 5). The analysis for the 2016 sightings of large juvenile and adult marine turtles (Figure 6 and Table 8) also suggests that it is important to quantify the heterogeneity in marine turtle diving behavior across species and depth strata. As explained above, depth-corrected diving data are available for green turtles in Torres Strait (Hagihara et al. 2016a) but the bathymetry of Torres Strait is very different from the east coast and we decided that it would be inappropriate to use these data to adjust the results from this survey for availability bias.

Despite the effort undertaken to correct for availability bias using the Hagihara and Fuentes methods, it is important to appreciate that the dugong and turtle population estimates reported here are underestimates because we have not attempted to estimate abundance for areas where dugongs and turtles were not sighted (which is theoretically possible but very difficult in practice; see Martin et al. 2014).

4.3 Effects of weather and climate on dugong fecundity and neonatal mortality

The animals classified as calves during dugong aerial surveys are believed to be aged from neonates to about 18 months. Thus, the proportion of calves recorded during an aerial survey (calf production) is a reflection of births (which are expected to reflect the effect of environmental conditions over several years on female fecundity) and neonatal survivorship (which can be affected by the more immediate effect of an extreme weather event on the mortality of both mothers and calves, especially as a result of starvation due to seagrass loss). This survey added to the time-series of data on the percentage of dugong calves sighted during aerial surveys analysed by Fuentes et al. (2016), who explored the relationships between this parameter and lagged (by 1-4 years) versions of four climatic drivers (rainfall anomaly, Southern Oscillation El Niño Index [SOI], NINO 3.4 sea surface temperature index, and number of tropical cyclones) at a range of spatially distinct locations in Queensland. Fuentes et al. (2016) found that the relationships between the proportion of dependent calves and these climatic drivers varied spatially and temporally at sub-regional scales.

The proportion of calves was negatively correlated with various features of La Niña episodes (lagged high SOI—above average rainfall, cyclones) in the northern and southern GBR, Hervey Bay and Moreton Bay, even though the response differed between these regions. Fuentes et al. (2016) concluded that the response pattern reflected the declining status of seagrass associated with these climatic variables (Preen and Marsh 1995; Rasheed et al. 2014; Coles et al. 2015). Calf counts were also negatively correlated with lagged NINO 3.4 in the northern and southern GBR, a feature of the El Niño phase based on sea surface temperature, which likely affects seagrass beds directly as a result of thermal stress (Campbell et al. 2006; Collier and Waycott 2014).

Fuentes et al. (2016) found that the climatic covariates that were significantly associated with the proportion of dependent calves in a dugong population were always lagged, presumably reflecting the need for dugongs to be in good condition prior to and during the prolonged period of pregnancy and lactation (Marsh and Kwan 2008). Thus, dugong calf counts appear to be more influenced by the condition of the mother several years prior to a survey than the more immediate impacts of climatic drivers and storms on dugongs (Heinsohn and Spain 1974, Preen and Marsh 1995, Marsh et al. 2011). The deterioration of intertidal seagrass in much of the southern GBR region for several years prior to the extreme weather of the summer of 2010/11 (Table 19), is a plausible explanation for the failure of the 2011 survey to detect dugong calves in the southern GBR region in 2011. Conversely, the subsequent recovery of seagrass in much of the region (Table 19) is a plausible explanation for the increase of the percentage calves.

Responses to the extreme weather events of 2010/11 along the eastern Queensland coast, which included the strongest La Niña weather pattern since 1973, major floods and three cyclones, were most evident in the southern GBR region. Fuentes et al. (2016) found that the influence of extreme weather events on the proportion of dependent calves was also obvious in Hervey Bay, where the proportion of dependent calves fluctuates over time (Figure 3). Preen and Marsh (1995) found that the proportion of dugong calves in Hervey Bay declined from 22% to 2.2% in a year following two floods and a cyclone in 1992, which caused the loss of more than 1000 km^2 of seagrass in the region. However, the calf counts were within normal range in 2011 and 2016 as shown by comparing the data in Figure 3 with Fuentes et al. (2016), despite the overall decline in estuarine and coastal meadows in the Burnett-Mary region since the 2005 survey (McKenzie et al., 2016), possibly due to dugongs accessing deeper water seagrass meadows in this region (Figure 5).

Despite Moreton Bay being adjacent to the major city of Brisbane, the important dugong habitat in the eastern bay (Figure 16) has a relatively low level of anthropogenic impact due to its physical separation from the main terrestrial interface with the Queensland coast and daily flushing regime with ocean waters (Lyons et al. 2013). Moreton Bay is also south of the main cyclone belt on the east coast of Australia (http://www.bom.gov.au/climate/maps/averages/tropical-cyclones/) and does not have a history of large natural physical disturbance such as storms and cyclones (Lyons et al. 2013). Despite the major Brisbane River floods of 2011, the proportions of calves were within normal range in 2011, 2013, and 2016, presumably reflecting the oceanic nature of the water quality over the Eastern Banks (Figure 16).

4.4 Effects of weather and climate on population size

The dugong population size estimates obtained from aerial surveys are standardised indices of relative abundance. As explained above, we consider that the estimates from the Hagihara method should be more robust than the previous methods and it is these estimates that are discussed here. The differences in dugong density between surveys are confounded by temporary immigration in and out of the survey area. Such movements occur along the coast and possibly offshore where there are deep water and reef top seagrass beds (McKenzie et al. 2016, Coles et al. 2009) although offshore movements of dugongs have not been confirmed by satellite tracking (Marsh and Rathbun 1990, Preen 1999 and unpublished, Sheppard 2006). The changes in population size will also be affected by inter-annual fluctuations in dugong mortality (Table 20) that are associated with by sub-regional climatic drivers (Meager and Limpus 2014), particularly the sustained periods of elevated freshwater discharge and low air temperatures associated with La Niña episodes. These climatic variables influence the extent and biomass of the seagrasses on which dugong depend for food as explained above.

The differences between the 2005, 2011 and 2016 estimates of the dugong population sizes of Moreton Bay and Hervey Bay were not significant (Tables 11 and 13), although there were significant differences between surveys in the distribution of dugongs within both bays, suggesting temporal differences in the health of their seagrass beds. Cope et al.'s (2015) pedigree analysis indicates that dugongs move between Moreton Bay and Hervey Bay more often than suggested by genetic analysis (Seddon et al. 2014) or the limited telemetry conducted to date (Sheppard et al. 2006; Zeh et al. 2016). Dugongs have also been tracked moving between Hervey Bay and further north (Sheppard et al. 2006) and it is likely that dugongs moved out of the southern GBR to south-east Queensland as a result of the seagrass dieback further north prior to the 2011 survey (Table 19). However, the results of the aerial surveys cannot confirm the nature and extent of such movements.

Nonetheless, the total population estimates for the southern stock in 2005 (2586 $\pm$ 384) and 2011 (2479 $\pm$ 506) were close (Table 15) with density analysis showing no significant difference between the two years. These results suggest that most of the dugong movements in response to the seagrass loss in much of the southern GBR region between 2009-2013 (Table 19) were within the region south of the Whitsundays to the Queensland-New South Wales border. This finding accords with the stock structure suggested by the deep genetic break around Midge Point (Alexandra McGowan and David Blair et al. unpublished). However, this putative stock structure cannot explain the >35% increase in the size of the southern stock detected by the 2016 survey (Table 15), which, as explained above, is also too high to be explained by natural increase. The most plausible explanation for this result is that dugongs move across the deep genetic break around Midge Point but that there is limited interbreeding between the two stocks. Seddon et al. (2014) detected genetic differences between the Moreton Bay and Hervey Bay dugong populations, even though the pedigree analysis and satellite tracking indicated movement between these regions. Non-breeding movements across the Midge Point genetic break would be consistent with these findings.

The fluctuations in the population size of the northern stock detected by the aerial surveys is much greater than for the southern stock and consistent with the genetic homogeneity of dugong population north of Townsville through Torres Strait (Blair et al. 2014 and unpublished data). The dugong population estimates for the region from the Whitsundays north to Hinchinbrook fluctuated from 706 $\pm$ 214 in 2005, 180 $\pm$ 107 in 2011, and 2117 $\pm$ 550 in 2016 (Table 15). The change was particularly large for Block C8 near Townsville ranging from 193 $\pm$ 101 in 2005, to too small to estimate in 2011 (when the intertidal seagrass cover had been very poor for three years (Table 19) to 1171 $\pm$ 423 in 2016 (Table 14) coincident with seagrass recovery (Table 19). These results not only confirm the importance of Cleveland Bay as dugong habitat (Marsh 2000) but also suggest considerable movement of the dugongs within the northern stock and the need to coordinate aerial surveys across the entire region from the Whitsundays through Torres Strait.

4.5 *Use of spatial models in dugongs and marine turtles conservation management*

The chief value of the spatial models of the distribution and relative abundance of dugongs and large juvenile and adult marine turtles illustrated in Figures 16 to 19 is the identification of high density areas as priorities for systematic conservation planning and spatial risk assessment (Grech and Marsh 2008; Grech et al. 2011) for these Matters of National Environmental Significance. An action that reduces the Area of Occupancy of endangered species such as loggerhead, olive ridley and leatherback turtles is regarded as a significant impact under the EPBC Act, as is an action that reduces the Area of Occupancy of 'important populations' of vulnerable species such as green, flatback and hawksbill turtles (Commonwealth of Australia 2013). The spatial models presented in this report should assist in identifying and classifying the importance of the in-water Areas of Occupancy for marine turtles in the survey region.

An action is classified as having a significant impact on a migratory species such as the dugong if there is a 'real chance or possibility that it will substantially modify an area of important habitat' for that species (Commonwealth of Australia 2013). In Australia, areas of important habitat for migratory species are typically identified as Biologically Important Areas. Such areas have yet to be formally identified for dugongs on the eastern coast of Queensland. The spatial models at Figures 16 to 19 should assist with this process, which was commenced in the 1990s with the selection of the Dugong Protection Areas (Marsh 2000).

The spatial models cannot provide insights into seasonal changes in habitat use by dugongs because our surveys were mostly conducted at the same time of the year to facilitate comparison between years. An important exception to the summer surveys of the southern GBR was the 2013 survey of Moreton Bay (Sobtzick et al. 2013 unpublished). The dugong distribution in Moreton Bay in 2013 differed from that of other survey years in Block MB5 which supported areas with very high dugong densities (Figure 16). This reflects the presumed requirement by dugongs to access warmer waters immediately outside Moreton Bay and close to South Passage in winter (Marsh and Sinclair 1989a). Thermoregulatory driven movements of dugongs have also been evidenced at finer spatial scales using GPS-satellite tracking technology in Moreton Bay (Preen 1992; Sheppard et al. 2006; Zeh et al. in prep) and in other sub-tropical regions such as Hervey Bay (Sheppard et al. 2006) and New Caledonia (Cleguer 2015). Cleguer (2015) also found local-scale seasonal changes in dugong habitat use in New Caledonia using aerial surveys (Cleguer 2015, Hagihara et al. 2016b).

4.6 *Implications for the Megafauna RIMReP*

The Reef 2050 Long-Term Sustainability Plan (Commonwealth 2015) commits GBRMPA to developing a Reef 20150 Integrated Monitoring and Reporting Program (RIMReP). Dugong and marine turtles are both essential components of the megafauna section of this plan. The results of this survey have several implications for the monitoring of dugongs and in-water large marine turtles in the GBRWHA as outlined below.

The objectives of the monitoring need to be clear. If the objective is to monitor population size, the monitoring should be conducted at the same time of year to minimize the confounding seasonal effects such as those illustrated in Figure 20. If the objective is to inform systematic marine conservation planning or significant impact assessment, it would be advisable to monitor at different times of year to capture seasonal differences in habitat use and threat exposure. If quantifying the hotspots for in-water habitat use is a priority, it will be important to quantify the heterogeneity in dugong and marine turtle diving behavior across species and depth strata for the GBR region. At present the dugong diving data are mostly from Moreton Bay (Sheppard et al. 2006; Hagihara 2015; Zeh et al. 2015; Cleguer 2015) and the turtle diving data are averaged across four locations including one outside Australia (Fuentes et al. 2015). In addition, it will be important to determine the species composition of large juvenile and adult marine turtles in the hotspots by identifying a sub-set of animals to species as has been done in Torres Strait (Hagihara et al. 2016a).

As explained above, recent genetic work indicates that the putative stock boundary for dugongs on the east coast of Queensland is in the vicinity of Midge Point (20.65ºS; 148.72ºE) (Alexandra McGowan, David Blair et al. unpublished data). This discovery vindicates the decision to include Moreton Bay and Hervey Bay and Torres Strait in the time series of GBR surveys for dugongs but suggests that the latitude of the division between the northern and southern surveys should be reviewed to better reflect the underlying genetic structure of the dugong populations in the region.

The analysis above indicates that weather and climate have a profound effect on dugong populations on the east coast of Queensland, probably largely through the loss of seagrass habitat and the associated effects of dugong mortality (Heinsohn and Spain 1978, Preen and Marsh 1995, Marsh et al. 2011, Meager and Limpus 2014), fecundity (Marsh and Kwan 2008, Fuentes et al. 2016) and movements as evidenced by this report. Thus, aerial monitoring of dugongs (and the associated monitoring of in-water large juvenile and adult marine turtles) needs to be coordinated with the seagrass surveys of the region (e.g., McKenzie et al. 2016). The information on the dugong’s use of sub-tidal habitats that we have obtained from aerial surveys (e.g., Figure 5) and satellite tracking (see Sheppard et al. 2009, Marsh et al. 2011 and Hagihara et al. 2016a for references) also indicates the importance of monitoring sub-tidal as well as intertidal seagrass beds in the region.

The primary focus of the StrandNet database is to record information on where sick, injured, dying and dead marine wildlife including dugongs and turtles have been found in Queensland and assess causes of injury and death, if possible. StrandNet attempts to determine when marine animal deaths occur directly as a result of human causes and plays a role in raising community awareness about how these type of incidents caused by humans can be prevented. However, despite the best efforts of the staff of the Queensland Department of Environment and Heritage Protection, the cause of death can be determined for only a minority of stranded dugongs (e.g., see Meager and Limpus 2012). The poor condition of many of the stranded dugongs, and the location of the stranded dugongs in areas impacted by the extreme weather events (tropical cyclone and floods) of the summer of 2010-11 suggested that seagrass loss was a major contributing factor to the elevated dugong mortality in 2011 (Table 20). This result suggests that a major priority for future monitoring by StrandNet should be to attempt to record the body condition of stranded dugongs and marine turtles even when their cause of death cannot be determined. Such data would be an index of the health of the populations of dugongs and large marine turtles and that these data should be analysed in association with the data from the aerial surveys and seagrass monitoring.

The percentage of dugongs recorded as calves during aerial surveys (Figure 3) is another index of the health of the dugong population (Fuentes et al. 2016). Dunshea et al. (in prep.) have shown observer differences in recording dugong calves during dugong aerial surveys in the Northern Territory emphasising the need for observer training and for correcting for missed calves using Mark-Recapture methodology to improve the robustness of this index.

Unmanned aerial vehicles (UAVs) offer an attractive ‘human-risk free’ alternative to using light aircraft to survey dugongs and large juvenile and adult marine turtles. As a tool for conducting aerial surveys, UAVs may be cheaper and more accurate than manned surveys and enable surveys to be conducted in areas where it is difficult to use light aircraft. To be confident that using cameras mounted in UAVs can provide comparable, or preferably superior, data to human observers on-board light aircraft, Hodgson et al. (2013) conducted a direct comparison in Shark Bay, Western Australian, a relatively clear water area. They applied standard dugong survey methodology using a Partenavia aircraft and simultaneously flew the *ScanEagle* UAV, which captured continuous images along the same transect lines as the manned survey. Their results showed that dugong sighting rates were at least as high in the images as from the human observers. In addition, the UAV survey provided fine scale GPS-positions of individual dugongs, accurate measurements of the realised survey strip width via custom designed mapping software, and image analysis software to assess environmental conditions objectively and consistently. This accuracy provides more accurate estimates of dugong population size and habitat use from UAV surveys than manned surveys.

The limitation of the Shark Bay trial was that the waters were relatively clear – there was very little of the turbid water characteristic of dugong habitats on the east coast of Queensland. To ensure that future UAV dugong surveys are directly comparable to the historic time-series of manned surveys for dugongs and large juvenile and adult marine turtles analysed here, bridging studies need to be conducted. Such studies should include for both taxa: (a) a trial similar that conducted by Hodgson et al. (2013 and 2017) in the more turbid habitats typical of that on the east coast of Queensland, and (2) experimental trials to measure the detection biases associated with using a UAV rather than a manned aircraft and (3) testing the capacity of the UAV to provide more accurate counts of large groups of dugongs. The use of UAVs will not remove the detection biases but will modify them in a way that needs to be quantified to maintain the integrity of the time series.

5 CONCLUSIONS

The data collected by the 2016 aerial survey of dugongs from the region from north of Hinchinbrook Island to the Queensland – New South Wales border add to the previous evidence that indicates climate and weather have profound influence on that the abundance, distribution and fecundity of dugongs at sub-regional scales, mainly as a result of the impacts of climatic drivers of their seagrass habitats. Water quality is a major environmental driver of seagrass and dugong health as quantified for Cleveland Bay by the models of Wooldridge (2016). Thus, the management of water quality in the Great Barrier Reef World Heritage Area must continue to be an essential component of dugong conservation in the region along with the zonal management of activities that cause dugong mortality such as gill-netting, vessel strike and Indigenous hunting.

6 ADVICE FOR GBRMPA

- That GBRMPA continue its comprehensive approach to the management of dugongs in the Great Barrier Reef World Heritage Area by managing the direct impact of human induced mortality and the indirect impact of declining water quality on the dugong's seagrass habitats.
- That the Megafauna Specialist Group of RIMReP consider the implication of the findings of this report in designing future in-water monitoring of dugongs and in-water large juvenile and adult marine turtles.
- That GBRMPA consider funding an analysis of the historical records of marine turtles collected during the dugong surveys since the 1980s.
- That RIMReP consider the desirability of aligning the timing and spatial scope of the future monitoring of seagrasses in the GBRWHA and the aerial monitoring of dugongs and large and juvenile marine turtles.
- That StrandNet consider giving higher priority to the monitoring of the body condition (as opposed to the carcass condition) of stranded dugongs and marine turtles irrespective of whether the cause of death can be identified.

REFERENCES

Beaman, R.J. 2010, *Project 3DGBR: A high-resolution depth model for the Great Barrier Reef and Coral Sea.* Marine and Tropical Sciences Research Facility (MTSRF) Project 2.5i.1a Final Report, MTSRF, James Cook University, Cairns.

Blair, D., McMahon, A., McDonald, B., Tikel, D., Waycott, M., Marsh, H. 2014, Pleistocene sea level fluctuations and the phylogeography of the dugong in Australian waters. *Marine Mammal Science*, 30(1): 104-121.

Campbell, S.J., McKenzie, L.J., Kerville, S.P. 2006, Photosynthetic responses of seven tropical seagrasses to elevated seawater temperature. *Journal of Experimental Marine Biology and Ecology*, 330(2):455-68.

Chilvers, B.L., Delean, S., Gales, N.J., Holley, D.K., Lawler, I.R., Marsh, H., Preen, A.R. 2004, Diving behaviour of dugongs, *Dugong dugon*. *Journal of Experimental Marine Biology and Ecology*, 304:203-224.

Cleguer, C. 2015, Informing dugong conservation at several spatial and temporal scales in New Caledonia. PhD Thesis, James Cook University, Townsville.

Cleguer, C., Grech, A., Garrigue, C., Marsh, H. 2015a, Spatial mismatch between marine protected areas and dugongs in New Caledonia. *Biological Conservation*, 184: 154-162.

Cleguer, C., Limpus, C.G., Hamann, M., Marsh, H. 2015b, *Annual report on dugong tracking and habitat use in Gladstone in 2015.* Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program.

Cleguer, C., Preston, S., Hagihara, R., Shimada, T., Udyawer, V., Hamann, M., Simpson, S., Loban, F., Bowie, G., Fujii, R., Marsh, H. 2016, *Working with the community to understand use of space by dugongs and green turtles in Torres Strait.* Final Report to the Mura Badulgal Representative Native Title Body Corporate and the Department of Environment, National Environment Science Program Tropical Water Quality Hub. M Project No. 3.2. James Cook University, Townsville, Australia, 66 pp.

Coles, R., McKenzie, L., De'ath, G., Roelofs, A., Long, W. L. 2009, Spatial distribution of deepwater seagrass in the inter-reef lagoon of the Great Barrier Reef World Heritage Area. *Marine Ecology Progress Series,* 392: 57-68.

Coles, R. G., Rasheed, M. A., McKenzie, L. J., Grech, A., York, P. H., Sheaves, M., McKenna, S., Bryant, C. 2015, The Great Barrier Reef World Heritage Area seagrasses: managing this iconic Australian ecosystem resource for the future. *Estuarine, Coastal and Shelf Science*, 153:A1-A12.

Collier, C. J., Waycott, M. 2014, Temperature extremes reduce seagrass growth and induce mortality. *Marine pollution bulletin*, 83(2):483-490.

Commonwealth of Australia. 2013. Matters of National Environmental Significance. Significant Impact Guidelines 1.1. Environment Protection and Biodiversity Conservation Act 1999

Commonwealth of Australia. 2015. Reef 2050 Long-Term Sustainability Plan.

Commonwealth of Australia 2017. Recovery Plan for Marine Turtles in Australian Waters.

Cope R. C., Pollett, P. K., Lanyon, J. M. and Seddon, J. M. 2015. Indirect detection of genetic dispersal (movement and breeding events) through pedigree analysis of dugong populations in southern Queensland, Australia. *Biological Conservation*, *181* 91-101. doi:10.1016/j.biocon.2014.11.011

Dunshea, G., Groom, R., and Griffiths, A. in prep. Evaluating observer performance for dugong aerial surveys in turbid Northern Territory waters.

Fernandes L, Day J, Lewis A , Slegers S, Kerrigan B, Breen, D, Cameron D, Jago B, Hall J, Lowe, D, Innes J, Tanzer J , Chadwick V, Thompson, L, Gorman K, Simmons M, Barnett B, Sampson K , De'ath G , Mapstone B, Marsh H, Possingham H , Ball I, Ward T , Dobbs K, Zumend J, Slater, D, & Stapleton, K. 2005. Establishing representative no-take areas in the Great Barrier Reef: large-scale implementation of Theory on Marine Protected Areas. *Conservation Biology* 19: 1733-1744.

Fuentes, M.M.P.B., Bell, I., Hagihara, R., Hamann, M., Hazel, J., Huth, A., Seminoff, J., Sobtzick, S., Marsh, H. 2015, Improving estimates of in-water marine turtle abundance by adjusting aerial survey counts for perception and availability biases. *Journal of Experimental Marine Biology and Ecology*, 471:77-83.

Fuentes, M. M., Delean, S., Grayson, J., Lavender, S., Logan, M., Marsh, H. 2016. Spatial and temporal variation in the effects of climatic variables on dugong calf production. *PloS one*, 11(6):e0155675.

GBRMPA, 1981. Nomination of the Great Barrier Reef by the Commonwealth of Australia for inclusion on the World Heritage List. UNESCO, pp.37.

GBRMPA 2005. Research Needs for the Protection and Management of the Great Barrier Reef Marine Park.
http://elibrary.gbrmpa.gov.au/jspui/bitstream/11017/414/1/Research-needs-for-protection-and-management-of-the-Great-Barrier-Reef-Marine-Park-2005.pdf

Grech, A., Marsh, H. 2007, Prioritising areas for dugong conservation in a marine protected area using a spatially explicit population model. *Applied GIS*, 3:1-14.

Grech, A., Marsh, H. 2008, Rapid assessment of risks to a mobile marine mammal in an ecosystem-scale marine protected area. *Conservation Biology*, 22(3):711-720.

Grech, A., Sheppard, J., Marsh, H. 2011, Informing species conservation at multiple scales using data collected for marine mammal stock assessments. *PloS one*, 6(3): e17993.

Gredzens, C., Marsh, H., Fuentes, M. M., Limpus, C. J., Shimada, T., Hamann, M. 2014, Satellite tracking of sympatric marine megafauna can inform the biological basis for species co-management. *PloS one,* 9(6): e98944.

Hagihara, R. 2015, Linking wildlife tracking data with environmental features to improve understanding of dugong diving ecology and abundance. PhD Thesis, James Cook University, Townsville.

Hagihara, R., Cleguer, C., Preston, S., Sobtzick, S., Hamann, M., Shimada, T., and Marsh, H. 2016a. *Improving the estimates of abundance of dugongs and large immature and adult-sized green turtles in Western and Central Torres Strait.* Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited, Cairns, pp.53.

Hagihara, R., Cleguer, C., Garrigue, C. 2016b. *Improving the time series estimates of dugong abundance and distribution by incorporating revised availability bias correction.* Final report to the Agences des Aires Marines Protegees, pp.41.

Hagihara, R., Jones, R.E., Grech, A., Lanyon, J.M., Sheppard, J.K., Marsh, H. 2014, Improving population estimates by quantifying diving and surfacing patterns: a dugong example. *Marine Mammal Science*, 30:348-366.

Hagihara, R, Jones, R., Sobtzick, S., Cleguer, C., Garrigue, C., Marsh, H. in review, Compensating for geographic variation in detection probability improves visual survey abundance estimates of marine megafauna. *Marine Ecology Progress Series.*

Havemann, P., Thiriet, D., Marsh, H., Jones, C. 2005, Decolonising conservation? Traditional use of marine resources agreements and dugong hunting in the Great Barrier Reef World Heritage Area. *Environmental and Planning Law Journal*, 22:258-280.

Heinsohn, G. E., Spain, A. V. 1974, Effects of a tropical cyclone on littoral and sub-littoral biotic communities and on a population of dugongs (*Dugong dugon* (Müller)). *Biological Conservation,* 6(2):143-152.

Hodgson, A., Kelly, N., Peel, D. 2013, Unmanned aerial vehicles (UAVs) for surveying marine fauna: a dugong case study. *PloS one*, 8(11):e79556.

Hodgson, A., Peel, D., Kelly, N. 2017, Unmanned Aerial Vehicles (UAVs) for surveying marine fauna: assessing detection probability. *Ecological Applications. Doi:10.1002/eap.1519*

Lyons M.B., Roelfsema C.M., Phinn S.R. 2013, Towards understanding temporal and spatial dynamics of seagrass landscapes using time-series remote sensing. *Estuarine, Coastal and Shelf Science*, 120:42-53.

Marsh, H. 2000, Evaluating management initiatives aimed at reducing the mortality of dugongs in gill and mesh nets in the Great Barrier Reef World Heritage Area. *Marine Mammal Science* 16:684-694.

Marsh, H., Saalfeld, W. K. 1989, Distribution and abundance of dugongs in the northern great barrier-reef Marine park. *Wildlife Research*, 16(4):429-440.

Marsh, H., Sinclair, D.F. 1989a, An experimental evaluation of dugong and sea turtle aerial survey techniques. *Australian Wildlife Research*, 16:639-350.

Marsh, H., Sinclair, D.F. 1989b, Correcting for visibility bias in strip transect aerial surveys of aquatic fauna. *The Journal of Wildlife Management*, 53:1017-1024.

Marsh, H., Rathbun, G. B. 1990, Development and application of conventional and satellite radio-tracking techniques for studying dugong movements and habitat usage. *Australian Wildlife Research*, 17(1):83-100.

Marsh, H., Kwan, D. 2008, Temporal variability in the life history and reproductive biology of female dugongs in Torres Strait: The likely role of sea grass dieback. *Continental Shelf Research*, 28(16):2152-2159.

Marsh, H., Lawler, I. 2000, *Dugong distribution and abundance in the southern Great Barrier Reef Marine Park and Hervey Bay: Results of an aerial survey in October-December 1999.* Great Barrier Reef Marine Park Authority/James Cook University.

Marsh H., Lawler I. 2007, *Project 2: Dugong distribution and abundance on the urban coast of Queensland: a basis for management.* Marine and Tropical Science Research Facility, Interim Projects 2005-06 Final Report.

Marsh, H., Sobtzick, S. 2015, *Dugong dugon.* The IUCN Red List of Threatened Species 2015: e.T6909A43792211. http://dx.doi.org/10.2305/IUCN.UK.2015-4.RLTS.T6909A43792211.en

Marsh, H, Corkeron, P., Lawler, I., Preen, A., Lanyon, J. 1996, *The status of the dugong in the southern Great Barrier Reef Marine Park.* Report to the Great Barrier Reef Marine Park Authority.

Marsh, H., O'Shea, T. J., Reynolds III, J. E. 2011, *Ecology and conservation of the Sirenia: dugongs and manatees (No. 18)*. Cambridge University Press.

Marsh H., Penrose, H., Eros, C. and Hugues, J. 2002. Dugong: status reports & action plans for countries & territories. United Nations Environment Programme Early Warning & Assessment Report Series 1, 162pp.

Martin, J., Edwards, H.H., Bled, F., Fonnesbeck, C., Dupuis, J., Gardner, B., Koslovsky, S.M., Aven, A., Ward-Geiger, L., Carmichael, R.H., Fagan, D.E., Ross, M., Reinert, T. 2014, Estimating upper bounds for occupancy and number of manatees in areas potentially affected by oil from the Deepwater Horizon oil spill. *PLoS One,* 9:e91683.

McKenzie, L.J., Collier, C.J, Langlois, L.A, Yoshida, R.L, Smith, N., Waycott, M. 2016, *Marine Monitoring Program.* Annual Report for inshore seagrass monitoring: 2014 to 2015. Report for the Great Barrier Reef Marine Park Authority. TropWATER, James Cook University, Cairns. 236pp.

Meager, J. J., Limpus, C. J. 2012, *Marine wildlife stranding and mortality database annual report 2011. III. Marine Turtle.* Conservation Technical and Data Report, 3:1-46.

Meager, J. J., Limpus, C. 2014, Mortality of inshore marine mammals in eastern Australia is predicted by freshwater discharge and air temperature. *PloS one*, 9(4): e94849.

NPSR. 2015, *GBR Coastal Marine Park.* https://www.npsr.qld.gov.au/marine-parks/gbr_coast_marine_park.html

NPSR. 2016, *Great Sandy Marine Park.* http://www.npsr.qld.gov.au/parks/great-sandy-marine/

NPSR. 2017, *Moreton Bay Marne Park.* http://www.npsr.qld.gov.au/parks/moreton-bay/

Pollock, K.H., Marsh, H.D., Lawler, I.R., Alldredge, M.W. 2006, Estimating animal abundance in heterogeneous environments: an application to aerial surveys for dugongs. *Journal of Wildlife Management*, 70:255-262.

Preen, A. 1992, Interactions between dugongs and seagrasses in a subtropical environment. PhD Thesis, James Cook University, Townsville.

Preen, A. R. 1999, Dugongs in the Shoalwater Bay area. Draft Report for the Great Barrier Reef Marine Park Authority, Townsville, Australia.

Preen A. & Marsh, H. 1995. Response of dugongs to large-scale loss of seagrass from Hervey Bay, Queensland, Australia. Wildlife Research 22, 507-519.

R Core Team. 2015, R: A language and environment for statistical computing. R Foundation for statistical computing, Vienna, Austria. URL http://www.R-project.org/.

Rasheed, M. A., McKenna, S. A., Carter, A. B., Coles, R. G. 2014, Contrasting recovery of shallow and deep water seagrass communities following climate associated losses in tropical north Queensland, Australia. *Marine pollution bulletin*, 83(2):491-499.

Seddon, P. J., Griffiths, C. J., Soorae, P. S., Armstrong, D. P. 2014, Reversing defaunation: restoring species in a changing world. *Science*, 345(6195):406-412.

Sheppard, J.K., Preen, A.R., Marsh, H., Lawler, I.R., Whiting, S.D., Jones, R.E. 2006, Movement heterogeneity of dugongs, *Dugong dugon* (Müller), over large spatial scales. *Journal of Experimental Marine Biology and Ecology*, 334:64-83.

Shimada, T., Jones, R., Limpus, C., Groom, R., Hamann, M. 2016, Long-term and seasonal patterns of sea turtle home ranges in warm coastal foraging habitats: implications for conservation. *Marine Ecology Progress Series*, 562:163-179.

Sobtzick S., Hagihara R., Grech A., Marsh H. 2012, *Aerial survey of the urban coast of Queensland to evaluate the response of the dugong population to the widespread effects of the extreme weather events of the summer of 2010-11*. Final Report to the

Australian Marine Mammal Centre and the National Environment Research Program June 1 2012

White, G. C., K. P. Burnham. 1999, Program MARK: survival estimation from populations of marked animals. *Bird study,* 46 (Supplement):120-139.

Wooldridge, S. A. 2017, Preventable fine sediment export from the Burdekin River catchment reduces coastal seagrass abundance and increases dugong mortality within the Townsville region of the Great Barrier Reef, Australia. *Marine Pollution Bulletin,* 114(2): 671-678.

Zeh D.R., Heupel M.R., Hamann M., Limpus C.J., and Marsh H. 2016 Quick Fix GPS technology highlights risk to marine animals moving between protected areas. *Endangered Species Research.* 30: 37–44, doi: 10.3354/esr00725

Zeh D.R., Heupel M.R., Hamann M., Jones, R.J. Limpus C.J., and Marsh H. in prep. Evidence of behavioural thermoregulation by dugongs at the high latitude limit to their range in eastern Australia

APPENDICES

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

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

Appendix 2: Daily activities for the southern and northern survey teams during the 2016 dugong and marine turtle aerial survey.

Abbreviations used: No Survey (NS), Survey (S), Transit (T), Training Course (TC), Training Flight (TF). Refer to Figures 1 and 2 to locate the blocks mentioned in this table.

Date	Northern team		Southern team	
	Activity	Block surveyed	Activity	Block surveyed
24-25Oct-16	TC - Townsville	-	TC - Townsville	-
26-Oct-16	NS - Unsuitable weather	-	NS – Unsuitable weather	-
27-Oct-16	TF - Townsville	-	NS - Plane used by Northern team	-
28-Oct-16	S - Townsville	C8	NS - Plane used by Northern team	-
29-Oct-16	NS - Plane used by Southern team	-	TF - Townsville	-
30-Oct-16	NS - Unsuitable weather	-	NS - Unsuitable weather	-
31-Oct-16	S - Townsville	C8 and C9	NS - Unsuitable weather	-
1-Nov-16	S - Townsville and Hinchinbrook	C9 and C10	T - Townsville to Brisbane	-
2-Nov-16	S - Townsville and Hinchinbrook	C7, C9 and C10	NS - Plane unavailable	-
3-Nov-16	S - Townsville and Bowen	C5 and C7	NS - Plane unavailable	-
4-Nov-16	S - Townsville and Bowen	C5 and C6	NS - Plane unavailable	-
5-Nov-16	NS - Unsuitable weather	-	NS - Unsuitable weather	-
6-Nov-16	S - Townsville and Bowen	C4 and C5	S - Moreton Bay	1, 2, 5, 6 and 7
7-Nov-16	S - Bowen and Whitsundays	C3 and C4	NS - Unsuitable weather	-
8-Nov-16	S - Bowen and Whitsundays	C1, C2, C3 and S8	NS - Unsuitable weather	-
9-Nov-16	S - Mackay	S7 and S8	NS - Unsuitable weather	-
10-Nov-16	NS - Unsuitable weather	-	NS - Unsuitable weather	-
11-Nov-16	NS - Unsuitable weather	-	T - Moreton Bay to Hervey Bay	0, 1, 2, 3 and 4
12-Nov-16	S - Mackay	S7 and S8	NS - Unsuitable weather	-
13-Nov-16	S - Mackay	S6 and S7	NS - Unsuitable weather	-
14-Nov-16	S - Mackay	C3 and S6	S - Hervey Bay	1
15-Nov-16	S - Shoalwater Bay	S4	NS - Unsuitable weather	-
16-Nov-16	S - Gladstone	S6	NS - Unsuitable weather	-
17-18-Oct-16	NS - Unsuitable weather	-	NS - Unsuitable weather	-
19-Nov-16	S - Rockhampton	S3 and S2A	NS - Unsuitable weather	-
20-Nov-16	NS - Unsuitable weather	-	S - Hervey Bay	2
21-Nov-16	NS - Unsuitable weather	-	NS - Unsuitable weather	-
22-Nov-16	S - Shoalwater Bay and Gladstone	S3, S4 and S6	NS - Unsuitable weather	-
23-Nov-16	S - Shoalwater Bay	S4 and S5	NS - Unsuitable weather	-
24-Nov-16	S - Shoalwater Bay and Gladstone	S2, S2A, S4 and S5	S - Hervey Bay	2, 3, 4, 5
25-Nov-16	S - Gladstone	S2 and S3	S - Hervey Bay	3, 4, 5, 6, S1 and S3
26-Nov-16	T - Rockhampton to Townsville	-	S - Hervey Bay	1, T - Hervey to Moreton Bay
27-Nov-16	-	-	S - Moreton Bay	1 and 4
28-Nov-16	-	-	T - Brisbane to Townsville	-

Appendix 3: Sampling intensities for individual blocks in the various survey years.

(a) Moreton Bay Region						
	2005[1]		2011[2]		2016	
Block	**Block size (km^2)**	**Sampling intensity (%)**	**Block size (km^2)**	**Sampling intensity (%)**	**Block size (km^2)**	**Sampling intensity (%)**
MB 1	166	24.74	166	19.73	165	19.87
MB 2	691	13.45	691	10.91	687	11.19
MB 3	188	35.67	189	6.98	187	4.19
MB 4	389	50.07	389	37.55	386	37.6
MB 5	155	43.26	155	18.11	154	20.9
MB 6	226	29.67	226	18.83	224	19.52

(b) Hervey Bay Region						
	2005[1]		2011[2]		2016	
Block	**Block size (km^2)**	**Sampling intensity (%)**	**Block size (km^2)**	**Sampling intensity (%)**	**Block size (km^2)**	**Sampling intensity (%)**
HB 1	517	25.31	519	16.82	519	16.08
HB 2	1414	20.3	1415	15.49	1416	15.97
HB 3	1235	11.18	1246	16.83	1248	9.05
HB 4	1224	11.44	1233	8.49	1371	8.94
HB 5	546	10.86	409	11.40	411	8.15

(c) Southern Great Barrier Reef Region						
	2005[1]		2011[2]		2016	
Block	**Block size (km^2)**	**Sampling intensity (%)**	**Block size (km^2)**	**Sampling intensity (%)**	**Block size (km^2)**	**Sampling intensity (%)**
S1	n/a		1054	10.06	1096	8.82
S2	836	10.86	515	9.51	521	8.73
S2A	n/a		328	16.46	332	14.17
S3	1021	21.12	568	17.61	574	15.9
S4	n/a		2304	10.07	2343	8.95
S5	1271	21.8	1165	19.06	1189	17.3
S6	n/a		3715	8.08	3803	7.26
S7	n/a		736	9.78	758	8.74
S8	796	17.92	710	15.21	734	13.3
C1	371	18.23	342	18.71	354	16.41
C2	n/a		332	6.33	344	5.36
C3	1733	14.61	1701	13.40	1763	12.5
C4	466	19.57	428	18.46	444	16.62
C5	n/a		2097	9.82	2186	8.54
C6	244	23.35	221	19.46	230	16.68
C7	579	23.7	557	19.57	581	16.9
C8	620	32.64	572	19.23	598	18.18
C9	n/a		2905	9.23	3045	8.27
C10	288	23.64	456	20.39	480	18.31
C11	351	18.06	675	19.56	ns	
C12	n/a		5511	9.53	ns	

[1] Data from Marsh and Lawler (2007); [2] Data from Sobtzick et al. (2012)

Appendix 4: Weather conditions encountered during the 2016 aerial surveys of Moreton Bay, Hervey Bay and the southern GBR in comparison to previous surveys of the same areas: historical data from Marsh and Lawler (2007) and Sobtzick et al. (2012).

(a) Moreton Bay				
		2005	**2011**	**2016**
Max wind speed (km/h)		<10	<22	<19
Cloud cover range (oktas)		0-6	0-6	0-8
Min cloud height (ft)		2000	3000	3000
Beaufort sea state# (range)		1.8 (1-4)	1.94 (1-3)	1.37 (1-4)
Glare (range) #	North	1.76	1.74	2.28
	South	1.23	1.13	2.22
	Overall	1.49	1.52	2.27
Air visibility (km)		>10	N/A	>10
(b) Hervey Bay				
		2005	**2011**	**2016**
Max wind speed (km/h)		<10	<22	<22
Cloud cover range (oktas)		1-7	1-6	0-8
Min cloud height (ft)		2000	1900	3500
Beaufort sea state# (range)		2.2 (1-3)	1.29 (1-3)	1.6 (1-4)
Glare (range) #	North	1.44	2.24	2.81
	South	1.27	1.79	2.85
	Overall	1.35	2.01	2.83
Air visibility (km)		>10	N/A	>10
(c) Southern Great Barrier Reef Region				
		2005	**2011**	**2016**
Max wind speed (km/h)		<10	<31	<28
Cloud cover range (oktas)		0-5	1-8	0-4
Min cloud height (ft)		1000	1450	1000
Beaufort sea state# (range)		1.48 (0-4)	1.86 (0-3)	1.52 (0-4)
Glare (range) #	North	1.50	1.80	2.31
	South	1.50	1.76	2.15
	Overall	1.50	1.76	2.26
Air visibility (km)		>10	>8	>10

Means of modes for each transect

Appendix 5: Dugong and large marine turtle sightings in Moreton Bay during the 2016 survey

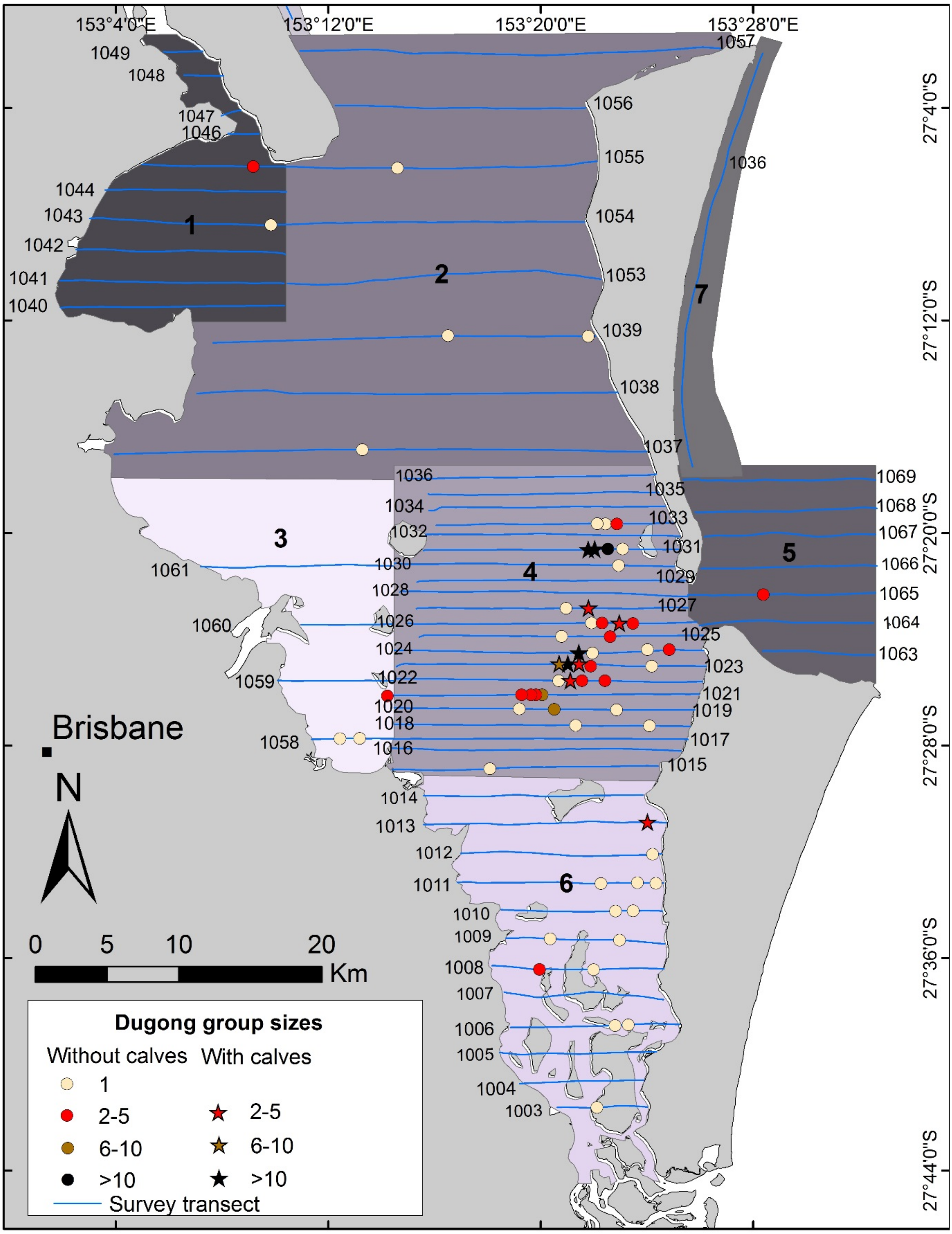


Figure 5.1. Distribution of dugong sightings in Moreton Bay in 2016.

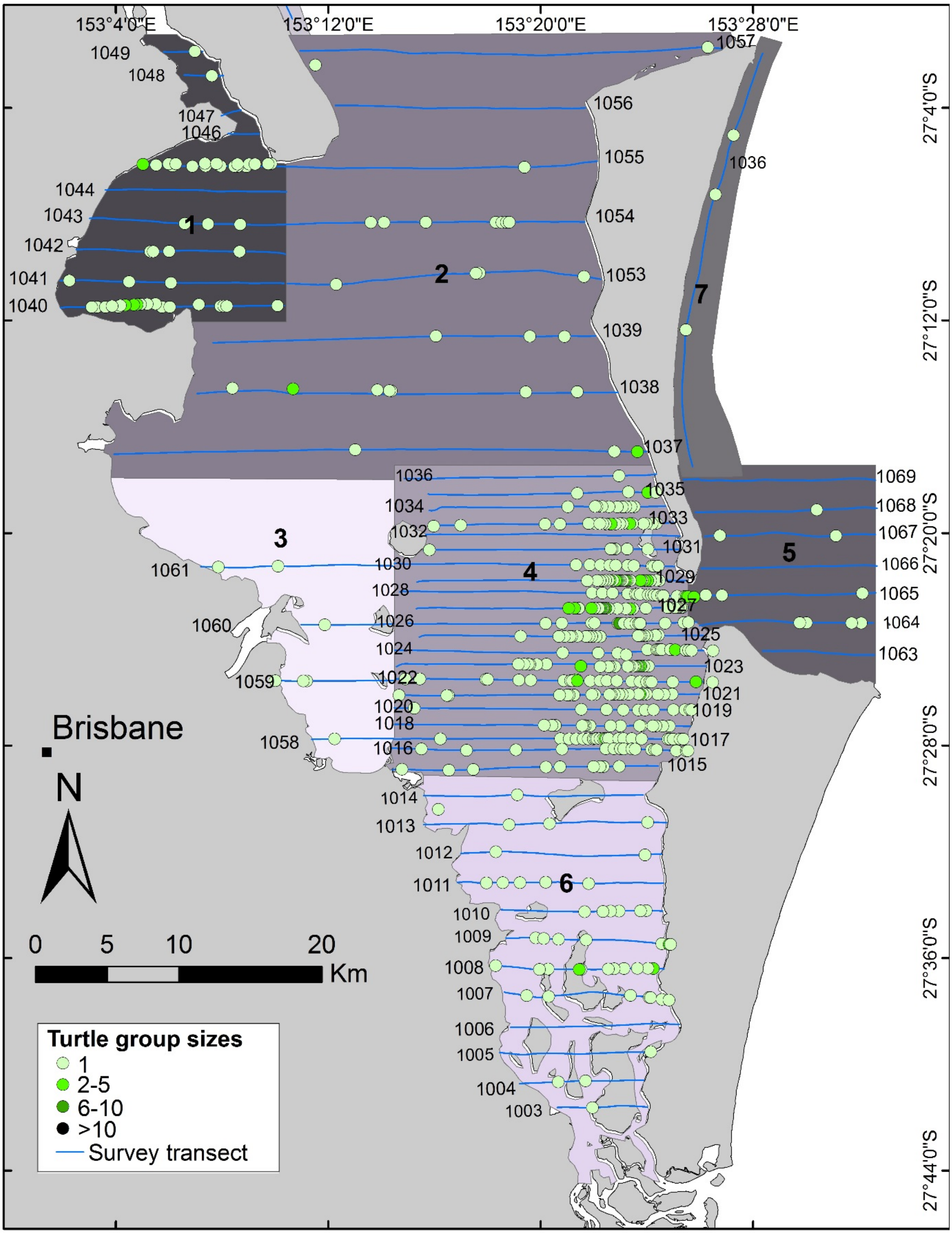


Figure 5.2. Distribution of turtle sightings in Moreton Bay in 2016.

Appendix 6: Dugong and large marine turtle sightings in Hervey Bay during the 2016 survey

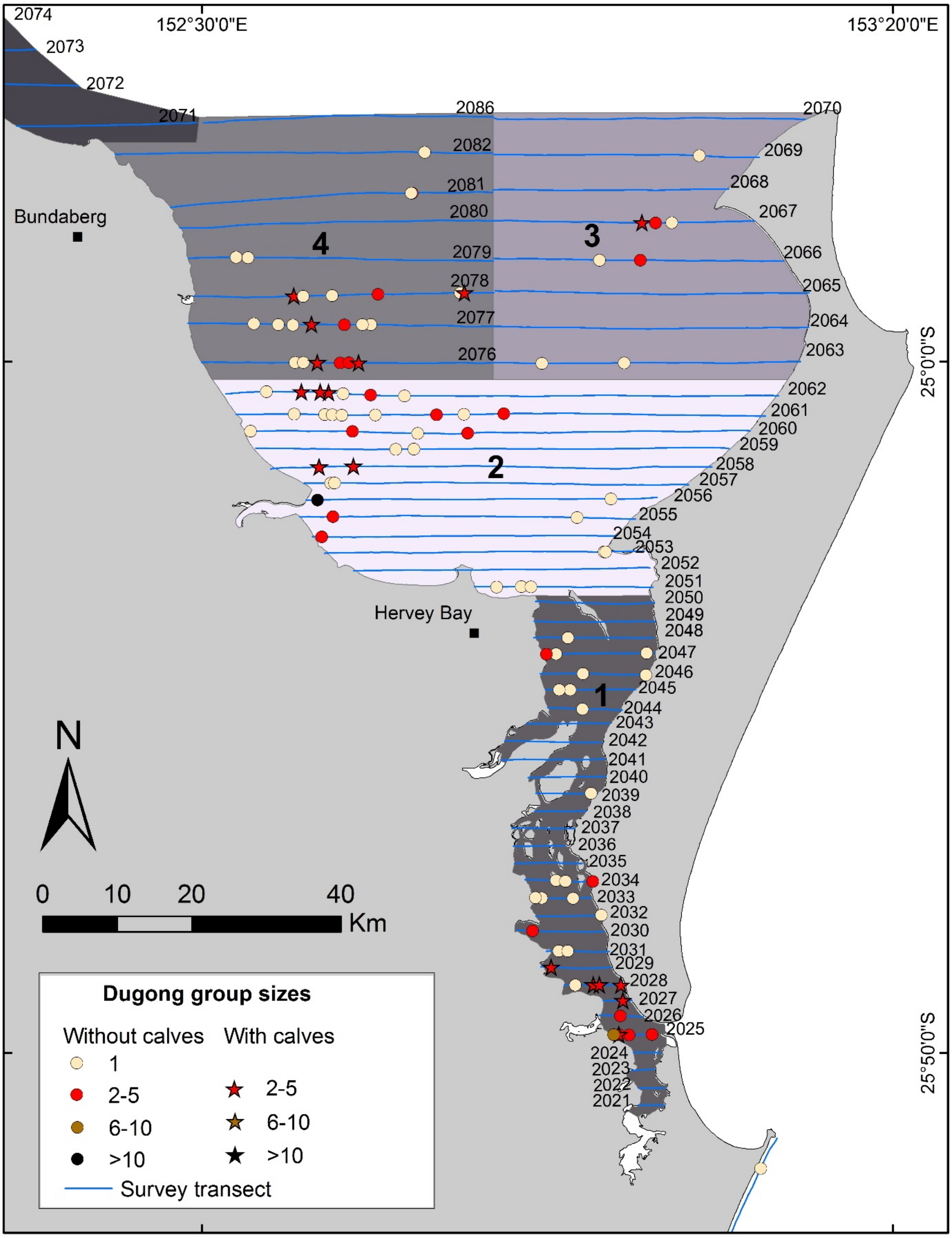


Figure 6.1. Distribution of dugong sightings in Hervey Bay in 2016.

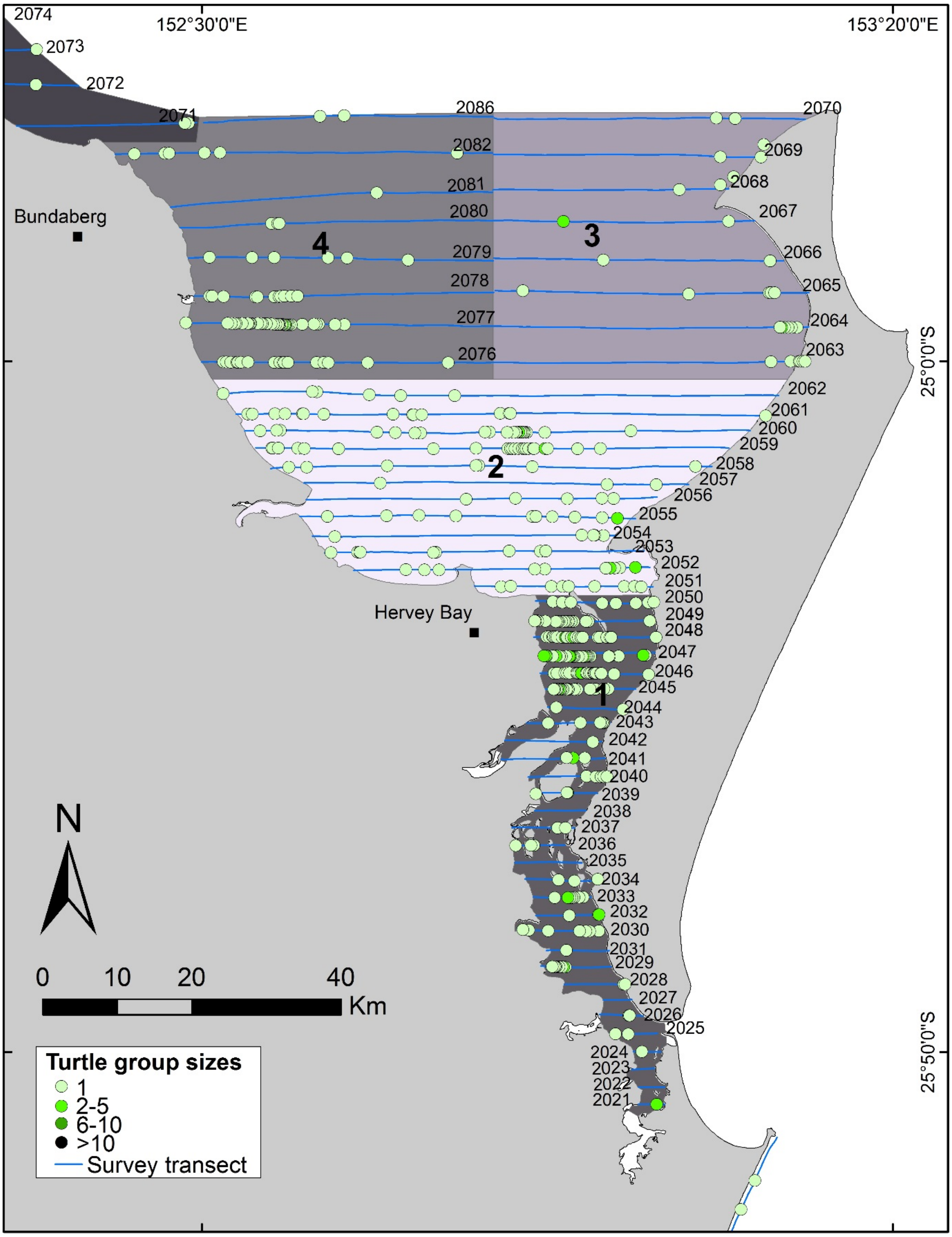


Figure 6.2. Distribution of turtle sightings in Hervey Bay in 2016.

Appendix 7: Dugong and large marine turtle sightings in the southern Great Barrier Reef region during the 2016 survey.

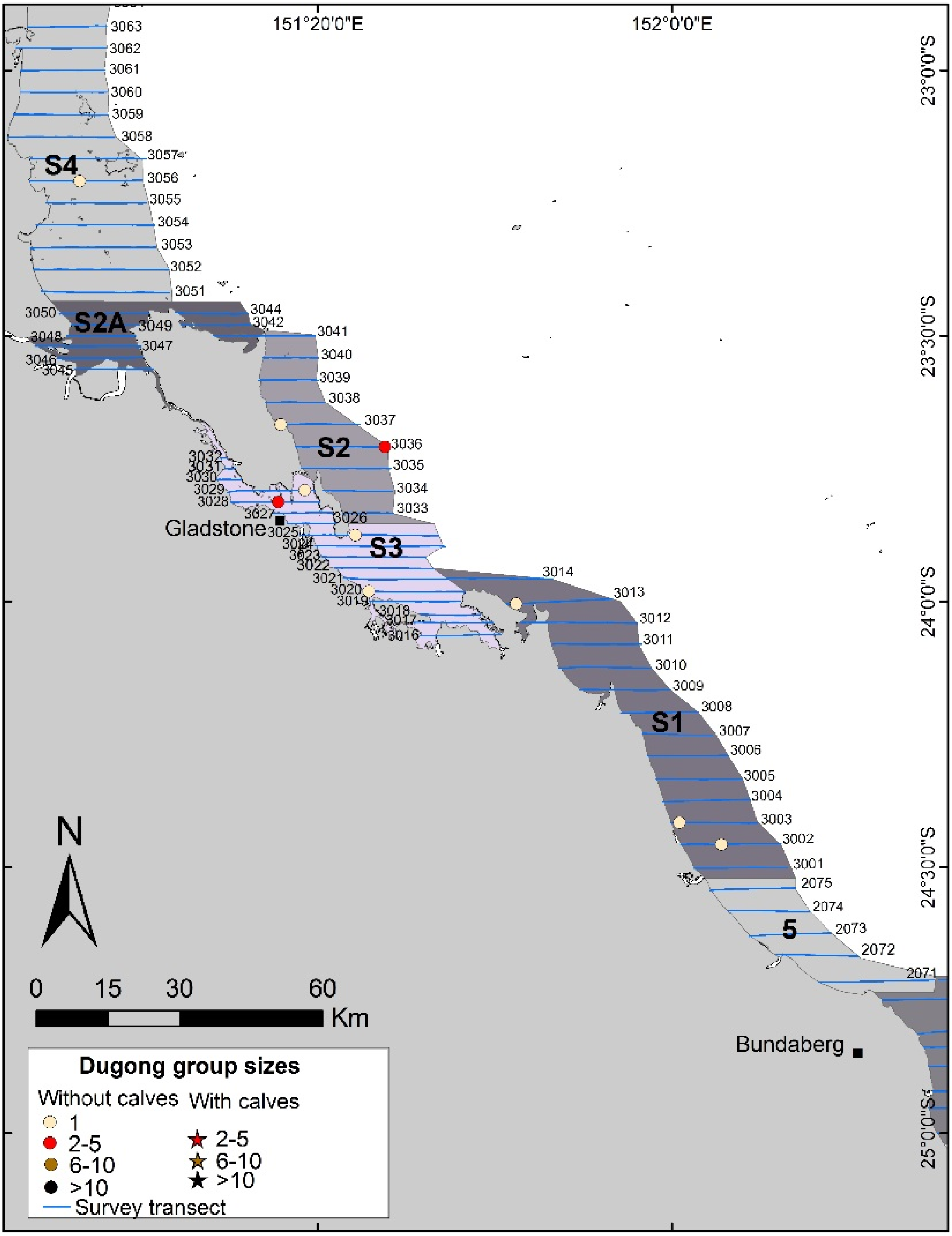


Figure 7.1. Distribution of dugong sightings in the Bundaberg-Gladstone region in 2016.

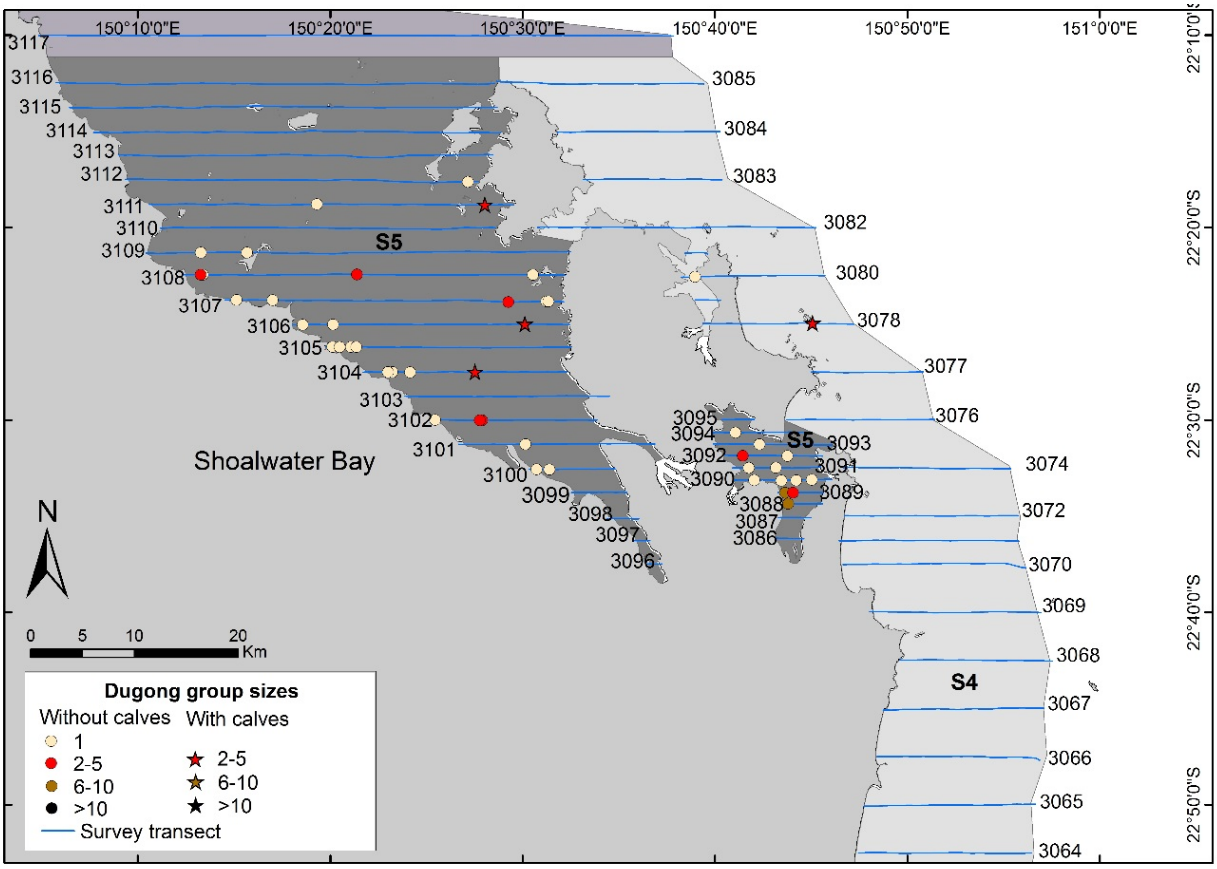


Figure 7.2. Distribution of dugong sightings in the Shoalwater Bay region in 2016.

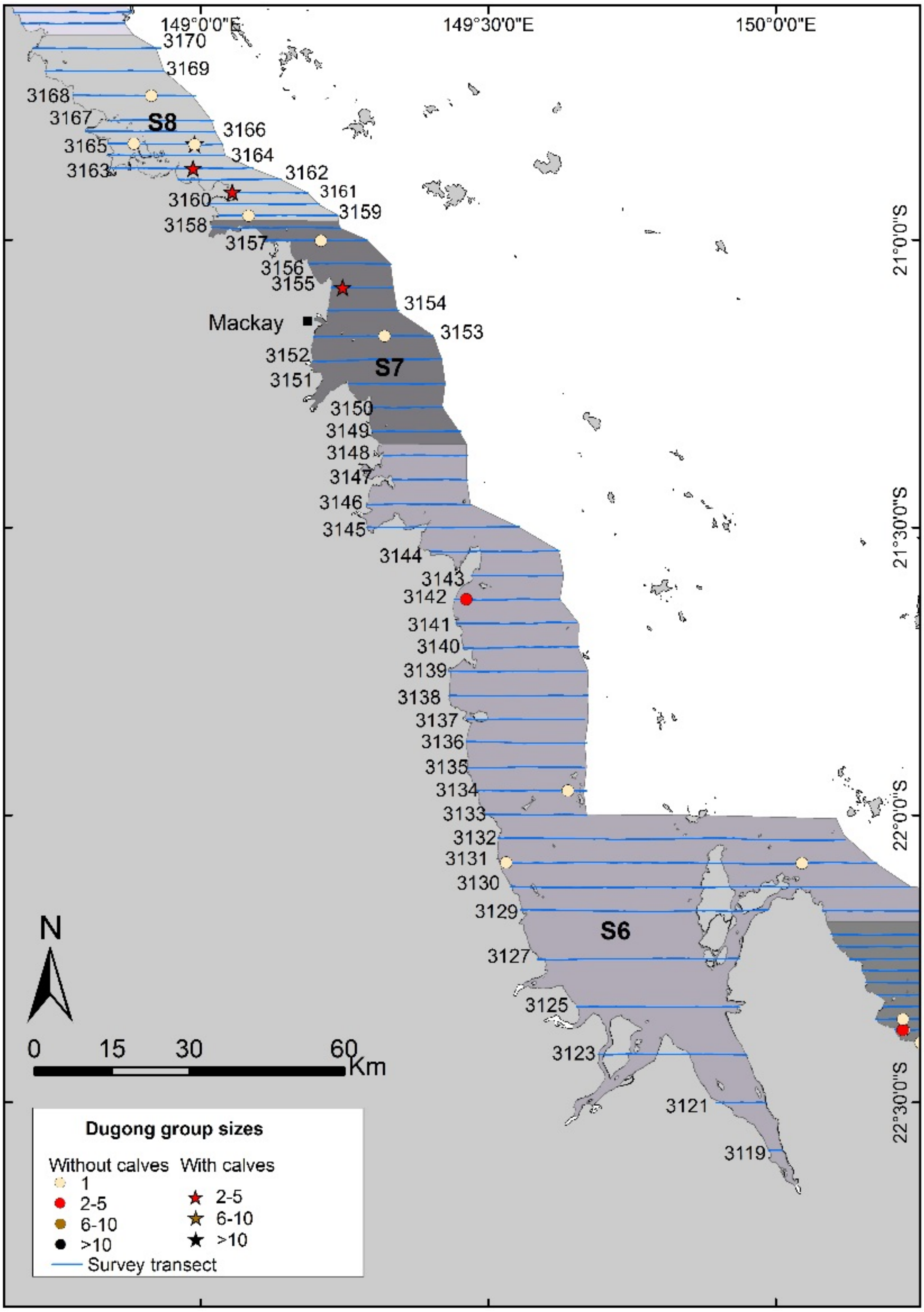


Figure 7.3. Distribution of dugong sightings in the Mackay region in 2016.

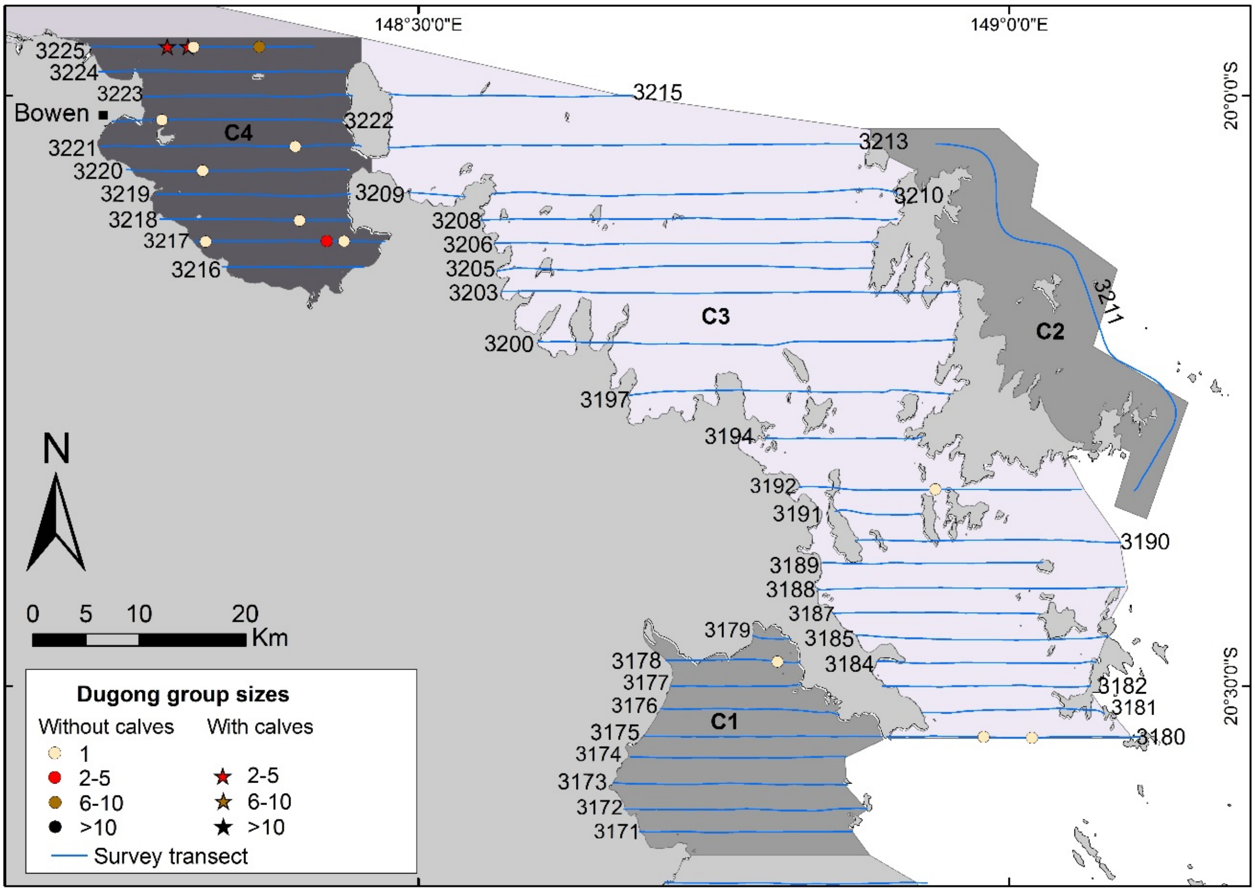


Figure 7.4. Distribution of dugong sightings in the Whitsundays region in 2016.

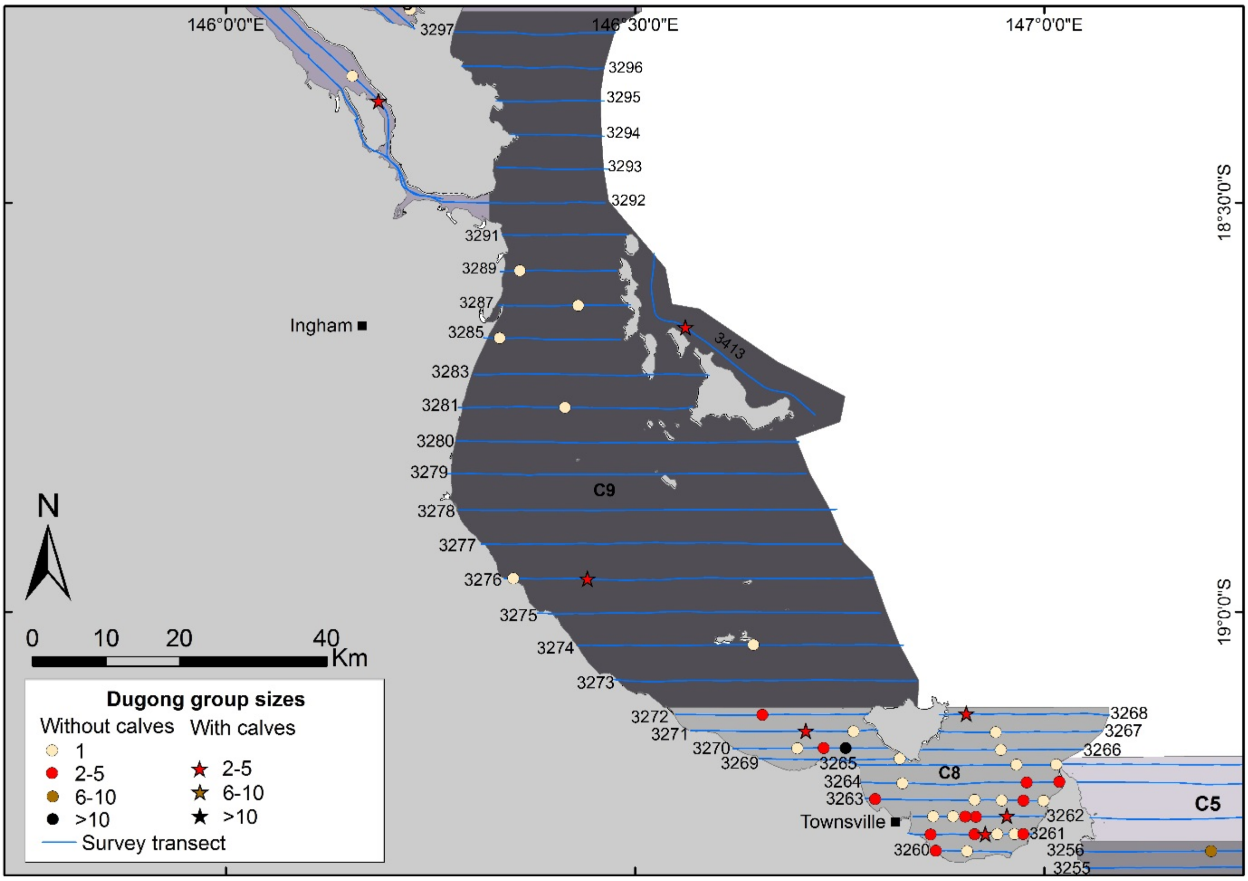


Figure 7.5. Distribution of dugong sightings in the Townsville region in 2016.

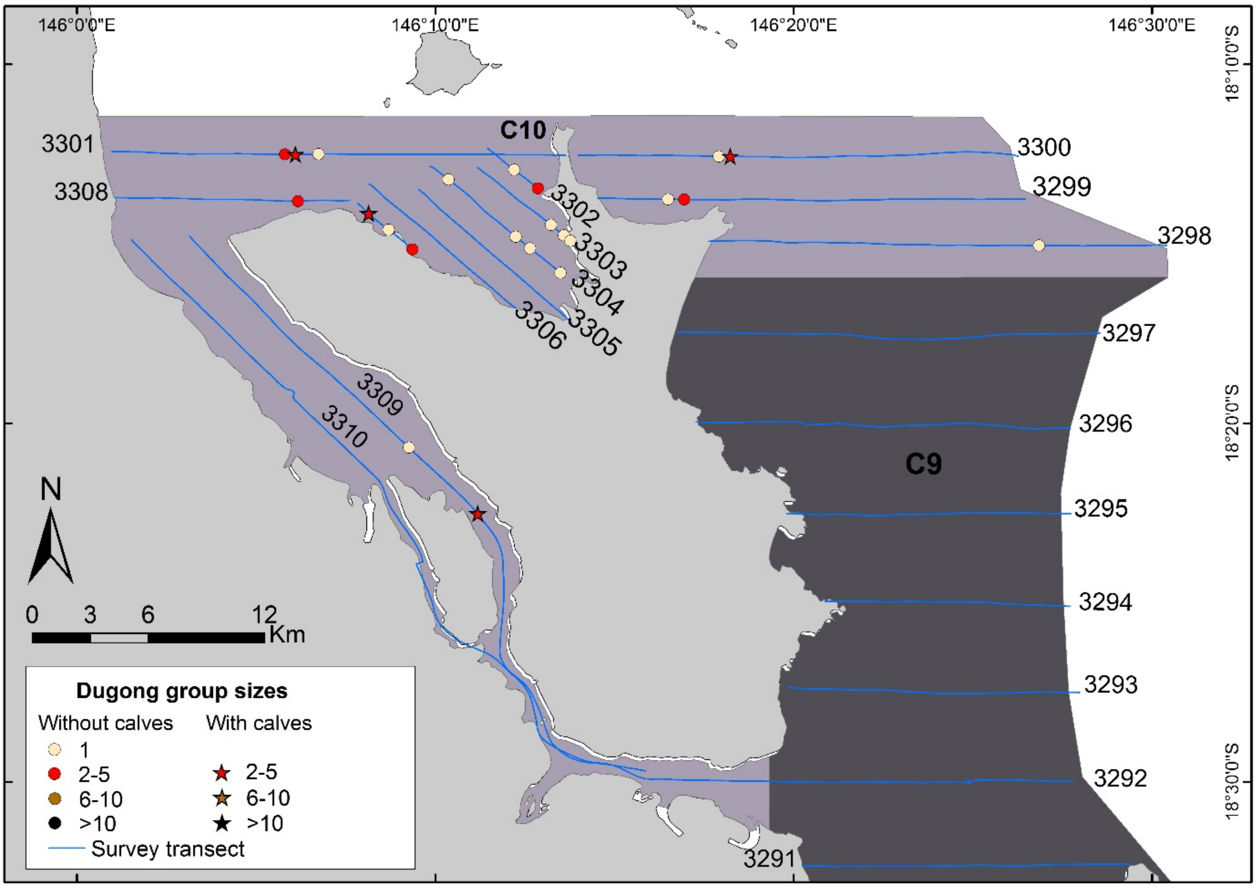


Figure 7.6. Distribution of dugong sightings around Hinchinbrook Island in 2016.

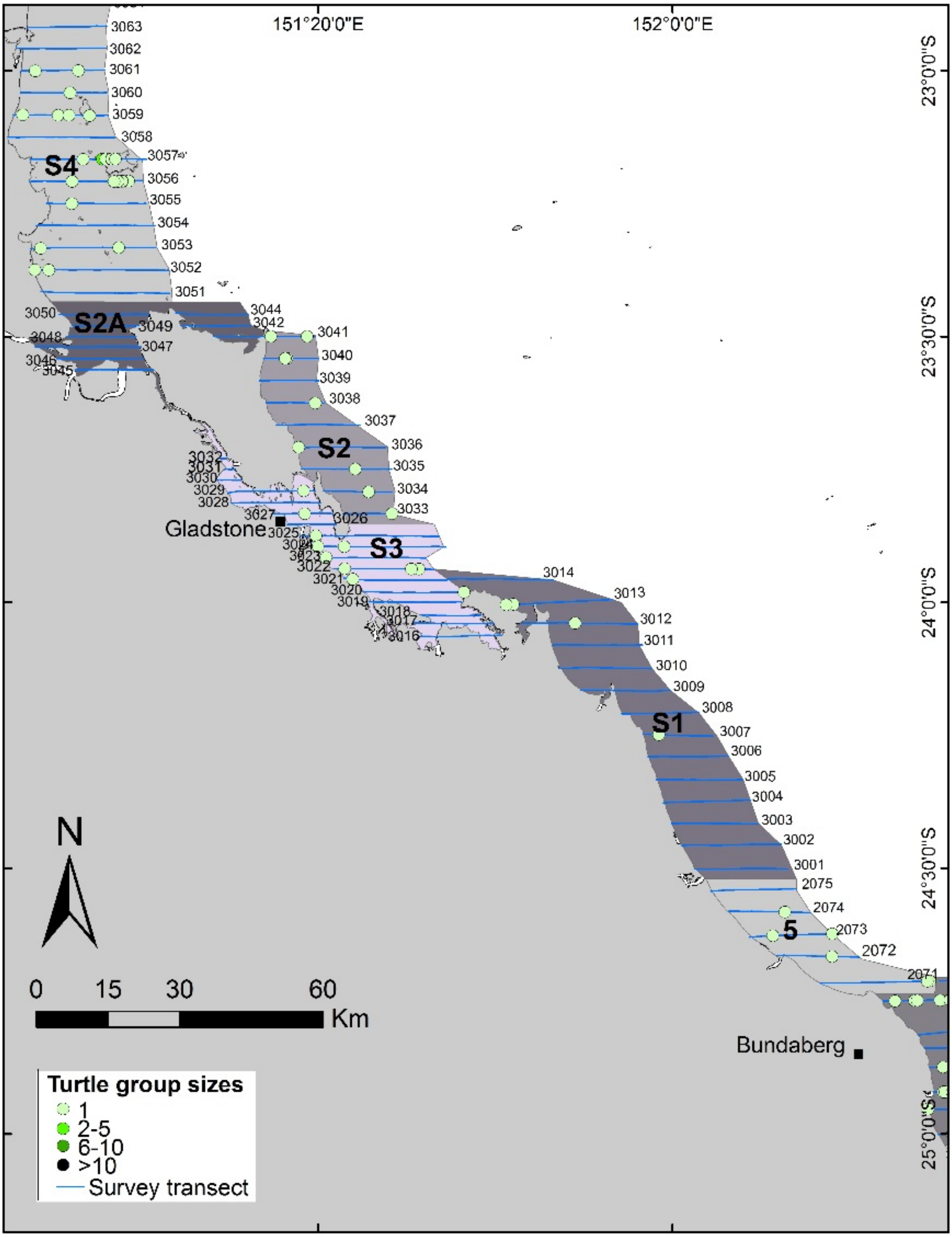


Figure 7.7. Distribution of turtle sightings in the Bundaberg-Gladstone region in 2016.

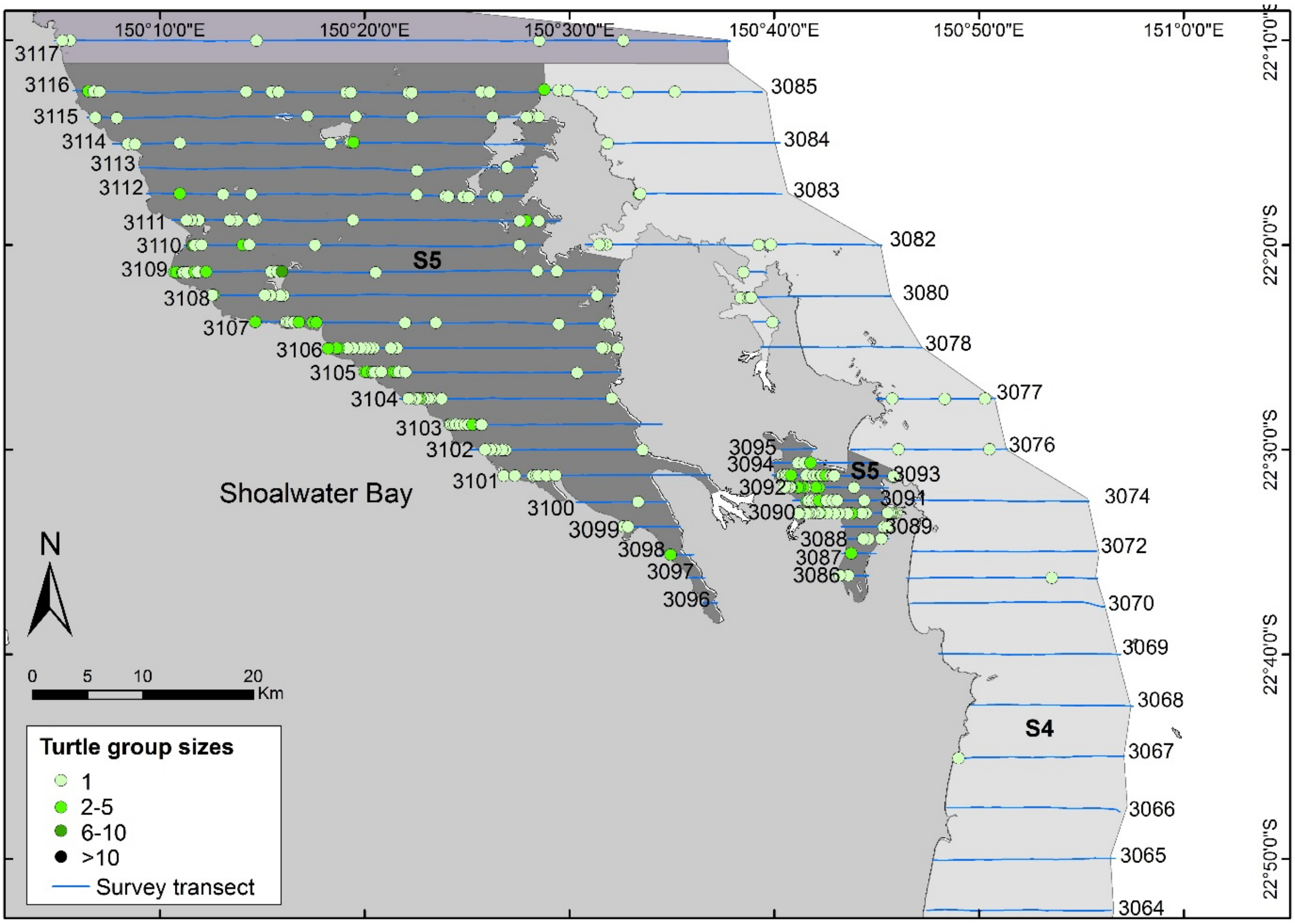


Figure 7.8. Distribution of turtle sightings in the Shoalwater Bay region in 2016.

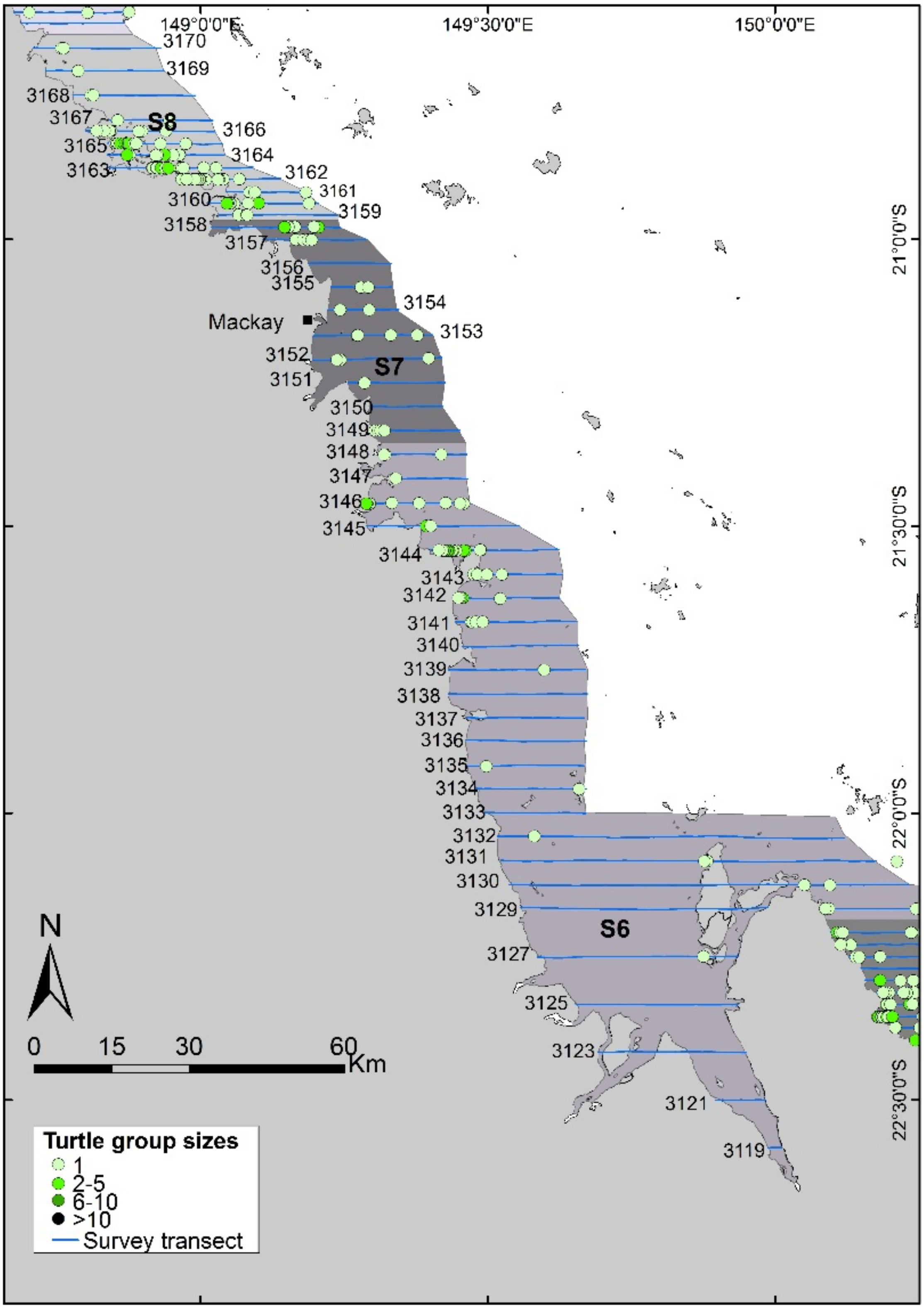


Figure 7.9. Distribution of turtle sightings in the Mackay region in 2016.

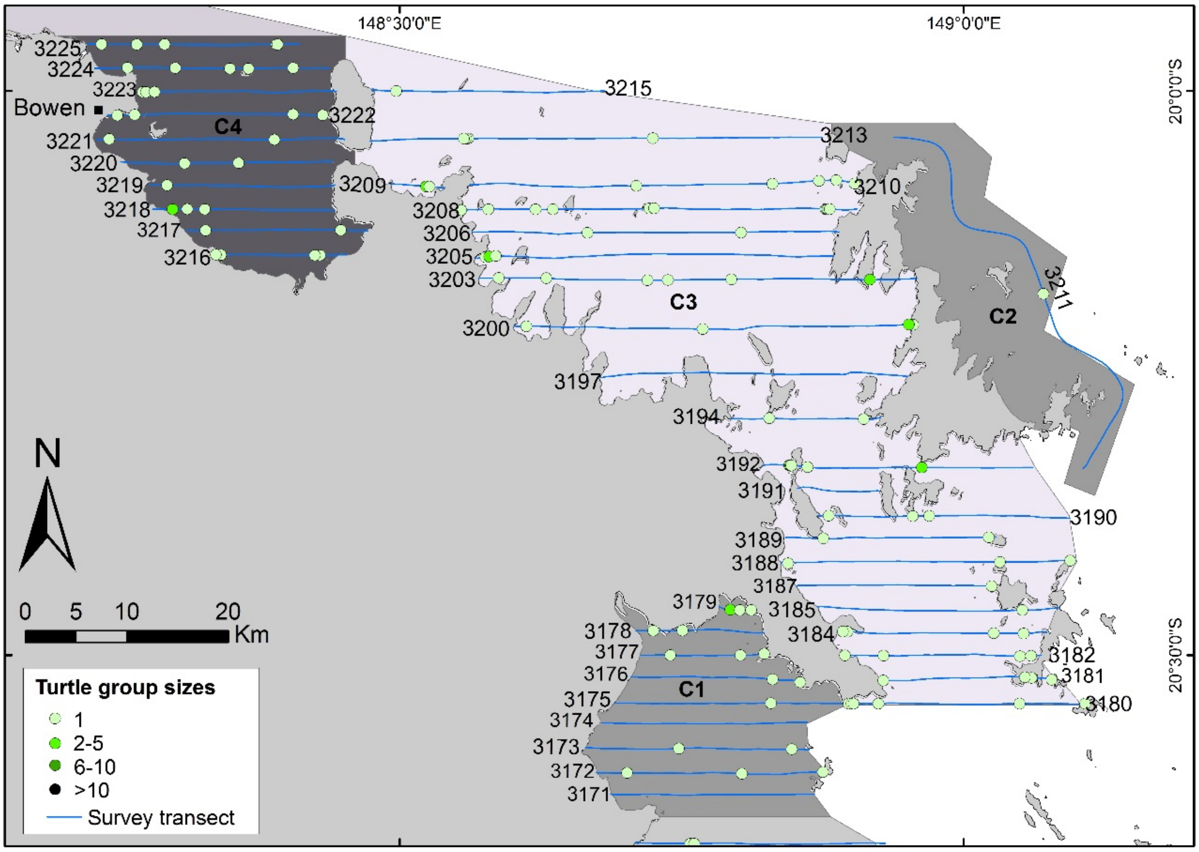


Figure 7.10. Distribution of turtle sightings in the Whitsundays region in 2016.

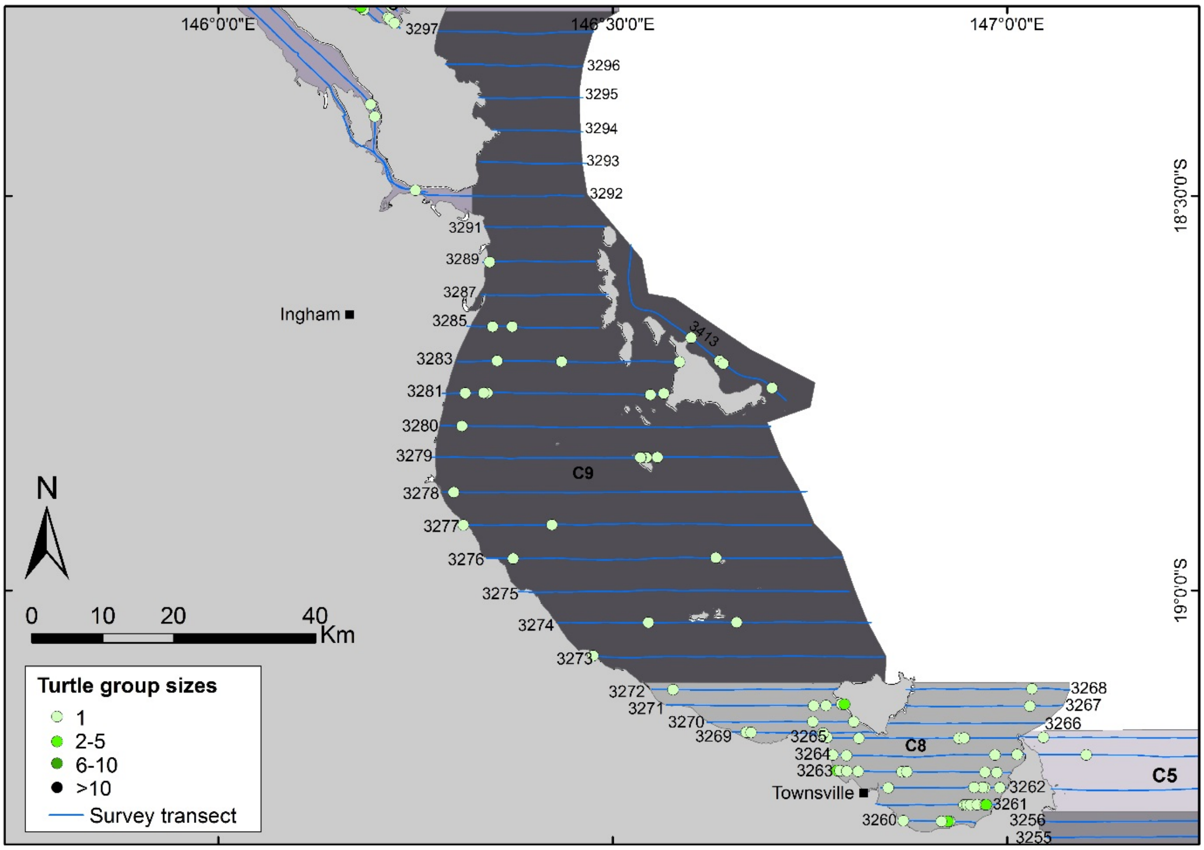


Figure 7.11. Distribution of turtle sightings in the Townsville region in 2016.

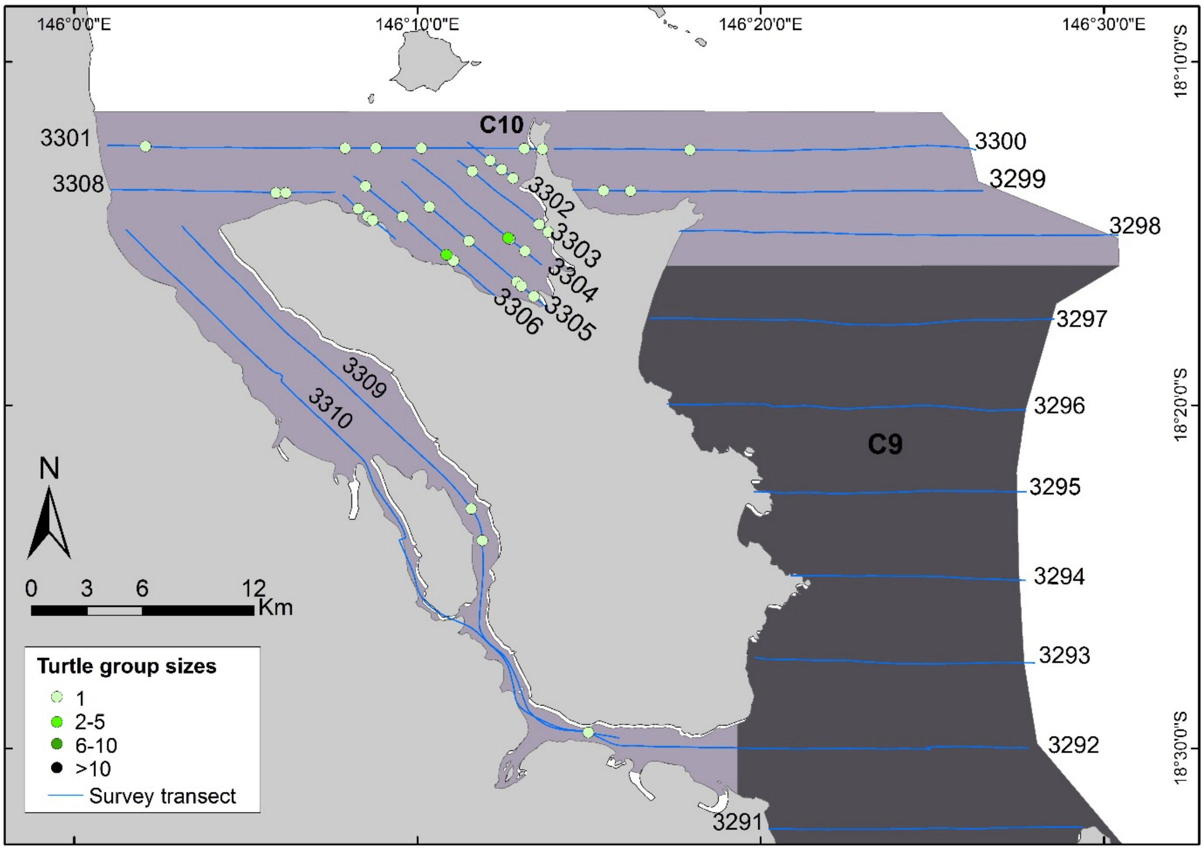


Figure 7.12. Distribution of turtle sightings around Hinchinbrook Island in 2016.

Appendix 8: Results of the log-linear models to test for temporal changes in the depth distribution of dugongs.

in: (a) Moreton Bay, (b) Hervey Bay and (c) Shoalwater Bay, (d) Cleveland Bay and (e) Hinchinbrook Island in the southern Great Barrier Reef region. Table (f) shows the parallel analysis on turtles.

(a) Moreton Bay Region				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	0.233	0.079	2.933	<0.01
Year 2001	0.947	0.093	10.139	<0.001
Year 2005	-0.662	0.136	-4.871	<0.001
Year 2011	0.874	0.094	9.256	<0.001
Year 2016	0.347	0.104	3.351	<0.001
Depth -5 - -10	-1.960	0.326	-5.998	<0.001
Depth -10 - -15	-4.710	1.003	-4.695	<0.001
Depth -15 - -20	-4.352	0.712	-6.116	<0.001
Depth <-20	-1.801	0.454	-3.966	<0.001
Year 2001: Depth -5 - -10	-1.640	0.556	-2.952	<0.01
Year 2005: Depth -5 - -10	1.943	0.382	5.081	<0.001
Year 2011: Depth -5 - -10	1.028	0.352	2.922	<0.01
Year 2016: Depth -5 - -10	1.428	0.357	3.996	<0.001
Year 2001: Depth -10 - -15	-25.25	1148	0.000	0.999
Year 2005: Depth -10 - -15	0.622	1.421	0.466	0.641
Year 2011: Depth -10 - -15	0.736	1.100	0.669	0.504
Year 2016: Depth -10 - -15	0.346	1.229	0.281	0.778
Year 2001: Depth -15 - -20	-25.940	1148	0.000	0.999
Year 2005: Depth -15 - -20	-24.330	1148	0.000	0.999
Year 2011: Depth -15 - -20	-1.567	1.228	-1.276	0.202
Year 2016: Depth -15 - -20	-25.340	1148	0.000	0.999
Year 2001: Depth <-20	-26.860	1148	0.000	0.999
Year 2005: Depth <-20	-25.250	1148	0.000	0.999
Year 2011: Depth <-20	-26.790	1148	0.000	0.999
Year 2016: Depth <-20	-19.570	1.100	-1.778	0.075

(b) Hervey Bay				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	-1.315	0.120	-10.923	<0.001
Year 2001	0.756	0.146	5.183	<0.001
Year 2005	0.123	0.165	0.742	0.458
Year 2011	0.243	0.161	1.513	0.130
Year 2016	0.070	0.167	0.418	0.676
Depth -5 - -10	0.564	0.186	3.034	<0.05
Depth -10 - -15	-0.248	0.245	-1.013	0.835
Depth -15 - -20	-1.260	0.373	-3.372	<0.001
Depth <-20	0.083	0.40	0.209	0.835
Year 2001: Depth -5 - -10	-0.643	0.243	-2.644	<0.01
Year 2005: Depth -5 - -10	1.470	0.352	-4.170	<0.001
Year 2011: Depth -5 - -10	-1.111	0.306	-3.633	<0.001
Year 2016: Depth -5 - -10	0.615	0.287	-2.140	<0.05
Year 2001: Depth -10 - -15	0.065	0.295	0.220	0.826
Year 2005: Depth -10 - -15	0.475	0.313	1.520	0.129
Year 2011: Depth -10 - -15	0.537	0.304	1.769	0.077
Year 2016: Depth -10 - -15	0.097	0.335	0.290	0.772
Year 2001: Depth -15 - -20	-0.351	0.479	-0.732	0.464
Year 2005: Depth -15 - -20	-0.816	0.634	-1.286	0.198
Year 2011: Depth -15 - -20	1.462	0.417	3.508	<0.001
Year 2016: Depth -15 - -20	1.434	0.425	3.373	<0.001
Year 2001: Depth <-20	-0.623	0.538	-1.158	0.247
Year 2005: Depth <-20	-0.682	0.648	-1.052	0.293
Year 2011: Depth <-20	0.113	0.518	0.219	0.827
Year 2016: Depth <-20	0.875	0.476	1.838	0.067

(c) Shoalwater Bay				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	-0.894	0.236	-3.792	<0.001
Year 2005		0.315	0.779	0.436
Year 2011	0.406	0.304	1.332	0.183
Year 2016	0.693	0.289	2.401	0.016
Depth -5 - -10	-2.507	1.027	-2.441	0.015
Depth -10 - -15	-2.603	1.027	-2.533	0.011
Depth -15 - -20	-2.603	0.745	-3.492	<0.001
Depth <-20	-2.581	11148	0.000	0.999
Year 2005: Depth -5 - -10	1.364	1.140	1.197	0.231
Year 2011: Depth -5 - -10	-0.406	1.447	-0.280	0.779
Year 2016: Depth -5 - -10	1.705	1.054	1.573	0.116
Year 2005: Depth -10 - -15	0.448	1.264	0.354	0.723
Year 2011: Depth -10 - -15	-0.406	1.447	-0.280	0.779
Year 2016: Depth -10 - -15	-0.693	1.443	-0.480	0.631
Year 2005: Depth -15 - -20	1.259	0.827	1.494	0.135
Year 2011: Depth -15 - -20	-20.540	11148	0.000	0.999
Year 2016: Depth -15 - -20	-25.690	11148	0.000	0.999
Year 2005: Depth <-20	25.850	11148	0.000	0.999
Year 2011: Depth <-20	-0.406	16240	0.000	0.999
Year 2016: Depth <-20	23.610	11148	0.000	0.999

(d) Cleveland Bay				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	-1.141	0.263	-4.331	<0.001
Year 2005	0.442	0.302	1.462	0.14
Year 2011	-2.890	1.027	-2.813	<0.01
Year 2016	1.386	0.264	5.261	<0.001
Depth -5 - -10	-0.220	0.196	-1.125	0.26
Depth -10 - -15	-1.976	0.435	-4.546	<0.001
Depth -15 - -20	-1.605	0.522	-3.075	<0.01
Depth <-20	-1.734	0.723	-2.399	<0.05

(e) Hinchinbrook Island				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	-0.172	0.250	-0.687	0.491
Year 2005	-0.693	0.433	-1.601	0.109
Year 2011	-0.693	0.433	-1.601	0.109
Year 2016	-0.375	0.391	-0.957	0.339
Depth -5 - -10	1.895	0.313	6.046	<0.001
Depth -10 - -15	0.061	0.348	0.174	0.862
Depth -15 - -20	-3.124	1.031	-3.031	<0.01
Depth <-20	-25.552	1148	0.000	0.999
Year 2005: Depth -5 - -10	-0.406	0.524	0.779	0.436
Year 2011: Depth -5 - -10	-0.847	0.624	-1.357	0.175
Year 2016: Depth -5 - -10	-1.166	0.596	-1.954	0.05
Year 2005: Depth -10 - -15	-0.754	0.705	-1.070	0.285
Year 2011: Depth -10 - -15	-0.266	1148	0.000	0.999
Year 2016: Depth -10 - -15	-2.459	1101	-2.233	<0.05
Year 2005: Depth -15 - -20	-23.610	1148	0.000	0.999
Year 2011: Depth -15 - -20	-23.610	1148	0.000	0.999
Year 2016: Depth -15 - -20	1.473	1.219	1.208	0.22
Year 2005: Depth <-20	-0.693	1624	0.000	0.999
Year 2011: Depth <-20	25.690	1148	0.000	0.999
Year 2016: Depth <-20	25.370	1148	0.000	0.999

(f) Turtles				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	0.160	0.200	0.801	0.42
Hervey Bay	-0.152	0.209	-0.728	0.47
Hinchinbrook	-0.160	0.304	-0.526	0.60
Moreton Bay	1.051	0.206	5.106	<0.001
Shoalwater Bay	1.676	0.209	8.025	<0.001
Depth -5 - -10	-0.926	0.314	-2.947	<0.01
Depth -10 - -15	-2.442	0.243	-10.040	<0.001
Depth -15 - -20	-2.403	1.020	-2.356	<0.05
Depth <-20	-1.146	0.735	-1.559	0.12
Hervey Bay: Depth -5 - -10	0.625	0.340	1.839	0.06
Hinchinbrook: Depth -5 - -10	1.715	0.492	3.483	<0.001
Moreton Bay: Depth -5 - -10	-0.020	0.339	-0.058	0.95
Shoalwater Bay: Depth -5 - -10	-0.727	0.361	-2.016	<0.05
Hervey Bay: Depth -10 - -15	1.609	0.291	5.527	<0.001
Hinchinbrook: Depth -10 - -15	0.884	0.601	1.470	0.14
Moreton Bay: Depth -10 - -15	0.050	0.314	0.158	0.87
Shoalwater Bay: Depth -10 - -15	NA	NA	NA	NA
Hervey Bay: Depth -15 - -20	2.032	1.028	1.976	<0.05
Hinchinbrook: Depth -15 - -20	-0.892	1.447	-0.617	0.54
Moreton Bay: Depth -15 - -20	-1.541	1.080	-1.426	0.15
Shoalwater Bay: Depth -15 - -20	-2.013	1.115	-1.805	0.07
Hervey Bay: Depth <-20	0.157	0.809	0.914	0.85
Hinchinbrook: Depth <-20	NA	NA	NA	NA
Moreton Bay: Depth <-20	-0.845	0.798	-1.062	0.29
Shoalwater Bay: Depth <-20	NA	NA	NA	NA

Appendix 9: Comparison of dugong population estimates obtained by the various techniques used to adjust for availability bias.

Moreton Bay

In 2016, the dugong population estimates for Moreton Bay were 654 ± 133 for the Pollock method and 601 ± 80 for the Hagihara method (Table 9.1 and Figure 9.1). Both methods provided comparable results due to the overall consistency across surveys of dugong sightings in the various depth categories (Figure 5), especially the large proportion of animals in large herds on the shallow Block MB4.

Table 9.1. Relative dugong abundance (± standard error) in Moreton Bay for 2005, 2011, and 2016 based on the Pollock and Hagihara methods.

Moreton Bay						
	Pollock method			Hagihara method		
Block	**2005**	**2011**	**2016**	**2005**	**2011**	**2016**
MB 1	95* (± 37)	tfs	tfs	49 (± 24)*	tfs	tfs
MB 2	tfs	tfs	tfs	tfs	tfs	tfs
MB 3	0	tfs	tfs	0	tfs	tfs
MB 4	301** (± 43)	569# (± 141)	492~ (± 113)	373 (± 71)**	552# (± 83)	447~ (± 75)
MB 5	0	tfs	tfs	0	tfs	tfs
MB 6	26 (± 21)	131 (± 66)	162 (± 70)	17 (± 14)	144 (± 66)	154 (± 27)
Total all blocks	**422 (± 60)**	**700 (± 156)**	**654 (± 133)**	**453 (± 97)**	**696 (± 106)**	**601 (± 80)**

Herds sighted: 2005: *10 dugongs; **31, 21 and 146 dugongs
2011: #44, 117 and 170 dugongs
2016: ~14, 33, 36, 45, and 49 dugongs

tfs – too few sightings for population estimations

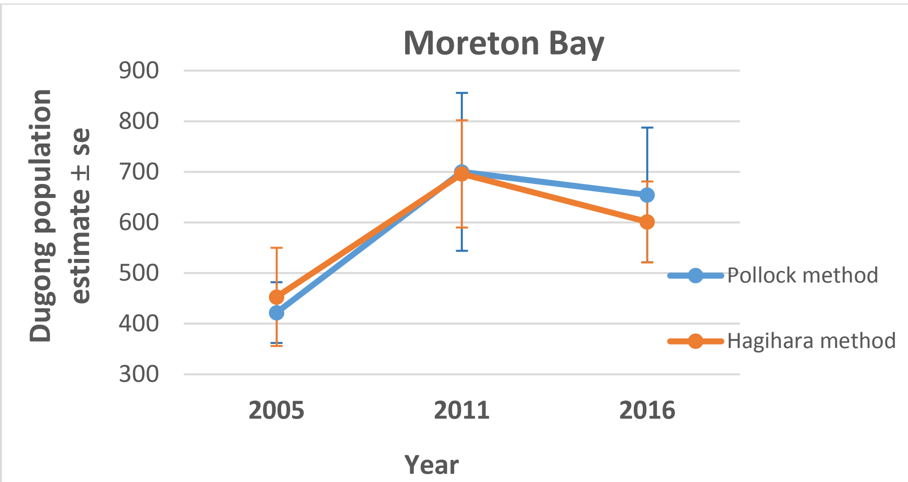


Figure 9.1. Dugong population size estimates ± se for the Pollock and Hagihara methods in 2005, 2011 and 2016 in Moreton Bay.

Hervey Bay

In 2016, the dugong population size in Hervey Bay was estimated to be 2647 ± 648 animals for the Pollock method and 2055 ± 382 animals for the Hagihara method (Table 9.2 and Figure 9.2). For both methods, the 2016 estimate is the highest since 2005. Most of this increase in dugong numbers occurred in Block HB4 (Table 9.2). The difference in the estimate of the dugong population size between the two methods is due to the complex pattern of the distribution of dugong sightings across depths in Hervey Bay (Figure 5).

Table 9.2. Relative dugong abundance (± standard error) in Hervey Bay for 2005, 2011 (incomplete survey), and 2016 based on the Pollock and Hagihara methods.

Hervey Bay						
	Pollock method			Hagihara method		
Block	**2005**	**2011**	**2016**	**2005**	**2011**	**2016**
HB 1	389 (± 130)	397 (± 152)	655 (± 310)	319 (± 133)	365 (± 90)	583 (± 176)
HB 2	1143 (± 353)*	1363 (± 536)#	768 (± 229)	816 (± 238)*	898 (± 413)#	684 (± 173)*
HB 3	545 (± 392)	148 (± 90)	273 (± 178)	253 (± 173)	103 (± 66)	178 (± 106)
HB 4	tfs	121 (± 116)	951 (± 490)	tfs	72 (± 96)	610 (± 272)
HB 5	0	0	0	0	0	0
Total all blocks	**2077 (± 543)**	**2029 (± 576)**	**2647 (± 648)**	**1388 (± 323)**	**1438 (± 438)**	**2055 (± 382)**

Herds sighted
2005: *13, 24, and 47 dugongs
2011: #25 dugongs
2016: *15 dugongs
tfs – too few sightings for population estimations

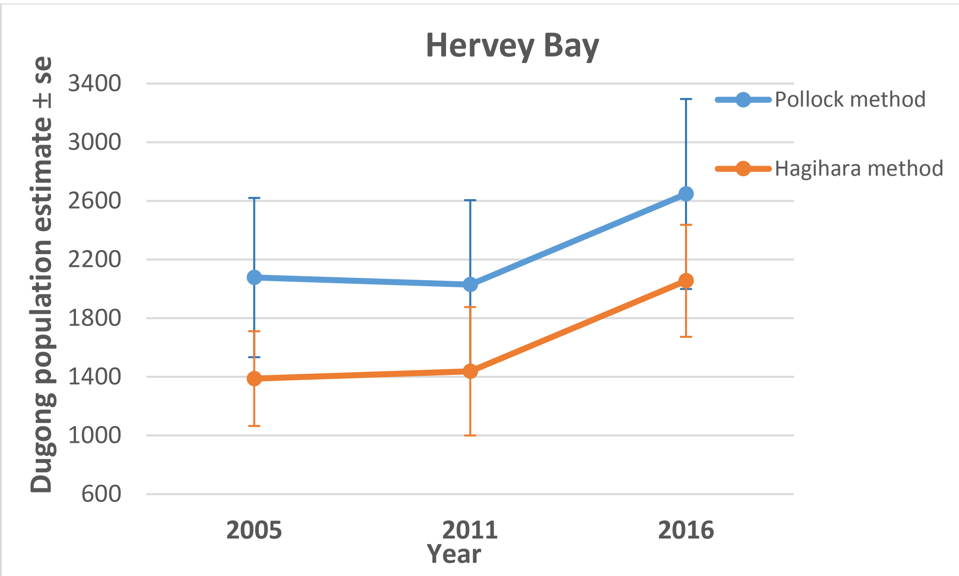


Figure 9.2. Dugong population size estimates ± se for the Pollock and Hagihara methods in 2005, 2011, and 2016 in Hervey Bay.

Southern GBR

The estimated size of the dugong population in the southern GBR in 2016 was 2543 ± 542 using the Pollock method and 2822 ± 600 using the Hagihara method (Table 9.3 and Figure 9.3). These estimates are the highest estimates of the last three surveys (Figure 9.3), and they represent a more than fivefold increase in numbers from the 2011 estimates. Most on the increase in population size estimates in 2016 results from blocks that are north of the Whitsundays (C-Blocks), with Block C8 (Townsville) contributing most (Table 9.3). The estimates of the dugong population size between the two methods are reasonably close due to the consistency of dugong depth distribution within locations in the region (Figure 5).

Table 9.3. Relative dugong abundance (± standard error) in the southern Great Barrier Reef for 2005, 2011, and 2016 based on the Pollock and Hagihara methods.

southern GBR						
	Pollock method			Hagihara method		
Block	**2005**	**2011**	**2016**	**2005**	**2011**	**2016**
S1	zzt	tfs	tfs	zzt	tfs	tfs
S2	tfs	0	tfs	tfs	0	tfs
S3	116 (± 64)	tfs	tfs	134 (± 82)	tfs	tfs
S4	zzt	dd	tfs	zzt	dd	tfs
S5	898 (± 295)	254 (± 124)	591 (± 231)	611 (± 174)	345 (± 229)	583 (± 222)
S6	dd	dd	tfs	dd	dd	tfs
S7	zzt	0	tfs	zzt	0	tfs
S8	tfs	tfs	125 (± 105)	tfs	tfs	122 (± 88)
Total S-Blocks	**1014 (± 302)**	**254 (± 124)**	**716 (± 254)**	**745 (± 192)**	**345 (± 229)**	**705 (± 239)**
C1	tfs	tfs	tfs	tfs	tfs	tfs
C2	ns	dd	0	ns	dd	0
C3	tfs	tfs	tfs	tfs	tfs	tfs
C4	145 (± 86)	tfs	231 (± 141)	74 (± 41)	tfs	265 (± 160)
C5	ns	dd	tfs	ns	dd	tfs
C6	331 (± 190)	80 (± 68)	tfs	173 (± 82)	64 (± 52)	tfs
C7	tfs	tfs	tfs	tfs	tfs	tfs
C8	216 (± 129)	tfs	960 (± 350)	193 (± 101)	tfs	1171 (± 423)
C9	zzt	tfs	326 (± 185)	zzt	tfs	361 (± 252)
C10	280 (± 130)	168 (± 132)	310 (± 230)	266 (± 165)	116 (± 93)	320 (± 187)
C11*	73 (± 50)	106 (± 88)	ns	107 (± 85)	59 (± 53)	ns
C12	zzt	tfs	ns	zzt	tfs	ns
Total C-Blocks	**1045 (± 282)**	**354 (± 173)**	**1827 (± 479)**	**813 (± 230)**	**239 (± 119)**	**2117 (± 550)**
Total all blocks	**2059 (± 413)**	**608 (± 213)**	**2543 (± 542)**	**1558 (± 300)**	**537 (± 223)**	**2822 (± 600)**
Total 2016 blocks only	**1986 (± 410)**	**502 (± 193)**	**2543 (± 542)**	**1451 (± 288)**	**478 (± 253)**	**2822 (± 600)**

tfs – too few sightings for population estimations; zzt – zig zag transects flown which do not allow population estimates; ns – not surveyed; dd – different design

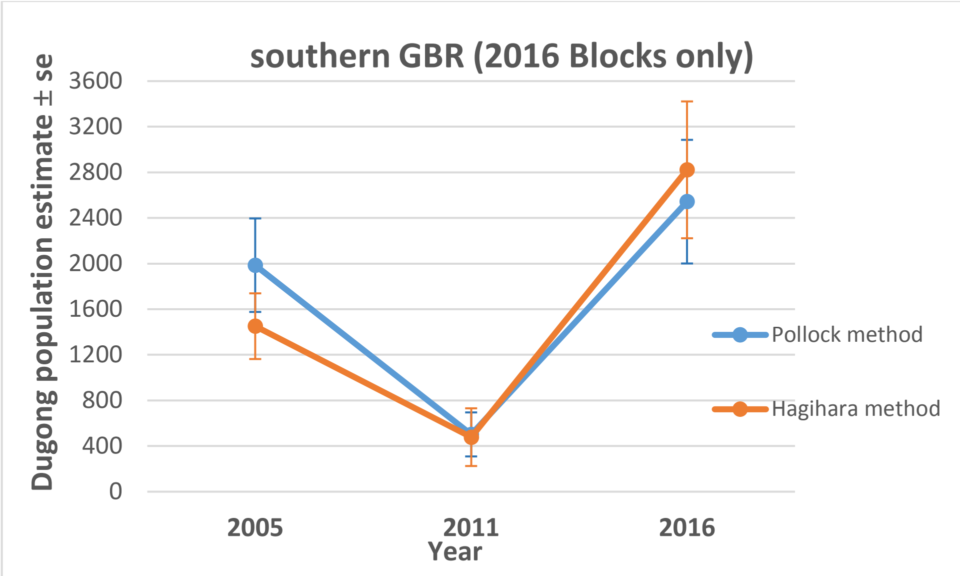


Figure 9.3. Dugong population size estimates ± se for the Pollock and Hagihara methods in 2005, 2011, and 2016 in the southern GBR (Blocks that were not surveyed in 2016 were omitted from the 2005 and 2011 totals).

Southern and northern dugong stocks

The estimated size of the southern dugong stock in 2016 was 4017 ± 709 using the Pollock method and 3361 ± 458 using the Hagihara method (Table 9.4 and Figure 9.4). These estimates are the highest estimates for the last three surveys (Figure 9.4) for both methods. The estimated size of the northern dugong stock that was observed in the southern GBR region (Blocks C1-C10 only), was 1827 ± 479 using the Pollock method and 2117 ± 550 using the Hagihara method (Table 9.4). As with the southern stock, these estimates were the highest estimates for the last three surveys for both methods (Figure 9.4). The differences between methods in the estimates of the dugong population size are due to the complex pattern of dugong distribution across water depths (Figure 5).

Table 9.4. Relative dugong abundance (± standard error) for the southern and northern stock for 2005, 2011, and 2016 based on the Pollock and Hagihara methods.

	Pollock method			**Hagihara method**		
Region	**2005**	**2011**	**2016**	**2005**	**2011**	**2016**
Moreton Bay	422 (± 60)	700 (± 156)	654 (± 133)	453 (± 97)	696 (± 106)	601 (± 80)
Hervey Bay	2077 (± 543)	2029 (± 576)	2647 (± 648)	1388 (± 323)	1438 (± 438)	2055 (± 382)
S-Blocks	1014 (± 302)	254 (± 124)	716 (± 254)	745 (± 192)	345 (± 229)	705 (± 239)
Total southern stock	**3,513 (± 624)**	**2,983 (± 610)**	**4,017 (± 709)**	**2,586 (± 384)**	**2,479 (± 506)**	**3,361 (± 458)**
Total northern stock (only sGBR blocks C1-C10)	**972 (± 278)**	**248 (± 148)**	**1827 (± 479)**	**706 (± 214)**	**180 (± 107)**	**2117 (± 550)**

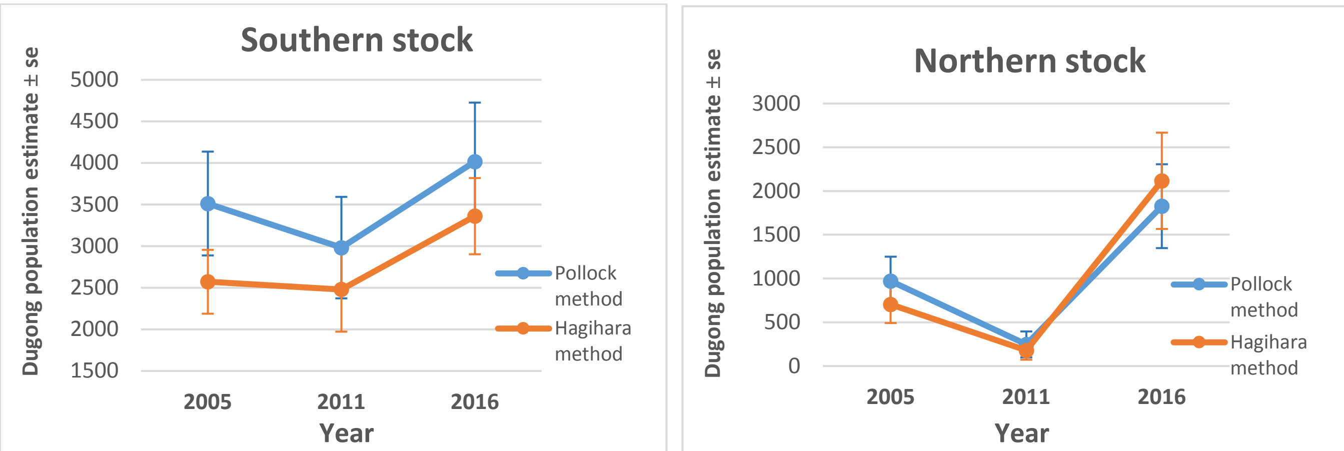
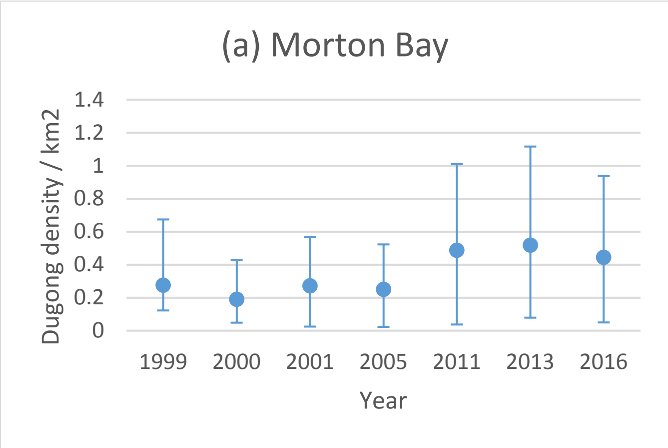
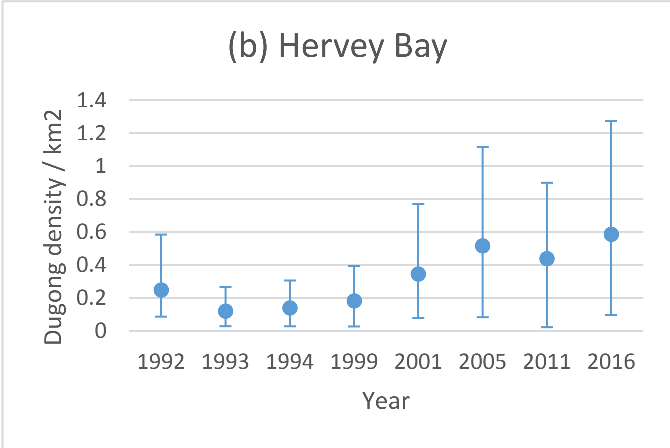


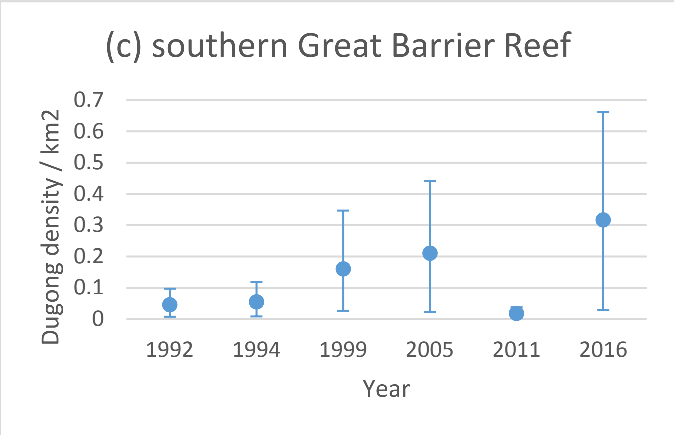
Figure 9.4. Dugong population size estimates ± se for the Pollock and Hagihara methods in 2005, 2011, and 2016 for the southern and northern dugong stocks.

Appendix 10: Time series of dugong densities in (a) Moreton Bay, (b) Hervey Bay and (c) the southern Great Barrier Reef regions using Marsh and Sinclair method

Densities were calculated by dividing the population size estimate for the year with the corresponding total surveyed area for the region. The 2006 survey of Hervey Bay was excluded since only two blocks were surveyed that year.







Appendix 11: Coefficients of the models used to examine dugong density calculated using the Hagihara method across surveys

of: (a) Moreton Bay, (b) Hervey Bay and (c) the southern GBR region.

(a) Moreton Bay using the negative binomial model and the results from the second flight over Block MB4.				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	-1.600	0.633	-2.527	0.012
Year 2011	-0.615	0.939	-0.655	0.513
Year 2013	-1.378	1.010	-1.367	0.172
Year 2016 - 1	-1.187	0.990	-1.200	0.230
Block MB2	-2.423	1.038	-2.334	0.020
Block MB4	1.849	0.819	2.258	0.024
Block MB5	-25.150	43260	-0.001	0.999
Block MB6	-1.718	0.930	-1.847	0.065
Year 2011:Block MB2	-0.603	1.723	-0.350	0.727
Year 2013:Block MB2	-22.010	40040	-0.001	0.999
Year 2016-1:Block MB2	1.790	1.481	1.208	0.227
Year 2011:Block MB4	0.429	1.137	0.377	0.706
Year 2013:Block MB4	0.748	1.195	0.626	0.532
Year 2016-1:Block MB4	0.073	1.181	0.061	0.951
Year 2011:Block MB5	23.070	43260	0.001	0.999
Year 2013:Block MB5	28.080	43260	0.001	0.999
Year 2016-1:Block MB5	24.960	43260	0.001	0.999
Year 2011:Block MB6	2.552	1.280	1.993	<0.05
Year 2013:Block MB6	2.672	1.344	1.987	<0.05
Year 2016-1:Block MB6	3.190	1.316	2.424	<0.05

(b) Hervey Bay using the negative binomial model				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	-1.004	0.271	-3.706	<0.001
Year 2011	-0.177	0.393	-0.452	0.651
Year 2016	0.271	0.387	0.700	0.484
Block HB2	-0.100	0.471	-0.212	0.832
Block HB3	-1.269	0.586	-2.166	0.030
Block HB4	-2.645	0.659	-4.013	<0.0001
Year 2011:Block HB2	-0.014	0.682	-0.020	0.984
Year 2016:Block HB2	-0.792	0.681	-1.163	0.245
Year 2011:Block HB3	-0.414	0.849	-0.488	0.626
Year 2016:Block HB3	-0.898	0.848	-1.060	0.289
Year 2011:Block HB4	-20.119	5484.52	-0.004	0.997
Year 2016:Block HB4	1.681	0.873	1.925	0.054

(c) the Southern GBR using the zero-inflated negative binomial model								
	Estimate	Std. Error	Z value	Pr(>|z|)	Estimate	Std. Error	Z value	Pr(>|z|)
	Count model				Binary model			
Intercept	0.5335	1.0390	0.513	0.608	2.0782	0.7849	2.648	0.008
Year 2011	-0.8387	0.3521	-2.382	<0.05	1.7798	0.4481	3.972	<0.0001
Year 2016	0.1164	0.2908	0.400	0.689	-0.1452	0.4147	-0.350	0.726
Block C4	-2.2349	1.0960	-2.039	<0.05	-3.2353	1.1404	-2.837	0.005
Block C6	-1.5180	1.0960	-1.385	0.166	-3.4943	1.4137	-2.472	0.013
Block C7	-2.3945	1.2111	-1.977	<0.05	-1.6597	1.0465	-1.586	0.113
Block C8	-1.0939	1.0820	-1.011	0.312	-2.8764	0.8811	-3.265	0.001
Block C9	-2.9201	1.1674	-2.501	<0.05	-1.4952	0.9478	-1.578	0.115
Block C10	-1.2982	1.0558	-1.230	0.219	-4.0119	1.0907	-3.678	<0.001
Block S1	-3.4138	1.2478	-2.736	<0.01	-1.4930	1.1370	-1.313	0.189
Block S2	-3.2405	1.4516	-2.232	<0.05	-0.7312	1.2772	-0.572	0.567
Block S2A	-1.7529	1.3781	-1.272	0.203	-0.2011	1.1102	-0.181	0.856
Block S3	-2.4103	1.1312	-2.131	<0.05	-1.5120	0.9319	-1.622	0.105
Block S4	-1.6906	1.2184	-1.388	0.165	0.0311	0.9459	0.033	0.974
Block S5	-1.0852	1.0339	-1.050	0.294	-3.2993	0.9012	-3.661	<0.001
Block S6	-2.6150	1.2286	-2.129	<0.05	-0.2571	0.9651	-0.266	0.790
Block S7	-2.0341	1.2922	-1.574	0.115	-0.9078	1.0466	-0.867	0.386
Block S8	-2.1036	1.0933	-1.924	0.054	-1.8723	0.9521	-1.966	<0.05
Log(theta)	-0.3915	0.2605	-1.503	0.133	-	-	-	-

Appendix 12: Comparison of the corresponding deviance tables obtained from analysis of the differences between survey years and blocks for southern and northern stocks using the negative binomial technique for dugong population estimates by the various techniques used to adjust for availability bias.

The results show that the substantive conclusions of the analyses are robust across the methods used for (a) Southern stock and (b) Northern stock.

(a) Southern stock						
Method	**Variable**	**DF**	**Deviance**	**Residual DF**	**Residual Deviance**	**Pr(Chi)**
Hagihara method	Null			777	860.81	
	Year	2	7.67	775	853.15	<0.05
	Block	19	325.14	756	528.01	<0.001
Marsh and Sinclair method	Null			324	322.40	
	Year	2	42.84	322	279.55	<0.001
	Block	18	67.49	314	212.06	<0.001
Pollock method	Null			569	744.09	
	Year	1	97.96	568	646.13	<0.001
	Block	19	302.90	549	343.23	<0.001
(b) Northern stock						
Method	**Variable**	**DF**	**Deviance**	**Residual DF**	**Residual Deviance**	**Pr(Chi)**
Hagihara method	Null			324	322.40	
	Year	2	42.84	322	279.55	<0.001
	Block	8	67.49	314	212.06	<0.001
Marsh and Sinclair method	Null			371	327.74	
	Year	4	42.98	367	284.76	<0.001
	Block	6	52.95	361	231.81	<0.001
Pollock method	Null			203	181.16	
	Year	1	21.16	202	160.00	<0.001
	Block	7	29.01	195	130.99	<0.001

Appendix 13: Coefficients of the negative binomial models used to investigate changes in dugong density across surveys for the southern stock

using (a) Marsh and Sinclair, (b) Pollock and (c) Hagihara methods.

(a) Marsh and Sinclair method				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	0.363	0.436	0.833	0.41
Year 2011	-0.310	0.222	-1.394	0.16
Year 2016	-0.911	0.226	-4.027	<0.001
Block MB2	-0.291	0.640	-0.456	0.65
Block MB3	-0.049	0.768	-0.063	0.95
Block MB4	1.900	0.494	3.846	<0.001
Block MB5	-1.017	0.716	-1.420	0.16
Block MB6	0.861	0.551	1.561	0.12
Block HB1	1.536	0.474	3.239	<0.01
Block HB2	2.912	0.541	5.382	<0.001
Block HB3	1.425	0.600	2.375	<0.05
Block HB4	1.448	0.614	2.360	<0.05
Block HB5	-30.310	589100	0.000	0.99
Block S1	-1.904	0.906	-2.100	<0.05
Block S2	-0.898	0.598	-1.501	0.13
Block S3	0.105	0.503	0.210	0.83
Block S4	-0.528	0.934	-0.889	0.37
Block S5	0.182	0.481	3.779	<0.001
Block S6	-0.038	0.615	-0.062	0.95
Block S7	0.630	0.803	0.785	0.43
Block S8	1.137	0.580	1.961	<0.05
(b) Pollock method				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	-1.272	0.585	-2.175	<0.05
Year 2016	2.207	0.232	9.511	<0.001
Block MB2	0.758	0.822	0.923	0.36
Block MB3	2.260	1.022	2.212	<0.05
Block MB4	2.338	0.664	3.520	<0.001
Block MB5	0.569	0.858	0.663	0.51
Block MB6	1.820	0.732	2.487	<0.05
Block HB1	2.138	0.639	3.349	<0.001
Block HB2	3.761	0.725	5.190	<0.001
Block HB3	2.299	0.797	2.883	<0.01
Block HB4	3.761	0.793	4.112	<0.001
Block HB5	-36.880	206700	0.000	0.99
Block S1	-2.647	0.973	-2.720	<0.01
Block S2	-1.149	0.900	0.000	0.202
Block S3	-1.144	0.762	-1.501	0.133
Block S4	-2.234	0.731	-3.057	<0.01
Block S5	1.074	0.731	1.678	0.09
Block S6	-1.863	0.640	-2.519	<0.05
Block S7	-1.158	0.874	-1.325	0.185
Block S8	9.860	0.742	1.329	0.184

(c) Hagihara method				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	0.400	0.436	0.918	0.36
Year 2011	-0.964	0.223	-4.323	<0.001
Year 2016	0.0184	0.214	0.086	0.93
Block MB2	-1.094	0.685	1.598	0.11
Block MB3	-0.410	0.807	-0.507	0.61
Block MB4	3.012	0.507	5.940	<0.001
Block MB5	-1.596	0.769	-2.074	<0.05
Block MB6	0.968	0.550	1.140	0.25
Block HB1	2.600	0.477	2.032	<0.05
Block HB2	0.571	0.541	4.811	<0.001
Block HB3	0.573	0.609	1.409	0.16
Block HB4	-30.640	0.613	0.935	0.35
Block HB5	-1.335	1152000	0.000	1
Block S1	-1.934	0.649	-2.058	<0.05
Block S2	-1.175	0.750	-2.578	<0.01
Block S3	-0.668	0.667	-1.224	0.22
Block S4	-1.361	0.546	-2.515	<0.05
Block S5	1.363	0.541	2.852	<0.01
Block S6	-1.418	0.558	-2.543	<0.05
Block S7	-0.759	0.671	-1.136	0.26
Block S8	0.162	0.575	0.281	0.78

Appendix 14: Coefficients of the negative binomial models used to investigate changes in dugong density across surveys for the northern stock

using (a) Marsh and Sinclair, (b) Pollock and (c) Hagihara methods.

(a) Marsh and Sinclair method years				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	-2.680	0.601	-4.462	<0.001
Year 1999	2.865	0.497	5.764	<0.001
Year 2005	1.762	0.505	3.490	<0.001
Year 2011	1.424	0.510	2.796	<0.01
Year 2016	2.969	0.487	6.095	<0.001
Block C3	0.046	0.549	0.084	0.93
Block C4	1.894	0.610	3.104	<0.01
Block C6	2.468	0.644	3.832	<0.001
Block C7	1.284	0.736	1.744	0.08
Block C8	2.456	0.569	4.316	<0.001
Block C10	3.084	0.596	5.174	<0.001
(b) Pollock method years				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	-1.130	0.637	-1.774	0.08
Year 2016	1.413	0.355	3.985	<0.001
Block C3	-0.621	0.735	-0.845	0.40
Block C4	0.793	0.803	0.988	0.32
Block C6	1.174	0.865	1.357	0.18
Block C7	0.857	0.873	0.982	0.33
Block C8	1.706	0.749	2.276	<0.05
Block C9	-0.507	0.736	-0.689	0.48
Block C10	1.637	0.750	2.183	0.03
(c) Hagihara method years				
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**
Intercept	-0.993	0.561	-1.771	0.07
Year 2011	-0.911	0.362	-2.517	<0.05
Year 2016	0.657	0.337	1.948	0.05
Block C3	0.071	0.622	-0.115	0.91
Block C4	1.491	0.666	2.239	<0.05
Block C6	2.135	0.700	3.049	<0.01
Block C7	1.134	0.752	1.508	0.13
Block C8	2.442	0.624	3.915	<0.001