Improving the time series of estimates of dugong abundance and distribution by incorporating revised availability bias corrections

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A Report to the Marine Mammal Centre

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EXECUTIVE SUMMARY

- In Australia, the dugong is a Matter of National Environmental Significance. While anecdotal evidence suggests that dugong numbers have decreased throughout most of their range, significant populations persist in Australian waters, which are now believed to support most of the world's dugongs.
- Since the 1980s, aerial surveys have provided information on dugong distribution and abundance for many parts of their distribution in Australia.
- This report improves the usefulness and validity of archival dugong aerial survey data for management by: (1) developing and using revised Availability Correction Factors that incorporate variations in dugong dive behaviour with bathymetry (referred to as the Hagihara method), to reanalyse archival aerial survey data for dugong abundance and distribution, and (2) using improved statistical and spatial modelling techniques.
- Archival data collected since 2002 from five regions in Australia were re-analysed: Moreton Bay, Hervey Bay, the southern Great Barrier Reef region, the northern Great Barrier Reef region and the Gulf of Carpentaria.
- Dugong population size estimations using the previous standard, the Pollock *et al.* (2006) method were compared with the population estimates using the Hagihara method. Estimated relative dugong densities were analysed using a zero-inflated model with a Negative Binomial distribution. Spatially explicit models of dugong relative density and were developed using the method of Grech and Marsh (2007) and Grech *et al.* (2011) with modifications reflecting (1) the results from the Hagihara method, (2) advances in the methodology (Empirical Bayesian Kriging), and (3) improved accuracy of recording aircraft altitude and GPS locations. The sustainable level of human-related mortalities for dugongs per region was estimated using the Potential Biological Removal (PBR) method developed by Wade (1998).
- While results varied between regions and survey years, the population estimates obtained using the Hagihara method were generally (but not always) lower than those obtained using the Pollock method. The precision of the estimates tends to be similar using the two methodologies. The chief advantage of the Hagihara method over the Pollock method is the increase in the accuracy of the population estimates. Nevertheless, the Hagihara population estimates should be regarded as standardised relative estimates rather than absolute estimates of dugong population size and density. The method is conservative and the estimates are likely underestimates.
- Cross-regional comparisons of dugong population size and area of high and very high density habitat emphasises the importance of the remote regions of the Gulf of Carpentaria and the northern Great Barrier Reef. The Hervey Bay and Moreton Bay dugong populations are clearly of regional significance. The status of the dugong in the southern Great Barrier Reef Region is an ongoing cause for concern.
- We conclude that the Hagihara method and the statistical and spatial modelling methods used in this report should be significant improvements over the previous methodologies used to study dugong distribution because of their improved accuracy and spatial resolution.

Contents

1 INTRODUCTION

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 (IUCN 2006), along with the other three species in the order Sirenia, the manatees (family Trichechidae). 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 the dugongs in its waters and the species is listed as a Matter of National Environmental Significance under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).

Dugongs occur along much of the tropical and sub-tropical coast of Australia from Shark Bay in Western Australia to Moreton Bay in Queensland (Figure 1). Within Queensland, the Cape York coast, the Great Barrier Reef and Torres Strait support globally significant populations of dugongs (Marsh *et al*. 2011). Indeed, the significance of the Great Barrier Reef to the dugong was explicitly mentioned in the nomination of the Great Barrier Reef as a World Heritage site (GBRMPA 1981).

Since the 1980s, aerial surveys have provided information on dugong distribution and abundance for many parts of their distribution in Australia (Figure 1). 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).

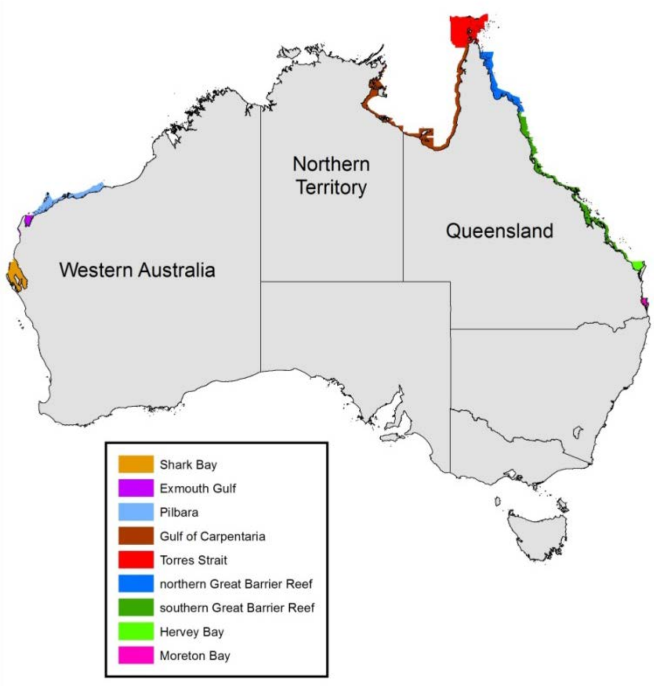

Figure 1 - Dugong aerial survey regions in Australia. Surveys from Queensland and the Gulf of Carpentaria are considered in this report.

Dugongs spend most of their time beneath the surface of the water and generally surface cryptically and only for 1-2 seconds (Chilvers *et al*. 2004). Thus the most challenging aspect of dugong aerial surveys is the problem of imperfect detection. The dugong survey methodology developed by Marsh and Sinclair (1989a) recognised two components of detection bias: Availability Bias (animals unavailable for detection due to survey conditions and animal behaviour) and Perception Bias (animals available but missed by aerial observers). Perception Bias can be addressed by tandem observers and a Mark-Recapture model and Pollock *et al.*'s (2006) improvements in this component of the dugong aerial survey methodology capitalised on improvements in Mark-Recapture methodology and software rather than field protocol. Overcoming Availability Bias is much more difficult. Marsh and Sinclair (1989b) compared the proportion of dugongs sighted at the surface of the water during an entire survey with a calm, clear water standard in which all dugongs were potentially available. Pollock *et al*. (2006) improved the methodology by correcting for the spatial heterogeneity in Availability Bias resulting from variable water turbidity and sea state. Their methodology, which is based on experimentally-determined detection zones, incorporates additional environmental data collected during each survey from 2002 and thus cannot be applied retrospectively to the earlier surveys. Hagihara *et al.* (2014) showed that the time a dugong spends near the water surface (and is therefore available to aerial observers) varies with water depth. This additional source of heterogeneity was not incorporated into the Pollock *et al*. (2006) methodology, which uses the **average** time dugongs spend near the surface based on depth measurements collected from dugong fitted with (now superseded) time-depth recorders (Chilvers *et al.* 2004).

In this report, we improve the usefulness and validity of archival aerial survey data for management by: (1) developing and using revised Availability Correction Factors that incorporate variations in dugong dive behaviour with water depth recorded using modern technology to reanalyse archival aerial survey data for dugong abundance and distribution, and (2) using improved statistical and spatial modelling techniques.

2 METHODOLOGY

2.1 Regions for which archival data were reanalysed

We analysed archival data collected since 2002 from the following Regions: Moreton Bay, Hervey Bay, the southern Great Barrier Reef region, the northern Great Barrier Reef region and the Gulf of Carpentaria. Although the archival data for several surveys (Moreton Bay and northern Great Barrier Reef 2000; and Moreton Bay and Hervey Bay 2001 in April and November) provided information on the sightings conditions (*e.g.,* water turbidity) for individual dugong sightings, these data were collected in a format that did not allow re-analysing the dataset with regards to the revised Availability Correction Factors. It was therefore not possible to recalculate the population abundance and standard errors for the above-mentioned surveys as required by the Hagihara method, (2014) and so pre-2002 surveys were excluded from the dataset.

Population sizes were not re-estimated for any of the aerial surveys conducted in Torres Strait. The availability probabilities developed by Hagihara *et al.* (Table 1) are based on data collected from 16 dugongs in Moreton Bay and Shoalwater Bay. We consider that dugong diving behaviour in Moreton Bay and Shoalwater Bay is likely to be very different from the behaviour in Torres Strait as a result of geographical differences in bathymetry and seagrass community structure. The depth distribution of seagrass in Torres Strait extends to 40 m (Long and Poiner 1997), and ~55,000 km^2 of seagrass (38% in Western and 49% in Central Torres Strait) occur in water >10 m deep (Taylor and Rasheed 2011).

Dugongs in Torres Strait are frequently sighted in waters 10 to <25 m deep during aerial surveys (Marsh and Saalfeld 1990; Marsh and Lawler 1992; Sobtzick *et al*. 2014). Satellite tracking of six dugongs in Torres Strait documented their occurrence in waters up to ~15 m deep in Central and Western Torres Strait (Gredzens *et al.* 2014). In contrast, seagrass in Moreton Bay mostly occurs in water <10 m deep over shallow banks (Phinn *et al.* 2008; Lyons *et al.* 2012), and most dugongs are consistently sighted in shallow water. In the inshore waters of Moreton Bay, 84 to 100% of satellite locations data fixes from four tagged dugongs were from waters less than 10 m deep (Hagihara 2015). Thus the probabilities of dugongs being available to aerial observers are likely to be very different in Torres Strait from the coastal environments analysed in this report.

Consequently, we did not attempt to extrapolate the availability detection probabilities reported here to the data from the dugong surveys of Torres Strait. We have received funding from the Torres Strait Regional Authority and the National Environmental Science Program to obtain empirical data on dugong diving behaviour from Torres Strait, and will subsequently reanalyse the archival data from that region for surveys conducted in 2001, 2006, 2011 and 2013. A reanalysis of the data for the entire time series of aerial surveys since 1987 using the Marsh and Sinclair (1989b) methodology (the only methodology for which all the data required are available) is at Appendix 4.

2.2 Aerial surveys

The aerial survey methodology followed the distance sampling technique detailed in Marsh and Sinclair (1989a, b) and later refined by Pollock *et al.* (2006). Transects chosen under a stratified random sampling design were flown by a 6-seat, high-wing, twin-engine Partenavia 68B as close as possible to a ground speed of 100 knots. The surveys were conducted at a height of 500 feet (152 m) above sea level in 2011 and 2013 and at 450 feet (137 m) in the other surveys. The experimental work of Marsh and Sinclair (1989a) indicates that there should be no difference in dugong sightability between survey heights of 152 m 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 color bands on the artificial wing struts. Two trained tandem teams of observers on each side of the aircraft scanned their respective transect and recorded 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 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 1–2seconds (Chilvers *et al*. 2004); (2) of the inherent limitations of using color bands on the wing struts (as approved by the Civil Aviation Safety Authority) to define distance categories. 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 surveys were conducted in passing mode. For each dugong sighting, the observers recorded the total number of animals seen, number at the surface of the water, number of calves (animals less than 2/3 of the size of the cow and swimming in close proximity), position in the transect distance class (*e.g.,* low or medium). On the relatively rare occasions (see footnotes to Tables 2,5,8,10,13) when groups of dugongs were sighted that were too large to accurately count in passing mode (usually 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.

2.3 Revised Availability Probabilities

Hagihara (2015) and Hagihara *et al*. (in prep., see Appendix 6) developed revised availability probabilities for dugongs in various combinations of the four Environmental Condition Classes (ECC, composite indices of water visibility and sea state conditions) and detection zones (*i.e.* the zone in which dugongs can be detected by aerial observers) for different depth categories (bathymetric bins). The detection zones were determined by conducting experiments using dugong replicas (Dugong Secchi Disks) that were submerged from a vessel in different environmental conditions and slowly released towards the water surface until observers hovering in a helicopter above the set-up could clearly see them. Using those detection zones and dive data from 16 dugongs tracked with a GPS unit and a Time depth Recorder (TDR) in Moreton and Shoalwater Bay, revised availability probabilities were calculated for four different depth categories per Environmental Condition Class (note: in ECC 1 all dugongs in the water column are by definition visible to aerial observers and the availability detection probability is therefore 1). For detailed methodologies see Hagihara (2015); the results are summarised in Table 1 and Figure 2.

Table 1 - Estimates of depth specific availability probability (Availability *pr*) for Environmental Conditions Classes 1-4 and four different detection zones, which resulted in 13 dugong sightability classes. Adapted from Hagihara *et al*. (in prep., see Appendix 6).

Environmental Condition Class	Detection zone (m)	Depth category	Availability *pr* (se)	Sightability class
1	all	all	1.000	1
2	0-0.2	<2	1.000	2
		2 to <5	0.780 (0.175)	3
		5 to <25	0.442 (0.175	4
		≥ 25	0.652 (0.188)	5
3	0-3.5	<3.5	1.000	6
		3.5 to <5	0.872 (0.186)	7
		5 to <25	0.693 (0.185)	8
		≥ 25	0.848 (0.197)	9
4	0-1.5	<1.5	1.000	10
		1.5 to <5	0.598 (0.165)	11
		5 to <25	0.338 (0.166)	12
		≥ 25	0.580 (0.183)	13

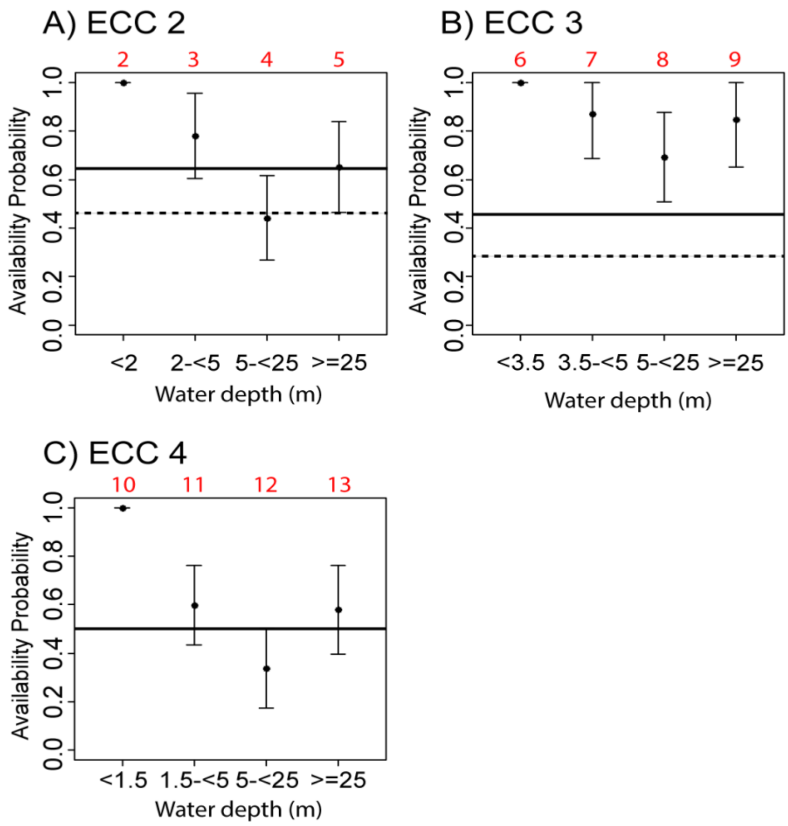

Figure 2 - Comparison of estimates of depth specific availability probability (Availability *pr*) for Environmental Conditions Classes (ECC) 2-4 from Hagihara *et al.* (in prep.) and constant availability probability from Pollock *et al.* (2006). The numbers in red indicate sightability classes. Sightability class 1 is not shown as the availability probability is 1 by definition. Horizontal lines represent constant availability detection probabilities after Pollock *et al*. for sea state $\leq$2 (straight line) and 3 (dotted line). For ECC 4, a dotted line is not visible as the availability estimates generated from both sea states overlap.

2.4 Improved relative abundance estimations

The eight availability probabilities developed by Pollock *et al.* (2006) were expanded to 13 sighting classes (see Table 1), accounting for the heterogeneity of dugong diving behaviour (and therefore different likelihood of being available to observers) with water depth. Estimates of relative dugong abundance were calculated using the method developed by Pollock *et al*. (2006) (hereafter referred to as the Pollock method) and incorporating the revised availability probabilities (hereafter referred to as the Hagihara method).

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 the MARK program (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.

2.5 Statistical analyses

Estimated relative dugong densities were analysed using a zero-inflated model with a Negative Binomial distribution (Lambert 1992, Marsh *et al*., in prep., see Appendix 4). This method is more appropriate for the dataset than the statistical approaches used previously (*e.g.*, Marsh *et al.*, 2007), because there were numerous transects on which no dugongs were sighted. To explore temporal and spatial variations in relative dugong density, year and block were used as categorical explanatory variables and the response variable was the corrected number of dugongs generated using the Hagihara method with transect area (km^2) as an offset. The zero-inflated models were performed in the R package glmmADMB (Skaug *et al.* 2014) in R 3.1.3 (R Core Team 2015).

To compare dugong density among survey years, a zero-inflated model with year as the single main factor was used. Additional zero-inflated models were used to examine whether the ranking of high dugong density blocks significantly changed over time. Nonetheless, detailed interpretation of the survey results focused on the observed data, rather than interpreting the results from the statistical models due to missing or insufficient data from some blocks. Zero-inflated models require sightings on at least one but preferably several transects in each block. Thus, blocks with insufficient data had to be removed from the analyses.

2.6 Improved spatial models

Spatially explicit models of dugong relative density and distribution for: (1) individual surveys; and (2) all surveys combined were developed using the method of Grech and Marsh (2007) and Grech *et al.* (2011) with the following modifications:

a. Input data were dugong counts corrected for perception and depth-specific availability probabilities (using the improved method described above).
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. EBK creates multiple simulations of the semivariogram by sequentially changing input parameters to find the best fit parameters for the input data. The search neighbourhood was set to a radius of 5000 m, which corresponds with the home range of dugongs at Burrum Heads, Hervey Bay (Sheppard *et al.* 2006).
c. Dugong relative density was calculated at a grid size of 1km^2, which corresponds to improved accuracy of plane altitude and 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/km^2), High (0.5 – 0.1 dugongs/km^2), Medium (0.1 – 0 dugongs/km^2) and Low (0 dugongs/km^2) relative dugong density.

Grid cells with 0 dugongs/km^2 were included: (1) to ensure that the spatial layers of relative dugong density extended across the entire survey area; (2) because dugongs 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 were not sighted (which is theoretically possible but very difficult; see Martin *et al.* 2014). This classification approach makes the assumption that dugong relative density is a robust index of dugong habitat utilisation. This assumption is partially justified because specialised areas for dugong reproduction and migratory corridors have not been identified and density estimates are regarded as a suitable surrogate measurement of habitat utilisation (Hooker and Gerber 2004).

2.7 Sustainable levels of anthropogenic mortality

The sustainable level of human-related mortalities for dugongs per Region was estimated using the Potential Biological Removal (PBR) method developed by Wade (1998) (and mandatory to use in the evaluation of the sustainability of marine mammal fisheries bycatch in the United States), and subsequently used for dugongs by Marsh *et al.* (2004). This technique estimates the maximum number of animals that can be removed from the population other than by natural causes, while allowing the population to reach an optimum sustainable level (i.e., between carrying capacity and maximum net productivity). The following is the formula to calculate the PBR:

$$PBR = N_{min} \times 0.5\ R_{max} \times RF \text{ (Wade 1998)}$$

where: N_{min} = the 20th percentile of a log-normal distribution based on an absolute estimate of the number of animals N in the population.

R_{max} = the maximum rate of increase, for which Marsh *et al*. (2004) use a range of estimates of 0.01 – 0.05 due to uncertainty of estimates of age of first reproduction, fecundity and natural mortality levels.

RF = a recovery factor of between 0.1 and 1, which if < 1, allows population growth and uncertainties in estimates of N_{min} or R_{max},

Because of the uncertainties about the life history and reproductive biology of dugongs, a range of estimates are presented for sustainable levels of human-caused mortalities of dugongs in each Region (e.g. Moreton Bay, southern Great Barrier Reef) using the PBR method. This range of estimates is for different rates of maximum population growth rate (R_{max}) based on studies of dugongs in eastern Australia (Marsh *et al.* 2004). In the main result section, the default value of 0.5 has been used for the Recovery Factor, while results for Recovery Factors 0.1, 0.5, and 1.0 are presented in Appendix 3.

3 RESULTS

3.1 Moreton Bay

3.1.1 Population estimates

The differences between the estimates of the Moreton Bay dugong population obtained from the Pollock and Hagihara methodologies varied by survey year: (1) in 2011 they were nearly identical,(2) in 2005, the Hagihara estimate slightly exceeded the Pollock estimate; in 2013 the Hagihara estimate exceeded the Pollock estimate by around ⅓ (Table 2 and Figures 3). The 2013 survey was conducted in winter; the other two surveys in summer. The winter distribution of dugongs in Moreton Bay differs from the summer distribution, with animals preferring warmer more oceanic waters in winter (e.g., Preen, 1992; Sheppard *et al*. 2006). A relatively large number of dugongs in 2013 was sighted in Block 5, where only one or no dugongs were seen in 2005 and 2011 (Figure 4). Of those sightings in Block 5 in 2013, seven (70%) were recorded in waters 5-<25m deep with an ECC of 4, resulting in a sightings class that has a lower availability probability for the method that for the Pollock method (Figure 2). Population estimates using the newer methodology were therefore higher in that block. In 2011, most of the dugong sightings (64%) occurred in ECC 1 (Figure 4) – a category that has an availability probability of 1 for both methodologies. Population size estimates were therefore nearly identical for both methodologies.

Table 2 – Relative dugong abundance (± standard error) in Moreton Bay for 2005, 2011, and 2013 based on the Pollock and Hagihara methods.

Block	2005		2011		2013	
	Pollock method	Hagihara method	Pollock method	Hagihara method	Pollock method	Hagihara method
1	95 (± 37)*	49 (± 24)*	tfs	tfs	tfs	tfs
2	tfs	tfs	tfs	tfs	0	0
3	0	0	tfs	tfs	0	0
4	301 (± 43)**	373 (± 71)**	569 (± 141)#	552 (± 83)#	338 (± 121)^	468 (± 137)^
5	0	0	tfs	tfs	162 (± 97)^^	212 (± 110)^^
6	26 (± 21)	17 (± 14)	131 (± 66)	144 (± 66)	51 (± 36)	79 (± 42)
Total	**422 (± 60)**	**453 (± 97)**	**700 (± 156)**	**696 (± 106)**	**551 (± 159)**	**759 (± 181)**
Herds sighted	*10 dugongs **31, 21 and 146 dugongs		#44, 117 and 170 dugongs		^45 and 58 dugongs ^^29 and 12 dugongs	

tfs – too few sightings for population estimations

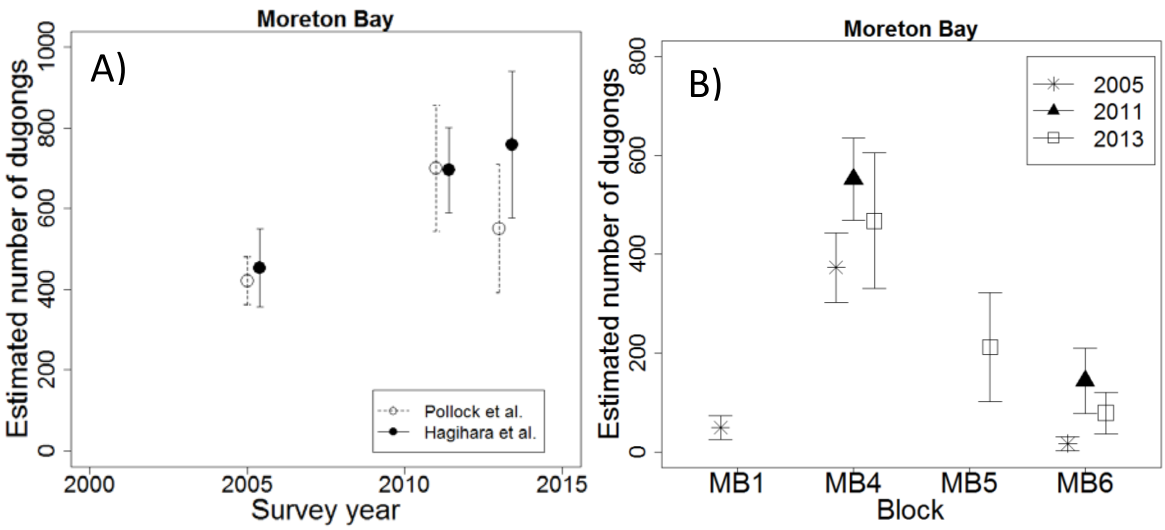

Figure 3 – Population estimates from surveys conducted in 2005, 2011 and 2013 based on A) Pollock method (open circles) and Hagihara method (closed circles) for all Moreton Bay blocks combined and B) Hagihara method only, blocks plotted separately for each year.

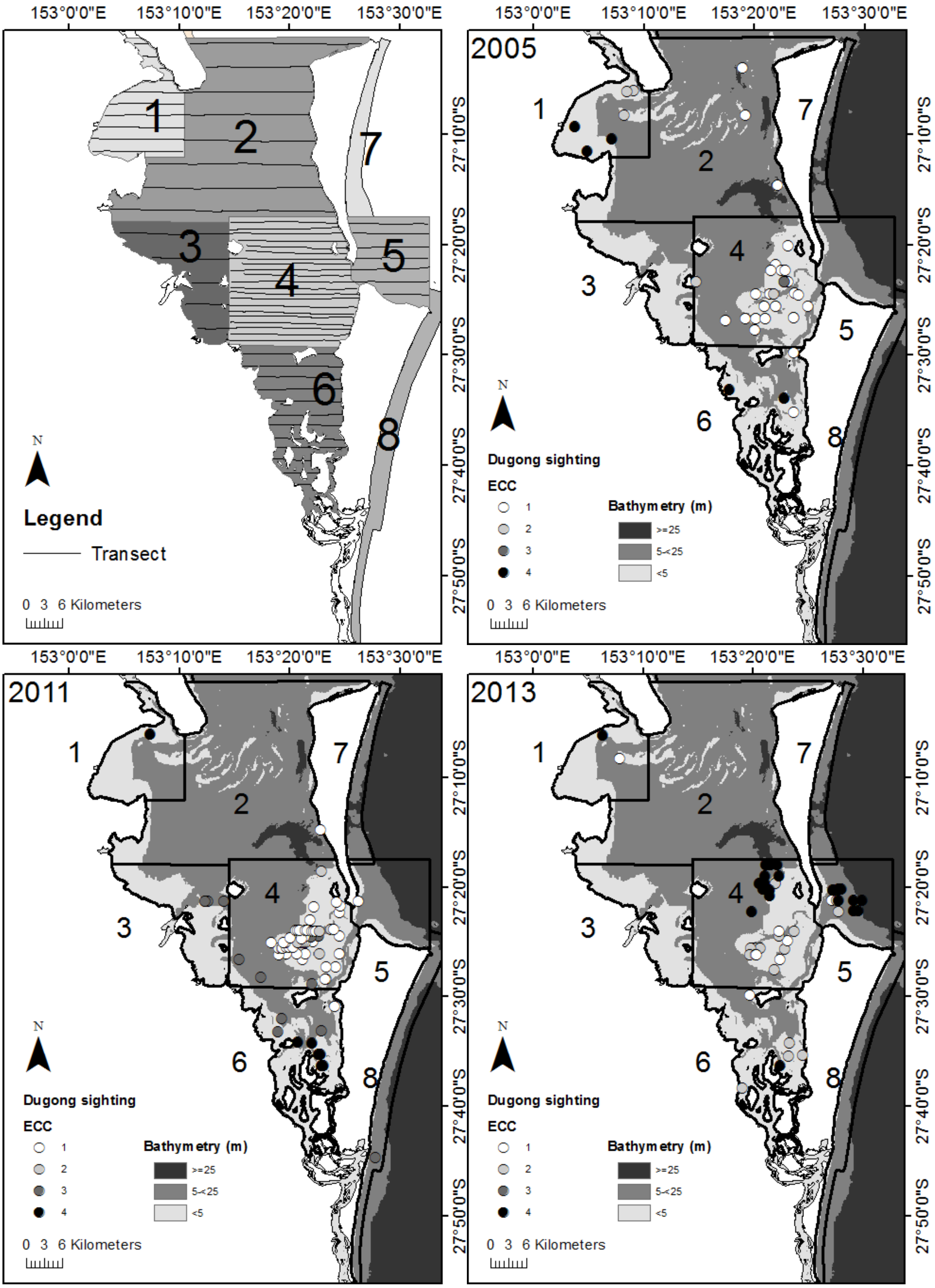

Figure 4 – Distribution of dugong sightings in Moreton Bay in 2005, 2011 and 2013 with respect to bathymetry and environmental conditions (ECC). Each dot represents a sighting of a dugong group.

3.1.2 Dugong density

Although dugong relative density in 2005 was slightly lower than in 2011 and 2013, no significant difference was found among the years analysed (2005, 2011 and 2013) (Figure 5).

The zero-inflated model with Year, Block and their interaction was significantly better than the model with Year and Block as main factors only. This result indicated that the ranking of individual blocks based on dugong density changed over the three survey years. Across years, Block 4 had the highest density of all block in all three surveys (Figures 6 and 7). The second highest block in 2005 was Block 1, Block 6 in 2011, and Block 5 in 2013 (Figures 6 and 7). Tables of pair-wise comparisons and coefficients of the statistical analysis are provided in Appendices 1 and 2.

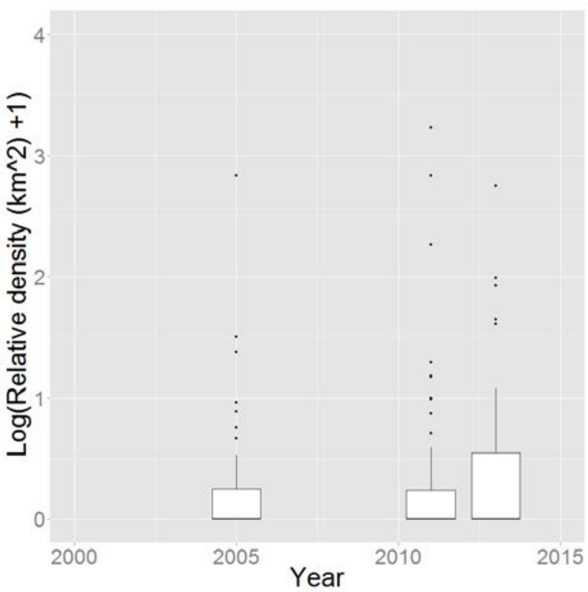

Figure 5 - Relative dugong density on natural logarithm (base 10) estimated using the Hagihara method for aerial surveys of Moreton Bay conducted in November 2005 and 2011 and July 2013. The figure includes all data. Error bars represent 95% confidence intervals.

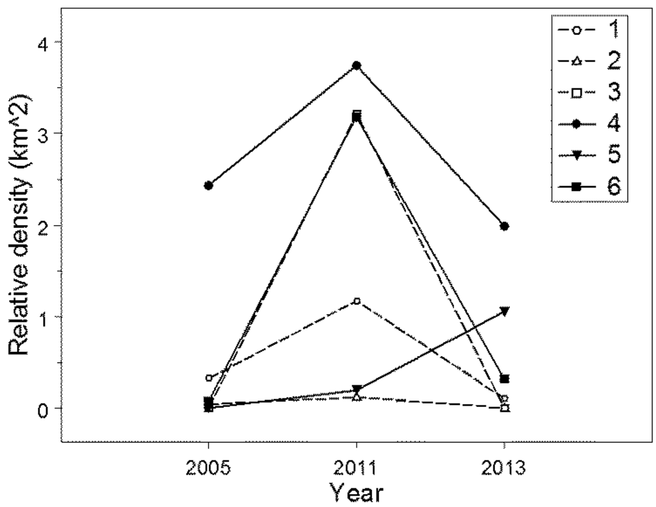

Figure 6 - Dugong relative density in Moreton Bay in all blocks and years using the Hagihara method.

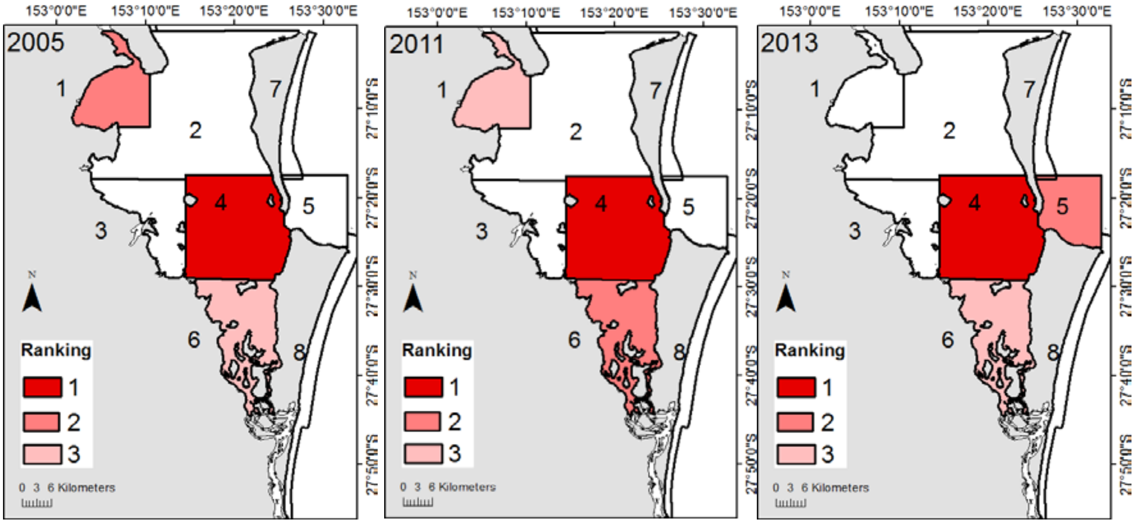

Figure 7 – Ranking of three highest density blocks in 2005, 2011 and 2013 in Moreton Bay. The ranking is based on mean dugong relative density in each survey year using the Hagihara method. The ranking is based on mean dugong density for each block and year.

3.1.3 Spatial models

The spatially-explicit models of dugong distribution and relative density in Moreton Bay in 2005 and 2011 (Figure 8A and B) also indicate that Block 4 had the highest density in those years. As in Figure 7, the 2011 model reflects the changes in seagrass distribution caused by flooding in early 2011 (http://www.health-e-waterways.org/reportcard/2011/subregion/Moreton%20Bay). Seagrass was lost south of Bribie Island in Deception Bay as a result of deteriorating water quality in the region caused by the northward movement of flood waters. As explained above, the 2005 and 2011 surveys were conducted in summer while the 2013 survey occurred in winter. Consequently, the 2013 dugong distribution differed from those in the other years with Block 4 and 5 supporting areas with very high dugong densities (Figures 8A, B, and C), presumably due to animals requiring easy access to the warmer waters close to south Passage and immediately outside the Bay in winter (Preen, 1992; Sheppard *et al*. 2006).

The spatial model that incorporated data from all three surveys (Table 3 and Figure 8D) showed that Blocks 2 and 3 had most of the region's low to medium dugong density, while all of the remaining three Blocks (1, 4-6) had high to very high dugong density. Overall, 33% of Moreton Bay was classified as having high to very high relative dugong density.

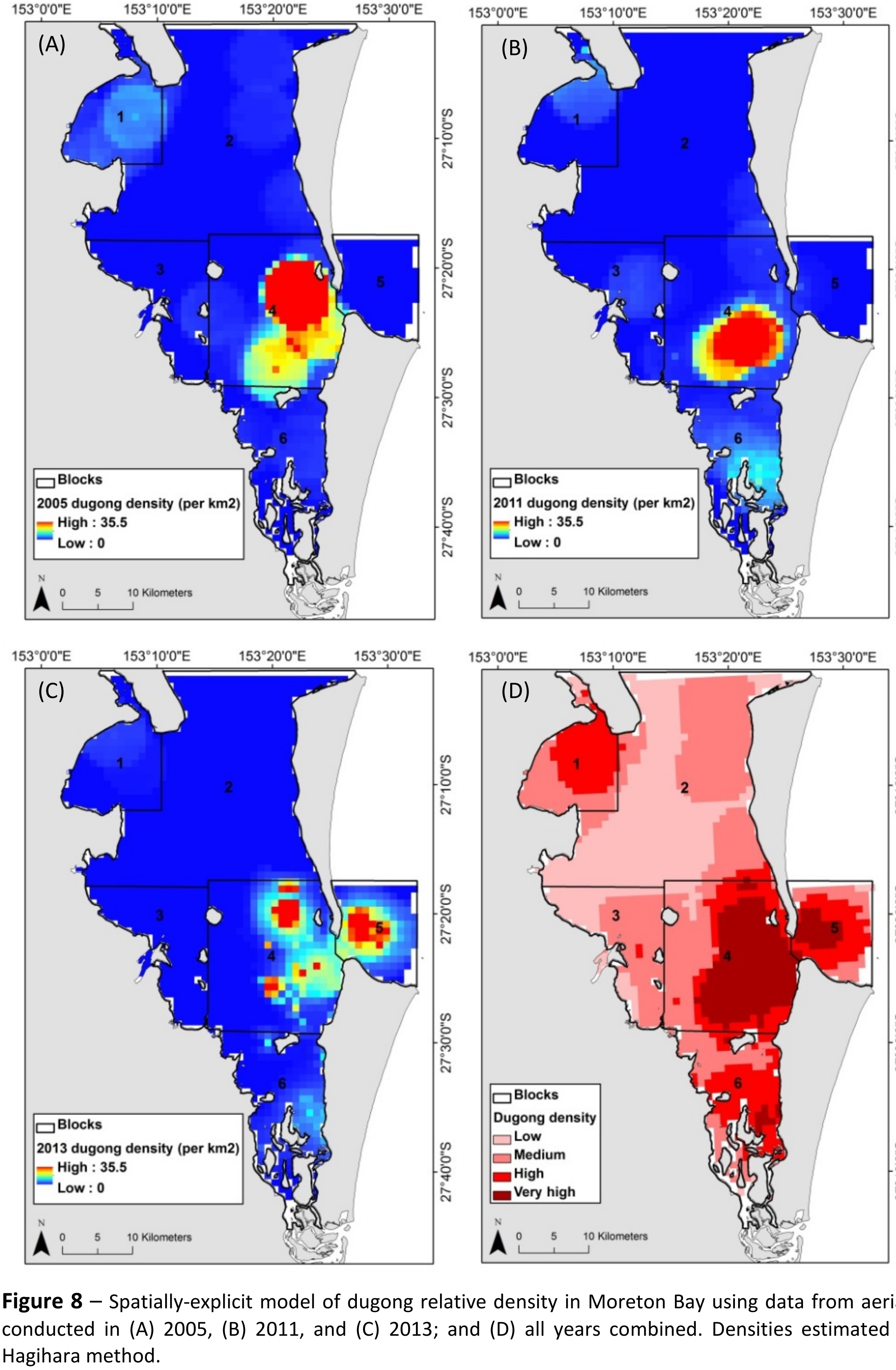

Figure 8 – Spatially-explicit model of dugong relative density in Moreton Bay using data from aerial surveys conducted in (A) 2005, (B) 2011, and (C) 2013; and (D) all years combined. Densities estimated using the Hagihara method.

Table 3 – Total area (km^2) and size of dugong density classes of low, medium, high and very high relative density predicted by the spatially explicit model (Figure 8) in different blocks in Moreton Bay (MB) covered by the 2005 and 2011 aerial survey.

Block	Size of relative dugong density class (in km^2)				Total Area (km^2)
	Low	Medium	High	Very high	
1	6	67	85	0	158
2	372	272	12	1	657
3	64	111	2	0	177
4	15	111	69	189	384
5	3	37	60	33	133
6	3	69	99	10	181
Entire MB	**463 (27%)**	**667 (40%)**	**327 (19%)**	**233 (14%)**	**1690 (100%)**

3.1.4 Sustainable levels of human-caused mortality

Assuming the population growth rate is in the middle of the range (R_{max} = 0.03, other values reported in Appendix 3), the total sustainable level of anthropogenic mortalities for the dugong population in Moreton Bay in 2005, 2011, and 2013 ranged from three to four animals when using the Pollock estimates, and from three to five animals when using the Hagihara estimates (Table 4).

Table 4 – Estimated sustainable levels of mortalities from anthropogenic sources for dugongs in Moreton Bay in 2005, 2011, and 2013 using the Potential Biological Removal method (Wade 1998).

Year	Methodology	RF	N	SE	CV	N_{min}	PBR		
							R_{max}= 0.01	R_{max}= 0.03	R_{max}= 0.05
2005	Pollock method	0.5	422	60	0.142	375	1	3	5
	Hagihara method	0.5	453	97	0.214	379	1	3	5
2011	Pollock method	0.5	700	156	0.223	582	1	4	7
	Hagihara method	0.5	696	106	0.152	613	2	5	8
2013	Pollock method	0.5	551	159	0.289	434	1	3	5
	Hagihara method	0.5	759	181	0.238	623	2	5	8

RF = recovery factor; N = dugong population estimate; SE = standard error; N_{min} = the 20th percentile of a log-normal distribution based on N; PBR = potential biological removal; R_{max} = maximum rate of increase

3.2 Hervey Bay

3.2.1 Population estimates

Aerial surveys conducted in Hervey Bay covered the entire Bay in 2005 and 2011, while the 2006 survey only covered Blocks 1 and 2 (for location of Blocks refer to Figure 10).

The estimated dugong population size using the Pollock method was 2077 ± 543 dugongs in 2005, 1044 ± 399 dugongs in 2006 (incomplete survey), and 2029 ± 576 dugongs in 2011 (Table 5 and Figure 9). The estimated dugong population size using the Hagihara method was more consistent across surveys: 1388 ± 323 dugongs in 2005, 1445 ± 545 dugongs in 2006 (incomplete survey), and 1438 ± 438 dugongs in 2011.

The larger Hagihara population estimate in Block 2 in 2006 (1336 ± 544) compared to the Pollock estimate (936 ± 397) resulted from many dugong sightings (69%) being recorded under ECC 4 and water 5-25m deep (Figures 10), conditions for which the availability detection probability was smaller for the Hagihara method than for the Pollock method (Figure 2). A smaller percentage of dugongs was sighted in Block 1 in 2006 (14%) under ECC 4 and water 5-25m deep, compared to Block 1 in 2005 (33%) and 2011 (27%).

Table 5 – Relative dugong abundance (± standard error) in Hervey Bay for 2005, 2006 9incomplete survey), and 2011 based on the Pollock and Hagihara methods.

Block	2005		2006		2011	
	Pollock method	Hagihara method	Pollock Method	Hagihara method	Pollock Method	Hagihara method
1	389 (± 130)	319 (± 133)	108 (± 37) #	109 (± 38)#	397 (± 152)	365 (± 90)
2	1143 (± 353)*	816 (± 238)*	936 (± 397) ##	1336 (± 544)##	1363 (± 536)^	898 (± 413)^
3	545 (± 392)	253 (± 173)	Ns	ns	148 (± 90)	103 (± 66)
4	tfs	tfs	Ns	ns	121 (± 116)	72 (± 96)
5	0	0	Ns	ns	0	0
6	zzt	zzt	Ns	ns	Zzt	zzt
Total	**2077 (± 543)**	**1388 (± 323)**	**1044 (± 399)**	**1445 (± 545)**	**2029 (± 576)**	**1438 (± 438)**
Herds sighted	*24, 47 and 13 dugongs		#22 dugongs ## 27 dugongs		^25 dugongs	

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

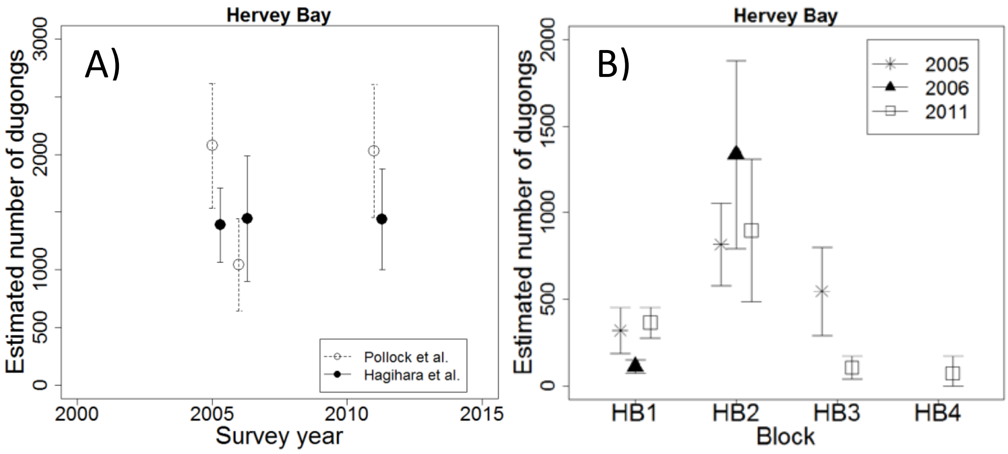

Figure 9 – Population estimates from surveys conducted in 2005, 2006 and 2011 based on A) Pollock method (open circles) and Hagihara method (closed circles) for all Hervey Bay blocks combined and B) Hagihara method only, blocks plotted separately for each year.

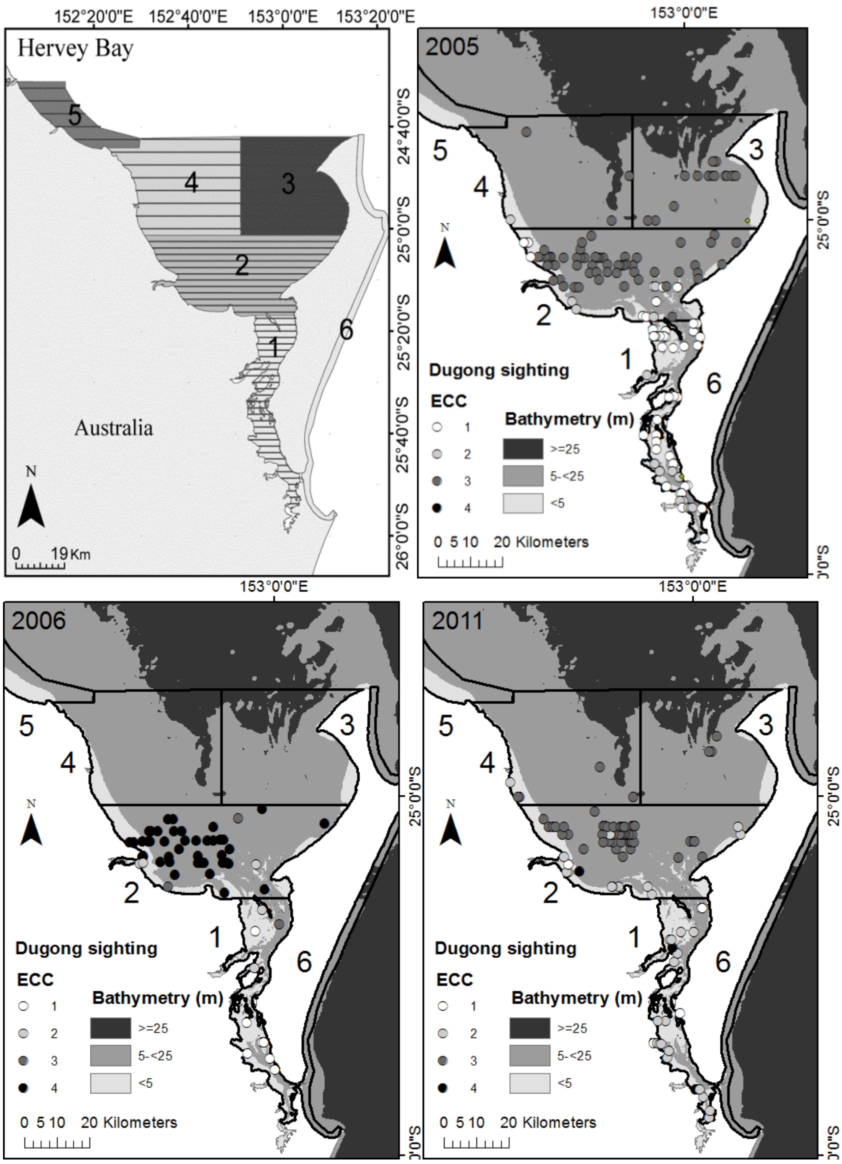

Figure 10 – Distribution of dugong sightings in Hervey Bay in 2005, 2006 and 2011 with respect to bathymetry and environmental conditions (ECC). Each dot represents a sighting of a dugong group. The 2006 survey was conducted over Blocks 1 and 2 only.

3.2.2 Dugong density

2006 was excluded from the following analyses because it was an incomplete survey. The dugong relative density was slightly lower (87%) in 2011 than in 2005, but this difference was not significant (Figure 11).

The best fitting model included Year and Block as the main factors (but not their interaction), indicating that there is no significant difference between years in the patterns of dugong density from blocks. Blocks 1 and 2 had significantly higher densities than Blocks 3 and 4 in both years (Figure 12). Block 1 had the highest density ranking, followed by Blocks 2 and 3 (Figure 13). Blocks 5 and 6 had zero dugong density in both years.

The population size estimate for Block 1 in 2005 (319 ± 133 dugongs) was lower than the estimate for Block 2 (816 ± 238 dugongs), but the density for Block 1 was higher than that of Block 2. This result was caused by the different sizes of the blocks: the area of Block 2 was 2.7 times more than Block 1 (1414 km^2 and 517 km^2, respectively). The same situation applied in 2011 for Blocks 1 and 2, where Block 1 had a higher density than Block 2. Tables of pairwise comparisons and coefficients of the statistical analysis are provided in Appendices 1 and 2.

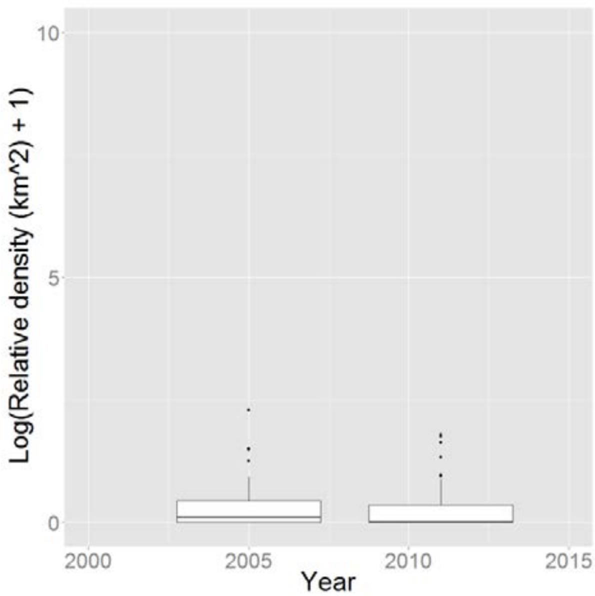

Figure 11 - Relative dugong density on natural logarithm (base 10) estimated using the Hagihara method for the 2005 and 2011 aerial surveys in Hervey Bay. The figure includes all data. The figure includes all data. Error bars represent 95% confidence intervals.

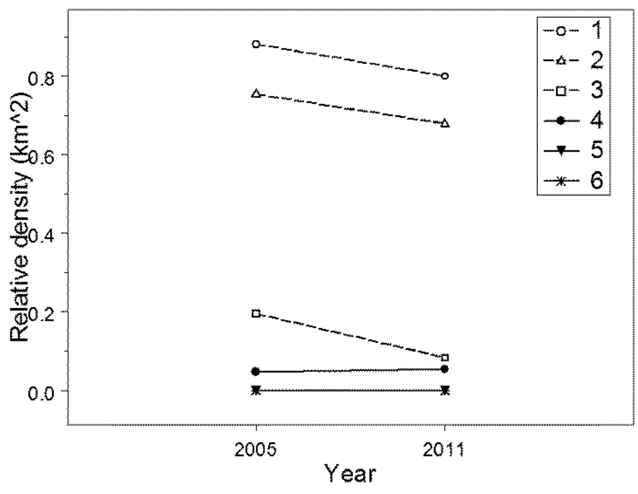

Figure 12 - Dugong relative density in Hervey Bay for all blocks and years combined using the Hagihara method. Note that the densities for Blocks 5 and 6 are zero.

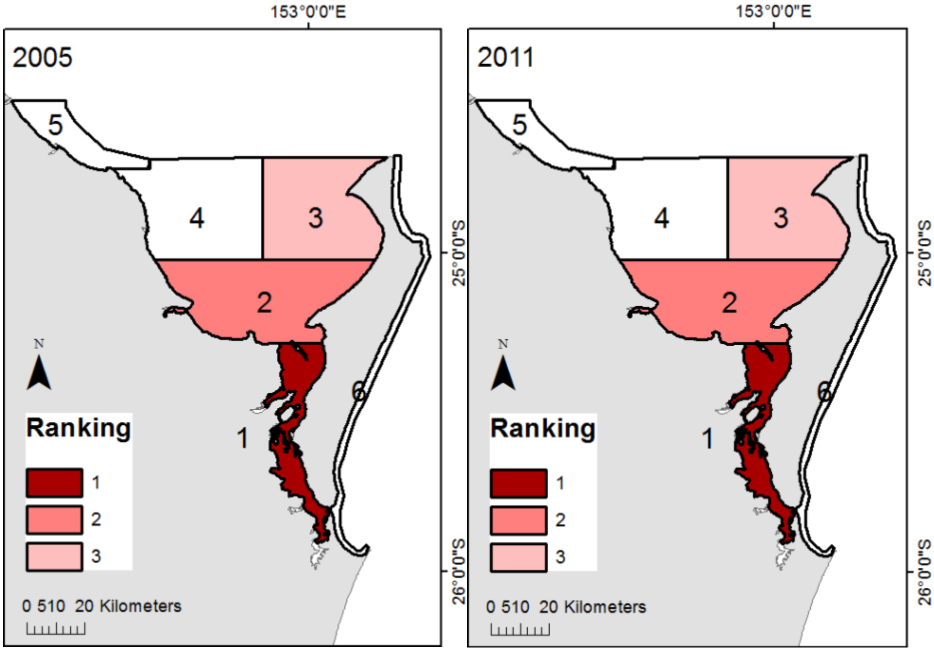

Figure 13 – Comparison between years of the density rankings of the three highest density blocks in 2005 and 2011 in Hervey Bay (Hagihara method). The ranking is based on mean dugong relative density in each survey year. The ranking was based on mean dugong density for each block and year.

3.2.3 Spatial models

The spatially-explicit models of dugong distribution and relative density for 2005, 2006, and 2011 (Figures 14A-C) show similar patterns for all three years in Hervey Bay. Block 2 had consistently the largest areas of the highest dugong density, while the southern end of Block 1 also had areas of high dugong density.

Combining data from all three years (Table 6 and Figure 14D), Blocks 1, 2, and 3 show large areas of high to very high dugong density, while Blocks 4 and 5 primarily contain areas of medium to low dugong density. Overall, 31% of Hervey Bay was classified as containing high to very high relative dugong density.

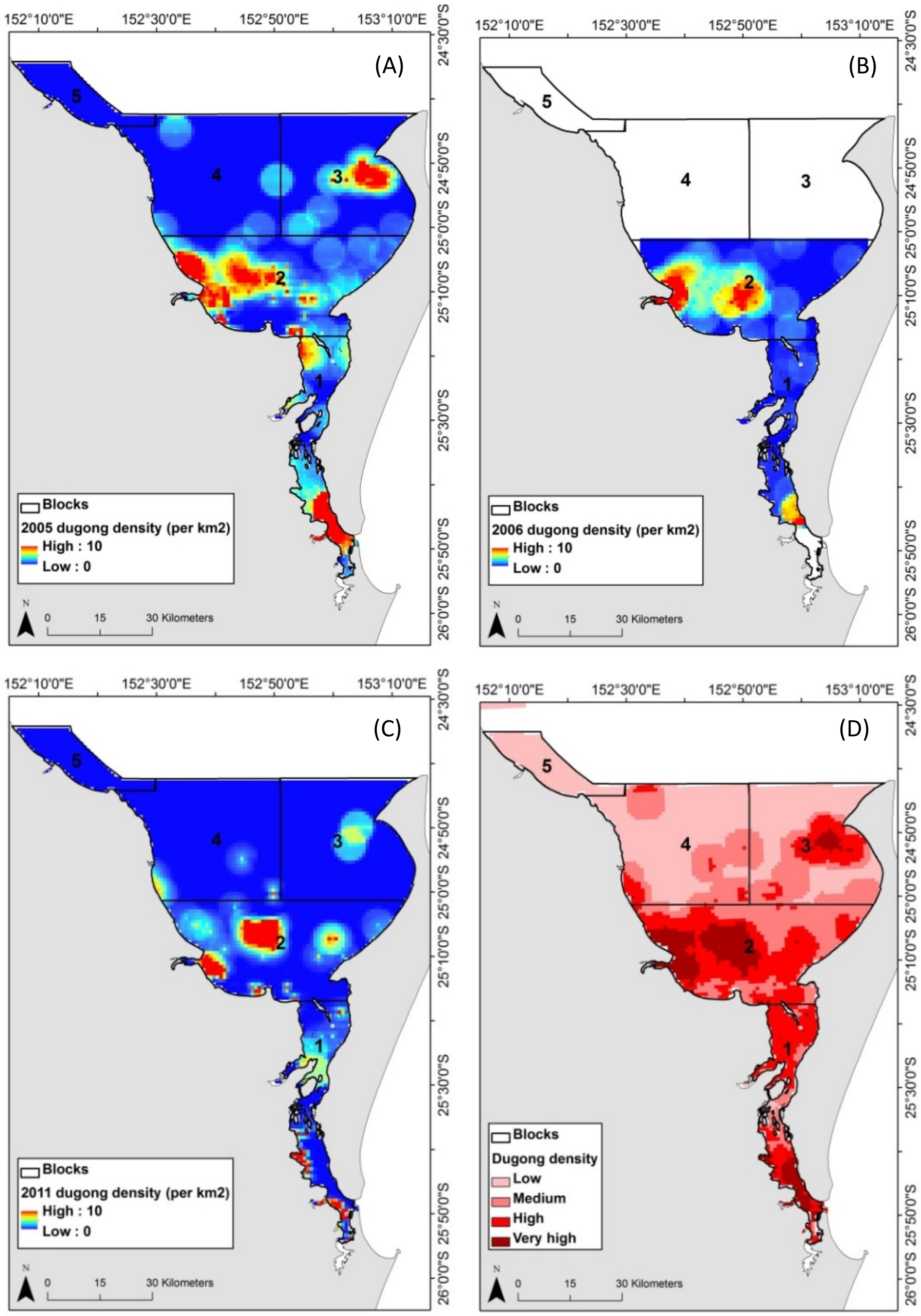

Figure 14 – Spatially-explicit model of dugong relative density in Hervey Bay using data from aerial surveys conducted in (A) 2005, (B) 2006 9incomplete survey), and (C) 2011; and (D) all years combined.

Table 6 – Total area (km^2) and size of dugong density classes of low, medium, high and very high relative density predicted by the spatially explicit model (Figure 14) in different blocks in Hervey Bay (HB) covered by the 2005, 2006 and 2011 aerial survey.

Block	Size of relative dugong density class (in km^2)				Total Area (km^2)
	Low	**Medium**	**High**	**Very high**	
1	8	85	285	79	457
2	9	495	573	309	1386
3	575	399	184	38	1196
4	872	392	64	2	1330
5	277	0	0	0	277
Entire HB	**1741 (37%)**	**1371 (30%)**	**1106 (24%)**	**428 (9%)**	**4646 (100%)**

3.2.4 Sustainable levels of human-caused mortality

The total sustainable level of anthropogenic mortalities for the dugong population in Hervey Bay (assuming the population growth rate is in the middle of the range; R_{max} = 0.03, other values presented in Appendix 3), in 2005, 2006, and 2013 ranged from eight to nine animals using the Hagihara population size estimates (Table 7). These PBR results show a smaller range than the PBR results from the Pollock method (six to 13 animals). The difference between the range of the two PBR estimates reflects the smaller variation in the population size estimates using the Hagihara method.

Table 7 – Estimated sustainable levels of mortalities from anthropogenic sources for dugongs in Hervey Bay in 2005, 2006, and 2013 using the Potential Biological Removal method (Wade 1998).

Year	Methodology	RF	N	SE	CV	N_{min}	PBR R_{max}= 0.01	PBR R_{max}= 0.03	PBR R_{max}= 0.05
2005	Pollock method	0.5	2077	543	0.261	1673	4	13	21
	Hagihara method	0.5	1388	323	0.233	1144	3	9	14
2006	Pollock method	0.5	1044	399	0.382	765	2	6	10
	Hagihara method	0.5	1445	545	0.377	1063	3	8	13
2013	Pollock method	0.5	2029	576	0.284	1605	4	12	20
	Hagihara method	0.5	1438	438	0.305	1119	3	8	14

RF = recovery factor; N = dugong population estimate; SE = standard error; N_{min} = the 20th percentile of a log-normal distribution based on N; PBR = potential biological removal; R_{max} = maximum rate of increase

3.3 Southern Great Barrier Reef

3.3.1 Population estimates

In 2005, dugong population size estimates for the entire southern Great Barrier Reef Region (see Figure 15) using the Hagihara method were 24% lower (2059 ± 413 dugongs) than the Pollock estimates (1558 ± 300 dugongs, Table 8 and Figure 16). In 2011, the Hagihara estimates (537 ± 223 dugongs) were 12 % lower than the Pollock estimates (608 ± 213 dugongs). These differences were caused by different distribution of dugong sightings between years across the 13 sightability classes. Table 8 and Figure 16 present results for all Blocks for which new population size estimates are available, while detailed maps (Figures 17 and 18) are presented only for Blocks for which the number of dugongs sighted was sufficient to generate estimates for both years (Blocks S5, C6, C10 and C11).

In 2005, the lower Hagihara estimate for Block S5 was caused by many dugong sightings being recorded under ECC 3 (Figure 17), for which the revised availability detection probabilities for all depth categories were higher than the Pollock probabilities (Figure 2). In contrast in 2011, the Hagihara estimate was slightly larger than the Pollock estimate (91 dugongs difference). Although many dugong sightings that year occurred in water <5 m deep, the recorded ECC for those sightings was 4 (Figure 17), resulting in an overall increase in estimated dugong numbers.

Similarly, the population size estimates for Block C6 in 2005 were higher for the Pollock than for the Hagihara method, while the difference in estimated population size in 2011 was smaller between the two methodologies. This result was caused by four out of five dugong sightings in 2011 (80%) being recorded in sightability class 3 (ECC 2 and water depth 2-<5 m), the availability detection probability of which is 0.780, whereas in 2005, 10 out of 20 sightings (50%) were recorded in sightability class 7 (ECC 3 and water depth 3.5-<5 m), the availability detection probability of which was higher (0.872) than that of the former combination of environmental conditions and water depth.

Block C10 showed only very small differences in estimated population size for both methodologies in 2005 (the Pollock estimate was higher). In 2005, 57% of the dugong sightings were recorded in ECC 4 (Figure 18), where depth-specific availability detection probabilities after the Hagihara method were lower than the homogeneous availability detection probabilities used for the Pollock method. At the same time, 42% of the dugong sightings were recorded in ECC 3 for which depth-specific probabilities were generally higher (Figure 2). This balance resulted in only a difference of 5% in this block using the two methods (Hagihara estimate was 95% of the Pollock estimate). In 2011, the difference in estimates from the Pollock and Hagihara methods was larger (31%), due to fewer sightings occurring in ECC 4 (44%) and more in ECC 3 (56%) that year.

Dugong population size estimates for Block C11 in 2005 were higher for the Hagihara method than for the Pollock method (Pollock estimate only 68% of the Hagihara estimate). This resulted from all dugong sightings in 2005 occurring in ECC 4, and most of those in waters 5-25m deep (Figure 18). In contrary, estimated dugong population size in 2011 based on the Pollock method was higher than for the Hagihara method, as a result of better survey conditions (and more dugong sightings being recorded in ECC 2 and 3 (Figure 18).

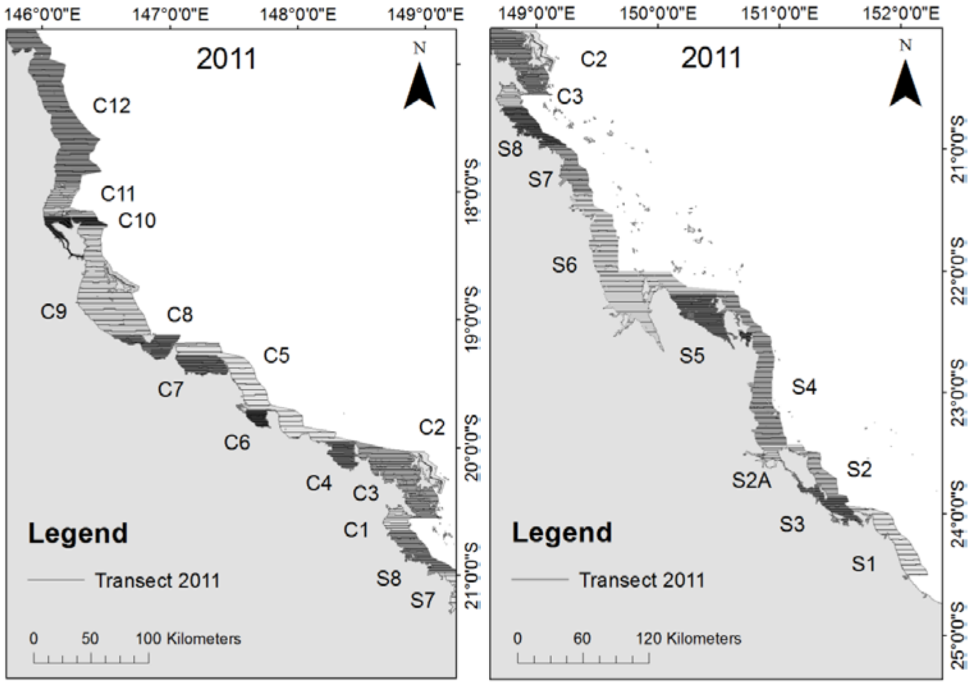

Figure 15 – Survey blocks and transects in the southern Great Barrier Reef region flown during the dugong survey in 2011.

Table 8 – Relative dugong abundance (± standard error) in the southern Great Barrier Reef for 2005, and 2011 based on the Pollock and Hagihara methods.

Block	2005		2011	
	Pollock method	Hagihara method	Pollock method	Hagihara method
S1	zzt	zzt	tfs	tfs
S2	tfs	tfs	0	0
S3	116 (± 64)	134 (± 82)	tfs	tfs
S4	zzt	zzt	dd	dd
S5	898 (± 295)*	611 (± 174)*	254 (± 124)	345 (± 229)
S6	dd	dd	dd	dd
S7	zzt	zzt	0	0
S8	tfs	tfs	tfs	tfs
C1	tfs	tfs	tfs	tfs
C2	ns	ns	dd	dd
C3	tfs	tfs	tfs	tfs
C4	145 (± 86)	74 (± 41)	tfs	tfs
C5	ns	ns	dd	dd
C6	331 (± 190)	173 (± 82)	80 (± 68)	64 (± 52)
C7	tfs	tfs	tfs	tfs
C8	216 (± 129)	193 (± 101)	tfs	tfs
C9	zzt	zzt	tfs	tfs
C10	280 (± 130)	266 (± 165)	168 (± 132)	116 (± 93)
C11	73 (± 50)	107 (± 85)	106 (± 88)	59 (± 53)
C12	zzt	zzt	tfs	tfs
Total	**2059 (± 413)**	**1558 (± 300)**	**608 (± 213)**	**537 (± 223)**

Herds sighted *12, 50, and 70 dugongs

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

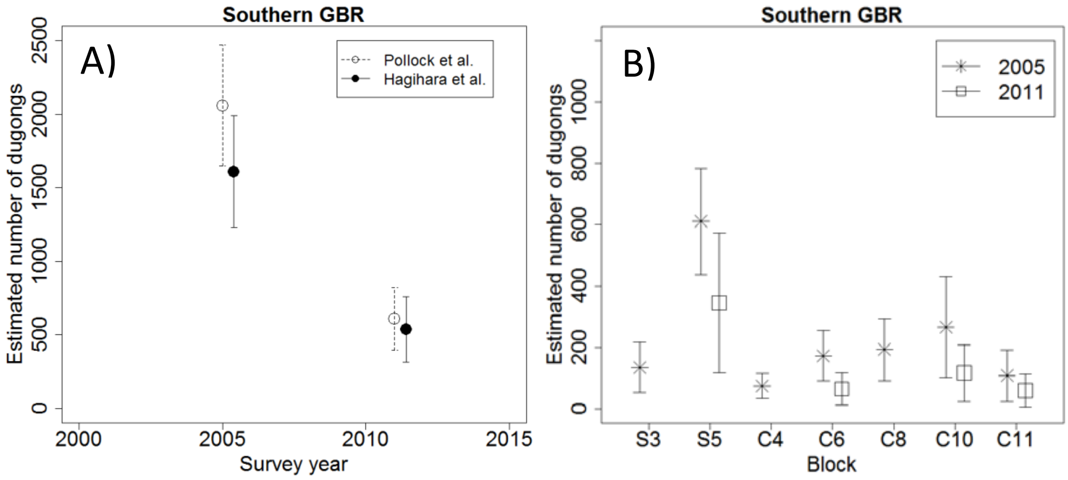

Figure 16 – Population estimates from surveys conducted in 2005, and 2011 based on: A) Pollock method (open circles) and Hagihara method (closed circles) for all southern Great Barrier Reef blocks combined and B) Hagihara method only, blocks plotted separately for each year.

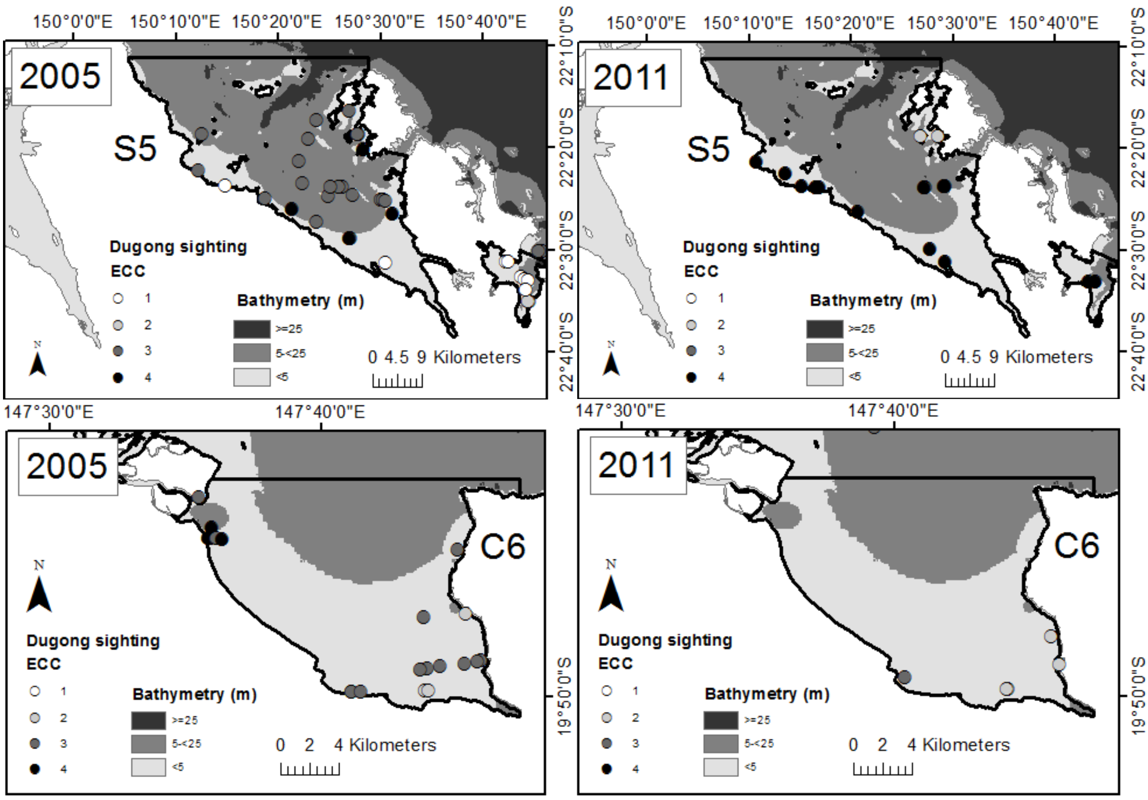

Figure 17 – Distribution of dugong sightings in the southern Great Barrier Reef Region, Blocks S5 (Shoalwater Bay) and C6 (Upstart Bay) in 2005, and 2011 with respect to bathymetry and environmental conditions (ECC). Each dot represents a sighting of a dugong group.

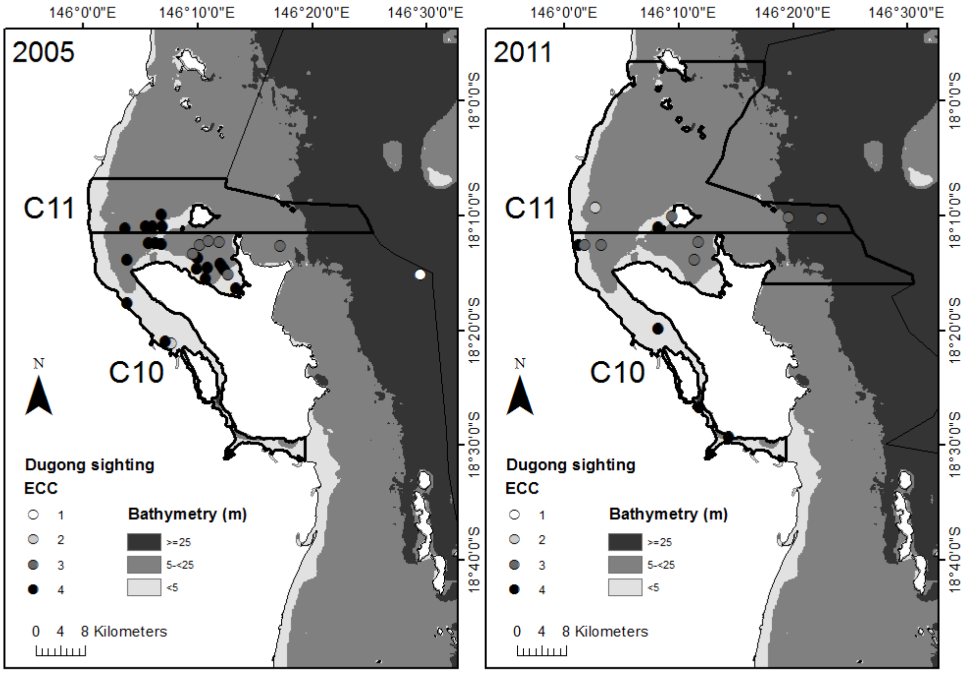

Figure 18 – Distribution of dugong sightings in the southern Great Barrier Reef Region, Blocks C10 and C11 (Hinchinbrook region) in 2005, and 2011 with respect to bathymetry and environmental conditions (ECC). Each dot represents a sighting of a dugong group. Note that the extent of Block C11 differed between years.

3.3.2 Dugong density

The relative dugong densities varied significantly between 2005 and 2011, with the 2011 density being only 19% of the 2005 density (Figure 19). For seven blocks (S3, S5, C4, C6, C8, C10 and C11), the dugong density in 2011 was significantly lower than that of 2005.

The model with Year and Block as main factors was the best model, indicating that there was no significant interaction between years and blocks in the patterns of dugong density. Across years, Blocks S5 (Shoalwater Bay) and C10 (Hinchinbrook) were significantly higher than Blocks S3 (Gladstone), C4 (Bowen area), C8 (Cleveland Bay) and C11 (north of Hinchinbrook). The three highest density blocks in both years 2005 and 2011 were S5, C10 and C6 (Upstart Bay), but the densities of the same blocks differed considerably between the years despite the lack of a significant interaction. In 2005, Block C10 had the highest dugong density, closely followed by S5. The mean dugong densities in these blocks were considerably higher in 2005 than in 2011 (Figure 20). In 2011, Block C10 has only 12% of the density in 2005. A similar pattern was found for Block S5. The highest dugong density in 2011 was found in Block C6, closely followed by S5 and C10 (Figure 20 and 21). The pair-wise comparisons and coefficients tables of the statistical analysis are provided in Appendices 1 and 2.

The population size estimate for Block C10 in 2005 (266 ± 165 dugongs) was lower than the estimate for Block S5 (611 ± 174 dugongs), but the density for Block C10 was higher than that of S5. This result is caused by the different sizes of the blocks: The area of Block S5 was 4.4 times that of Block C10 (1271 km^2 and 288 km^2, respectively). Similarly the surface area of Block S5 (1165 km^2) in 2011 was 5.3 times larger than that of Block C6 (221 km^2), and the population size estimates for this block was 64 ± 52 dugongs while that of Block S5 was 345 ± 229 dugongs.

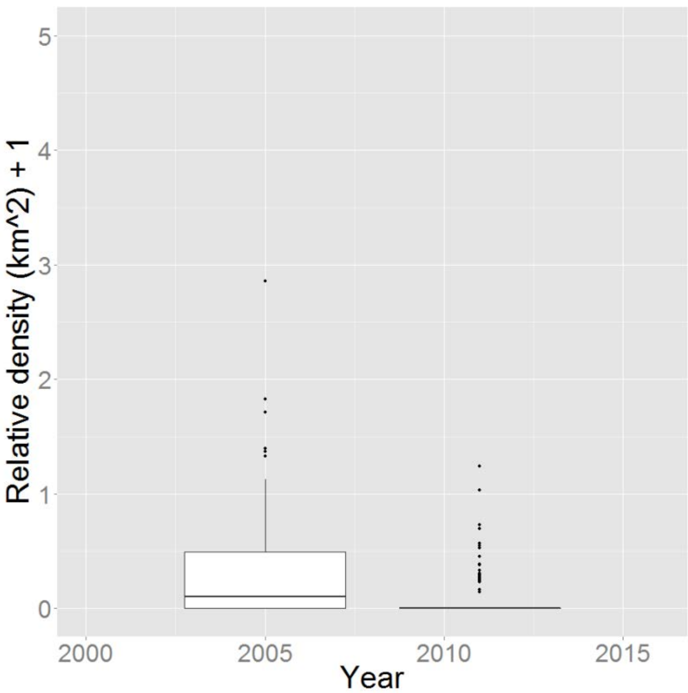

Figure 19 - Relative dugong density on natural logarithm (base 10) estimated using the Hagihara method for aerial surveys in the southern Great Barrier Reef in 2005 and 2011. The figure includes data from Blocks S3, S5, C4, C6, C8, C10 and C11. Error bars represent 95% confidence intervals.

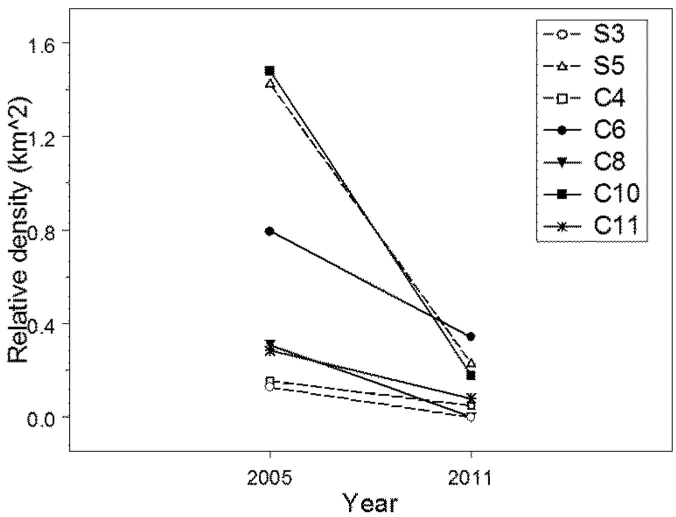

Figure 20 - Dugong relative density in the southern Great Barrier Reef from all blocks and years combined based on data from the Hagihara method.

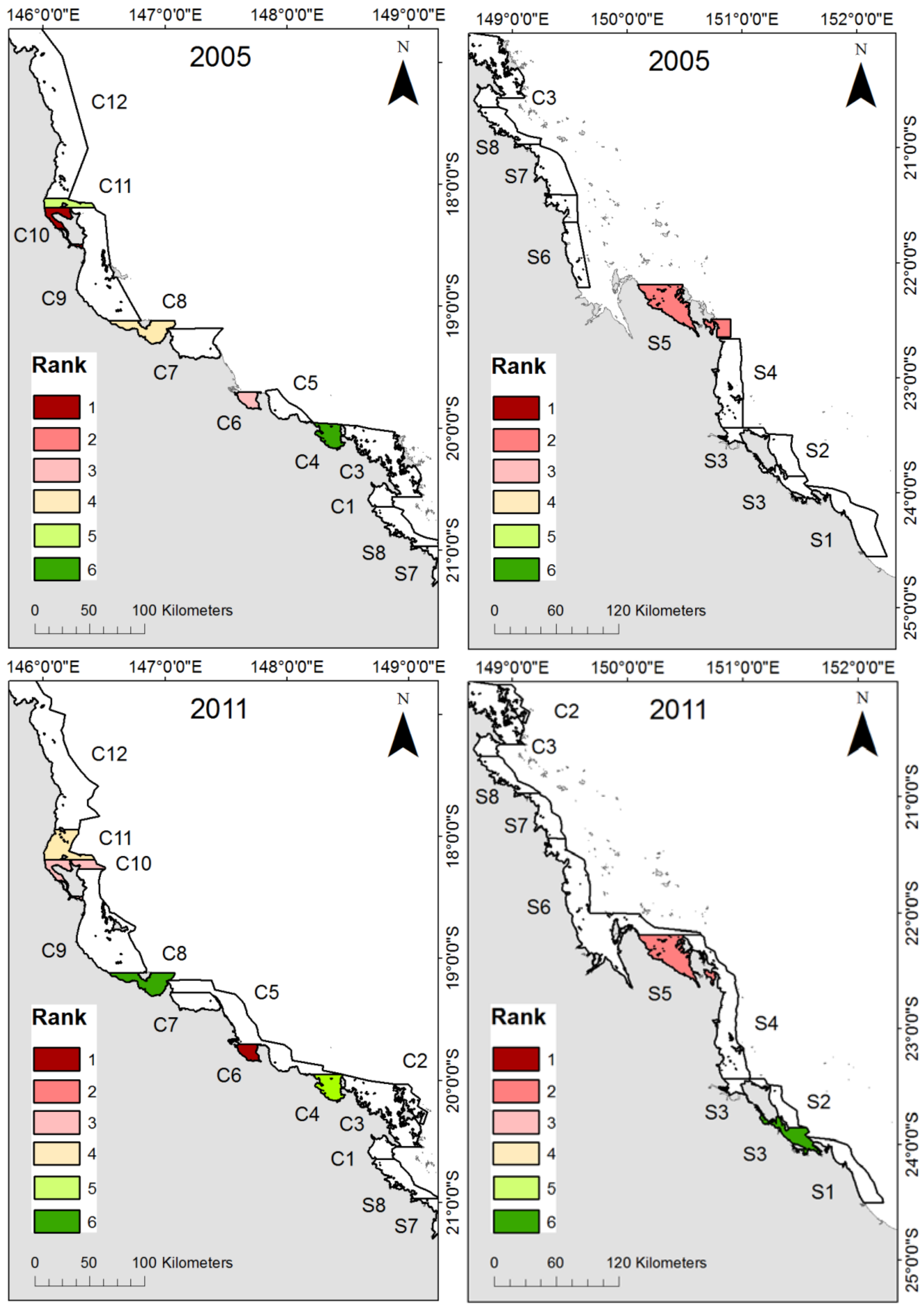

Figure 21 - Ranking of high density blocks in 2005 and 2011 in the southern Great Barrier Reef. The ranking is based on mean dugong relative density in each survey year (Hagihara method). The ranking was based on mean dugong density for each block and year.

3.3.3 Spatial models

The spatially-explicit models of dugong distribution and relative density for the southern Great Barrier Reef show large variation between 2005 and 2011. Overall, the dugong population size decreased from 2005 to 2011 by about two thirds (Table 8) and the 2011 model reflects the low numbers of animals observed. For numerous blocks (e.g. C8, C4, S3), there were too few dugong observations in 2011 for population size estimations (Table 8), so the following results will only concentrate on the blocks for which population size estimations were available for both years.

In Shoalwater Bay (Block S5), the spatially-explicit density model for 2011 shows larger areas of higher dugong densities than the 2005 model (Figure 22A and B), a result which seems to contradict the results of the population size estimations for that block in both years (611 ± 174 dugongs in 2005 and 345 ± 229 dugong in 2011). However, dugong distribution varied between both years with several large groups of dugongs being recorded clumped together in 2011. These aggregations result in the interpolation model predicting further large groups in spaces where data were not collected (i.e. between transects). In 2005, the group size was lower but with a wider spread over a larger area, resulting in the model predicting lower densities in spaces without observation data. The movement of very high density areas from the central to western edge of Shoalwater Bay between 2005 and 2011 could be either: (1) the result of the dugongs responding to tidal movements at the time of survey; or (2) changes in seagrass distribution due to the loss of deepwater seagrass. The data are not available to choose between these two hypotheses. Blocks C6 (Upstart Bay), C10 and C11 (Hinchinbrook Island area) show high dugong density areas in both years (Figure 22 C-F). Areas that had high dugong densities in 2005 but not 2011 (not shown) include around Magnetic Island and Cleveland Bay (Block C8), and the waters around Curtis Island and Rodds Bay (Block S2).

Due to the exceptionally low dugong numbers observed in the southern Great Barrier Reef in 2011 as a result of the extreme weather events in 2010/11 (Sobtzick *et al.,* 2012), we decided not to create a combined model for 2005 and 2011 because such a model would mask the differences between years.

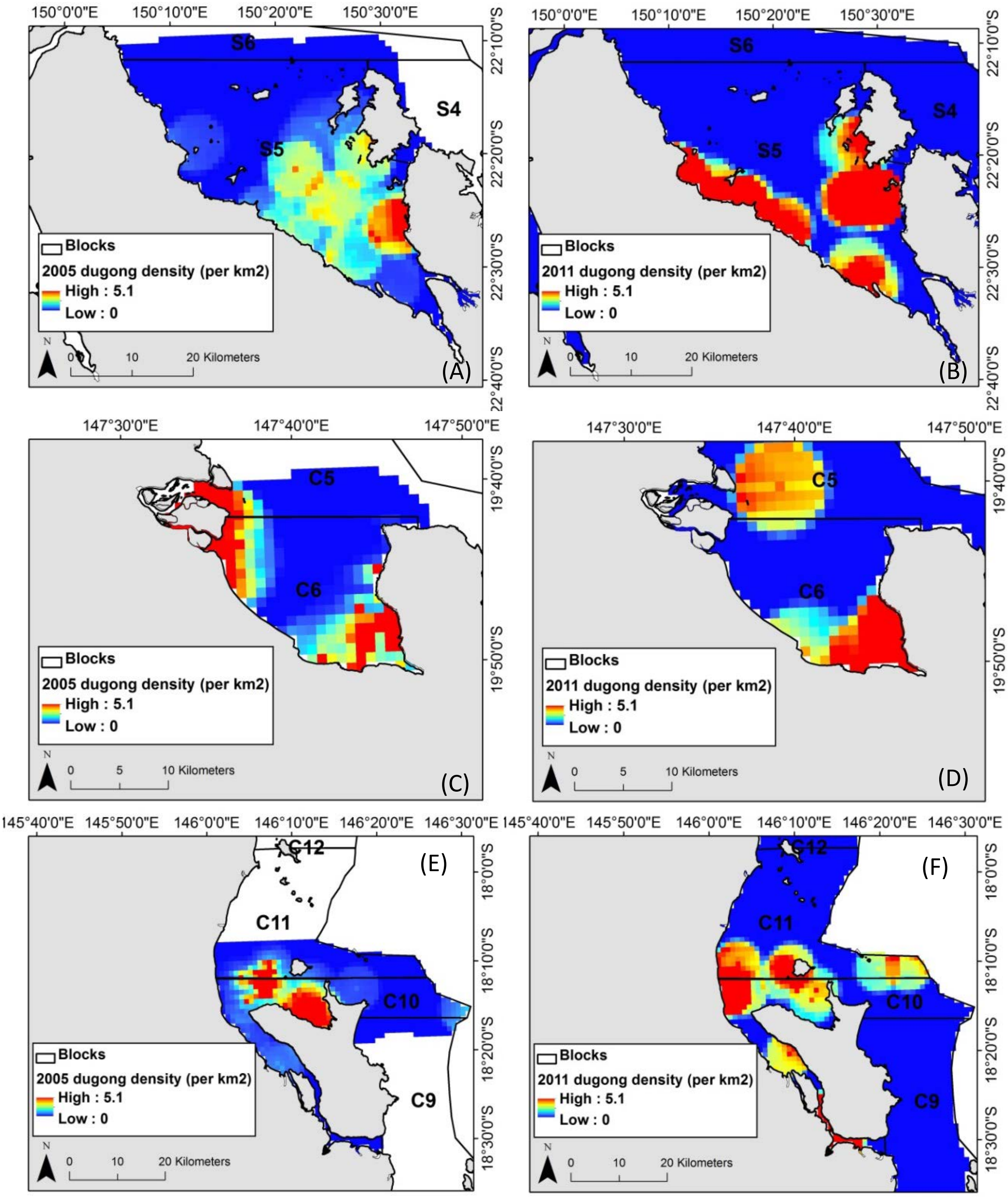

Figure 22 – Spatially-explicit model of dugong relative density in the southern Great Barrier Reef Block S5 in Shoalwater Bay (A and B); Block C6 (Upstart Bay; C and D); and Blocks C10 and C11 (northern end of Hinchinbrook Island; E and F) based on the surveys conducted in 2005 (A, C, and E); and 2011 (B, D, and F).

3.3.4 Sustainable levels of human-caused mortality

In the southern Great Barrier Reef, the total sustainable level of anthropogenic mortalities for the dugong population (assuming the population growth rate is in the middle of the range; R_{max} = 0.03, other values presented in Appendix 3), in 2005 has decreased from 13 animals (using the Pollock method) to ten animals (using the Hagihara method, Table 9). Values for 2011 are identical for both methods with three dugongs.

Table 9 – Estimated sustainable levels of mortalities from anthropogenic sources for dugongs in the southern Great Barrier Reef in 2005, and 2011 using the Potential Biological Removal method (Wade 1998).

Year	Methodology	RF	N	SE	CV	N_{min}	PBR		
							R_{max}= 0.01	R_{max}= 0.03	R_{max}= 0.05
2005	Pollock method	0.5	2059	413	0.201	1742	4	13	22
	Hagihara method	0.5	1610	382	0.237	1322	3	10	17
2011	Pollock method	0.5	608	213	0.350	457	1	3	6
	Hagihara method	0.5	537	223	0.415	384	1	3	5

RF = recovery factor; N = dugong population estimate; SE = standard error; N_{min} = the 20th percentile of a log-normal distribution based on N; PBR = potential biological removal; R_{max} = maximum rate of increase

3.4 Northern Great Barrier Reef

3.4.1 Population estimates

Survey blocks for 2006 and 2013 are displayed in Figure 23. For the 2006 survey, the Hagihara method resulted in smaller dugong population estimates than the Pollock method (6787 ±1281 and 8812 ±1769 dugongs, respectively, Table 10 and Figure 24). The 2006 surveys had 29% of sightings under ECC 2 or 4 and water depth 5 ≤ 25m, both of which have lower availability detection probabilities than the Pollock method (Figure 2). In 2013, Hagihara estimates were also smaller than the Pollock estimates (4517 ± 789 and 6558 ±1141 dugongs, respectively, Table 10 and Figure 24). In contrast to 2006, only 14% of all dugong sightings in 2013 were recorded in ECC 2 and ECC 4 and a water depth of 5 ≤ 25m, whereas 37% of sightings were in ECC 3, with a water depth of 5-<25 m, for which the Hagihara availability probability was higher than the constant availability probability of the Pollock method.

Similar population size estimates for both methodologies were calculated in blocks with large numbers of dugong sightings recorded in sightability classes 4 and 12 (ECC 2 and 4 and water depth 5 to <25m, see Table 2). For instance, the 2006 dugong sightings from Block N2 resulted in very similar abundance estimates for both methodologies (Pollock method.: 1293 ± 466 dugongs; Hagihara method: 1292 ± 391 dugongs) (Table 10 and Figure 25). This block had about half of all sightings (45%) in 2006 recorded in sightability classes 4 and 12. In 2013, none of the 60 dugong sightings in this block were recorded for sightabiliy classes 4 and/or 12, and population estimates for the Hagihara method were lower than for the Pollock method (563 ± 194 and 820 ± 278 dugongs, respectively).

In 2006, the difference between methodologies in the estimated numbers in Block N5 was large (Hagihara method 39% lower than Pollock method, Table 10 and Figure 26), for two reasons: (1) 26% of sightings (23 out of 89) were in sightability class 8 (see above); and (2) 12% of sightings (11 out of 89) were in sightability class 6 (ECC 3 and water depth <3.5 m). This sightability class has an availability probability of '1' for the Hagihara method, and sightings were therefore not corrected, resulting in lower population estimates for the Hagihara method than for the Pollock method.

Large differences between methodologies for the estimated dugong population size were found in blocks where a large number of dugong sightings were recorded in sightabilility class 8 (ECC 3 and water depth 5 to <25m). The Hagihara availability probability in this sightability class is higher than the one using the Pollock method, resulting in lower estimates. For example, the estimated population size in 2006 for Block N8 based on the Pollock method was 1407 ± 725 dugongs, whereas the Hagihara method resulted in 848 ± 422 (Table 10 and Figure 27). The difference between the two estimates is smaller in 2013 (25% dugongs fewer in block N8 for the Hagihara method). Nonetheless, there was a high proportion of dugong sightings in sightability class 8 for this Block in both years 97% in 2006 and 68% in 2013.

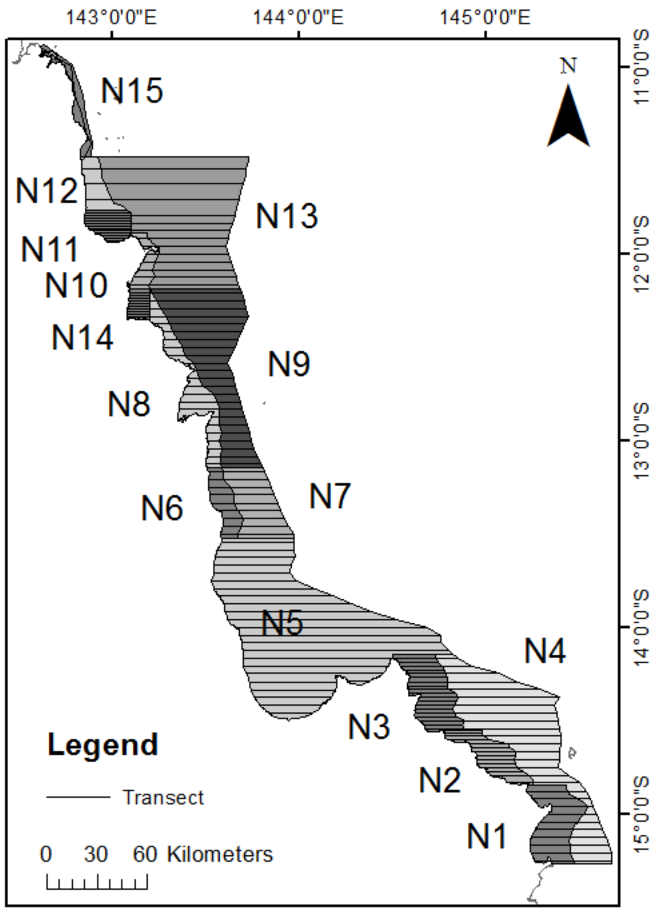

Figure 23 – Survey blocks and transects flown in the northern Great Barrier Reef Region during the dugong aerial surveys.

Table 10 – Relative dugong abundance (± standard error) in the northern Great Barrier Reef for 2006, and 2013 based on the Pollock and Hagihara methods.

Block	**2006** Pollock method	**2006** Hagihara method	**2013** Pollock Method	**2013** Hagihara method
N1	tfs	Tfs	Tfs	tfs
N2	1293 (± 466)[*]	1292 (± 391)[*]	820 (± 278)[#]	563 (± 194)[#]
N3	498 (± 249)	399 (± 165)	1077 (± 612)	630 (± 343)
N4	1629 (± 693)[**]	1631 (± 811)[**]	973 (± 367)	613 (± 202)
N5	3061 (± 1333)	1964 (± 769)	1990 (± 675)	1403 (± 509)
N6	tfs	tfs	504 (± 306)	408 (± 251)
N7	tfs	tfs	Tfs	tfs
N8	1407 (± 725)	848 (± 422)	979 (± 394)	731 (± 311)
N9	tfs	tfs	Tfs	tfs
N10	tfs	tfs	Tfs	tfs
N11	293 (± 116)	254 (± 100)	108 (± 71)	111 (± 72)
N12	tfs	tfs	Tfs	tfs
N13	492 (± 211)	309 (± 139)	0	0
N14	139 (± 106)	90 (± 60)	107 (± 75)	58 (± 41)
N15	tfs	tfs	0	0
Total	**8812 (± 1769)**	**6787 (± 1281)**	**6558 (± 1141)**	**4517 (± 789)**
Herds sighted	[*]20,20,15 and 27 dugongs [**]10 dugongs		[#] 49 dugongs	

tfs – too few sightings for population estimations

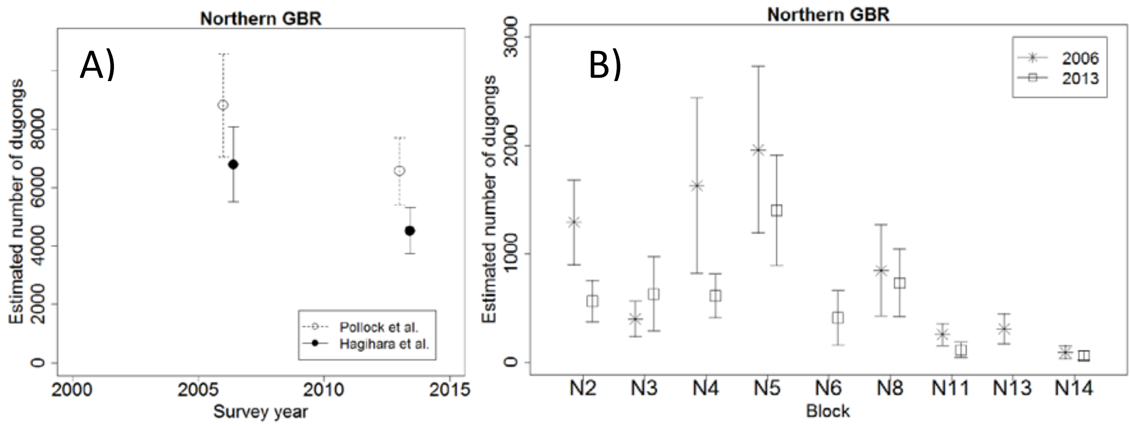

Figure 24 – Population estimates for surveys conducted in 2006, and 2013 based on A) Pollock method (open circles) and Hagihara method (closed circles) for all northern Great Barrier Reef blocks combined and B) Hagihara method only, blocks plotted separately for each year.

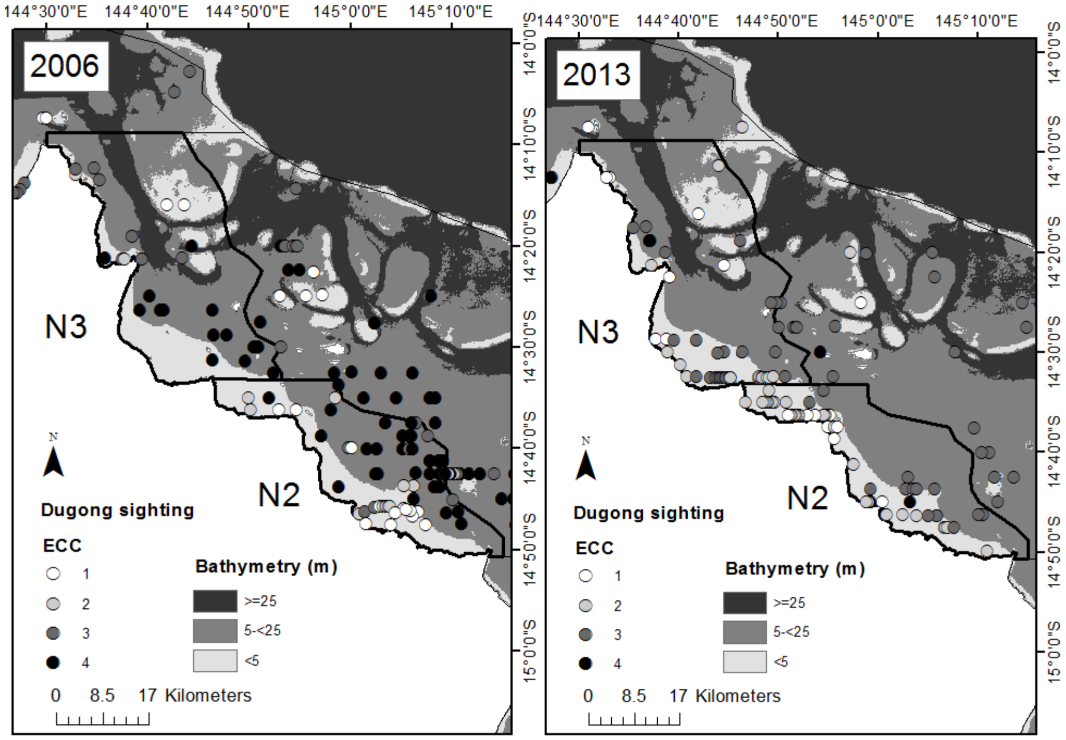

Figure 25 – Distribution of dugong sightings in the northern Great Barrier Reef Region, Blocks N2 and N3 (inshore Starcke River to Cape Melville region) in 2006, and 2013 with respect to bathymetry and environmental conditions (ECC). Each dot represents a sighting of a dugong group.

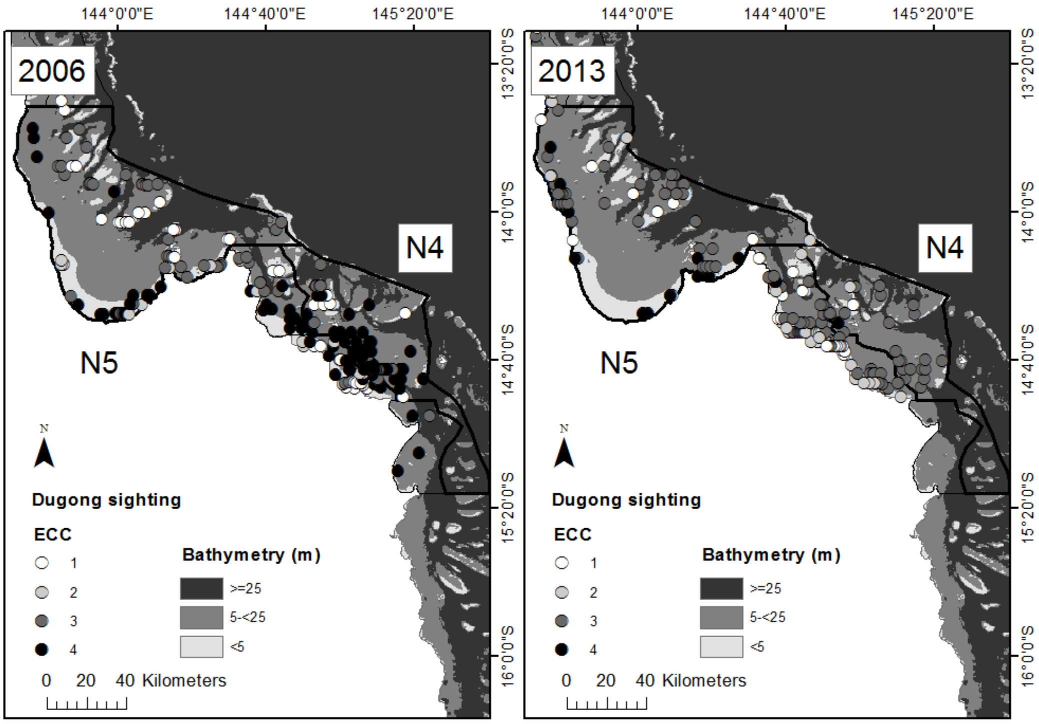

Figure 26 – Distribution of dugong sightings in the northern Great Barrier Reef Region, Blocks N4 (offshore Starcke River to Cape Melville) and N5 (Princess Charlotte Bay) in 2006, and 2013 with respect to bathymetry and environmental conditions (ECC). Each dot represents a sighting of a dugong group.

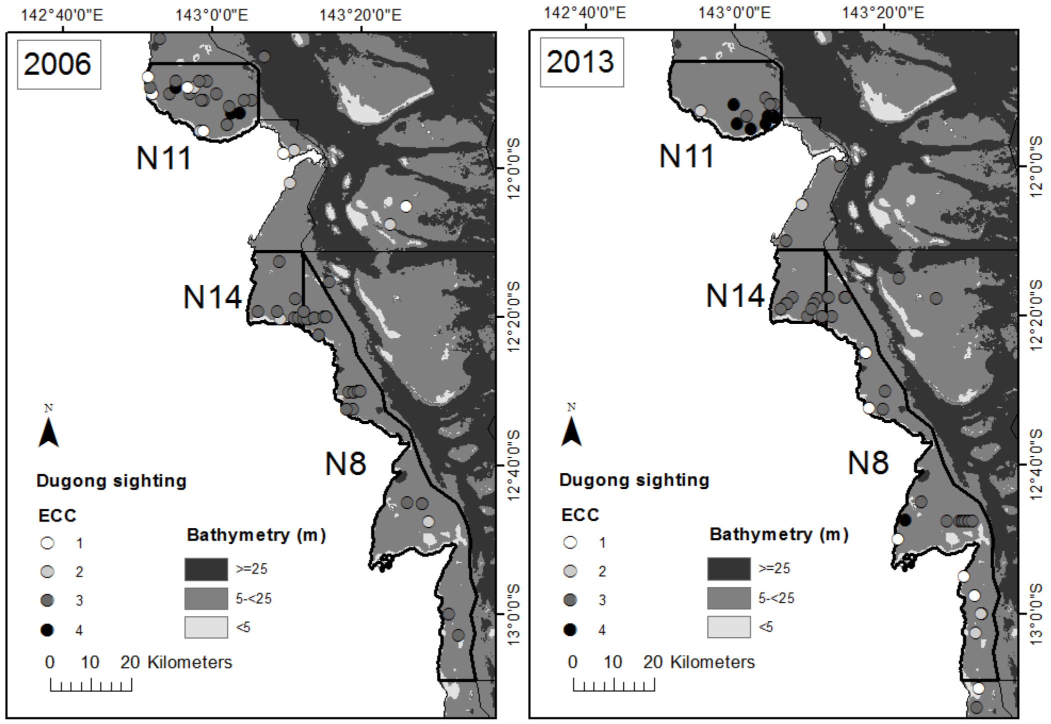

Figure 27 – Distribution of dugong sightings in the northern Great Barrier Reef Region, Blocks N8, N11, and N14 in 2006, and 2013 with respect to bathymetry and environmental conditions (ECC). Each dot represents a sighting of a dugong group.

3.4.2 Dugong density

Although dugong relative density in 2013 was slightly lower than that of 2006, no significant difference between 2006 and 2013 was found in the northern Great Barrier Reef region (Figure 28).

The model with Year, Block and their interaction was significantly superior to the model with Year and Block as main factors only, indicating the patterns of dugong density in the northern Great Barrier Reef blocks differed between 2006 and 2013. Block N2 had the highest density of dugongs in the survey region in both years. In 2006, the second highest mean density block was N8, and the third highest density block was block N11 (Figures 29 and 30). In 2011, the density of Block N2 was only 68% of its 2005 density. The second highest density block was N6, which had a 3.9 times higher density in 2011 than in 2005. Tables of the pair-wise comparisons and coefficient of the statistical analysis are provided in Appendices 1 and 2.

The population size estimate for Block N2 in 2011 (563 ± 194 dugongs) was lower than the estimate for Block N5 (1403 ± 509 dugongs), but the density for Block N2 was higher than that of N5 as a result of the different sizes of the blocks: Block N5 had 10.7 times more surface area than Block N2 (7276 km^2 and 677 km^2, respectively).

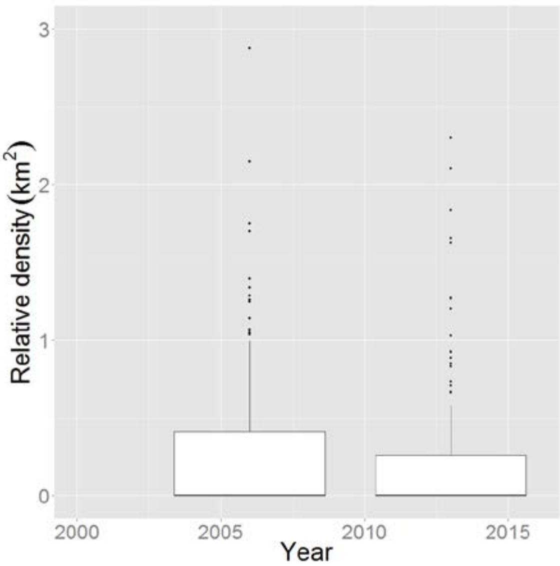

Figure 28 - Relative dugong density on natural logarithm (base 10) estimated in the northern Great Barrier Reef from 2006 and 2013 aerial surveys using the Hagihara method. The figure includes all data. Error bars represent 95% confidence intervals.

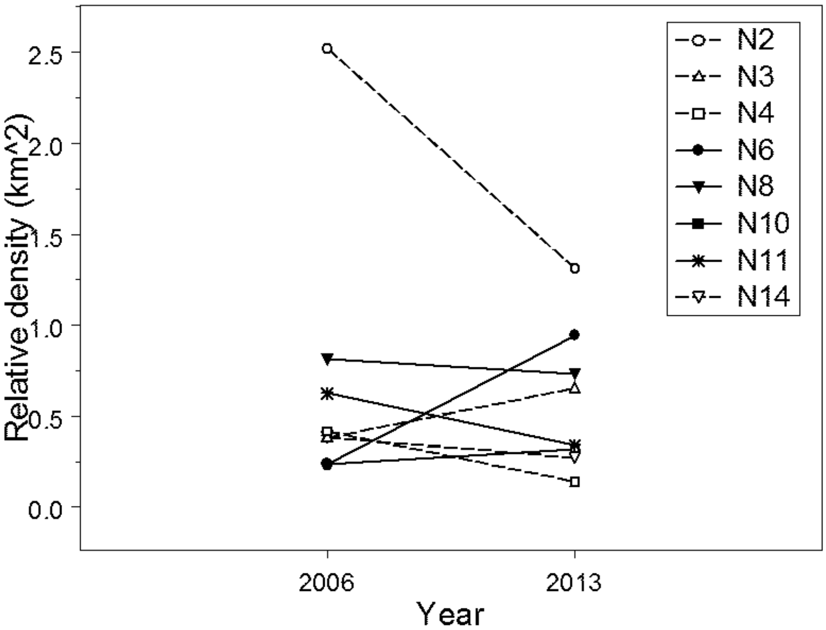

Figure 29 - Dugong relative density from blocks that had higher density for the northern Great Barrier Reef based on the Hagihara method. Not all blocks are shown.

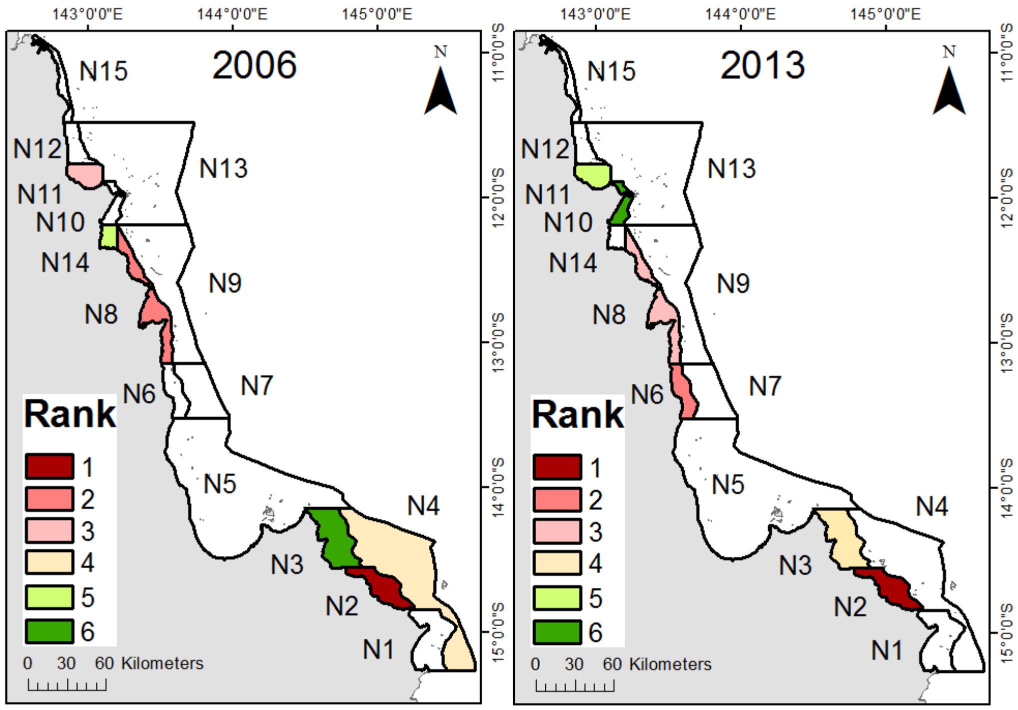

Figure 30 – Ranking of high density blocks in 2006 and 2013 in the northern Great Barrier Reef. The ranking is based on mean dugong relative density in each survey year based on the Hagihara method. The ranking was based on mean dugong density for each block and year.

3.4.3 Spatial models

The spatially-explicit models of relative dugong density and distribution in the northern Great Barrier Reef showed slight differences between 2006 and 2013 (Figure 31). In accordance with the population size estimations, Block N2 had fewer high density areas in 2013 than in 2006, while the number of high density area cells in Block N3 in 2013 exceeded that in 2006. In Princess Charlotte Bay (Block N5), dugongs appeared to have preferred the western coastal areas in 2013 as opposed to the more central distribution observed in 2006. The northern blocks (N8-N14) had generally fewer high density areas in 2013 than in 2006.

The spatial model that incorporated data from both aerial surveys (Figure 32 and Table 11) showed very high and high dugong relative densities in most of the coastal blocks (N2, N3, N4, N6, N8, N11) and on the large reefs in Princess Charlotte Bay (Block N5). Specific regions of very high dugong relative density were between Cape Flattery and Cape Bowen (Blocks N2-N4); Bathurst Bay (eastern Block N5); reefs in Princess Charlotte Bay (Block N5); between Princess Charlotte Bay and around Friendly Point (coastline of Blocks N5-N7); as well as Lloyd, Temple, and Shelburne Bays (Blocks N8, N14 and N11, respectively). Overall, 24% of the northern Great Barrier Reef region was classified as having high to very high relative dugong densities.

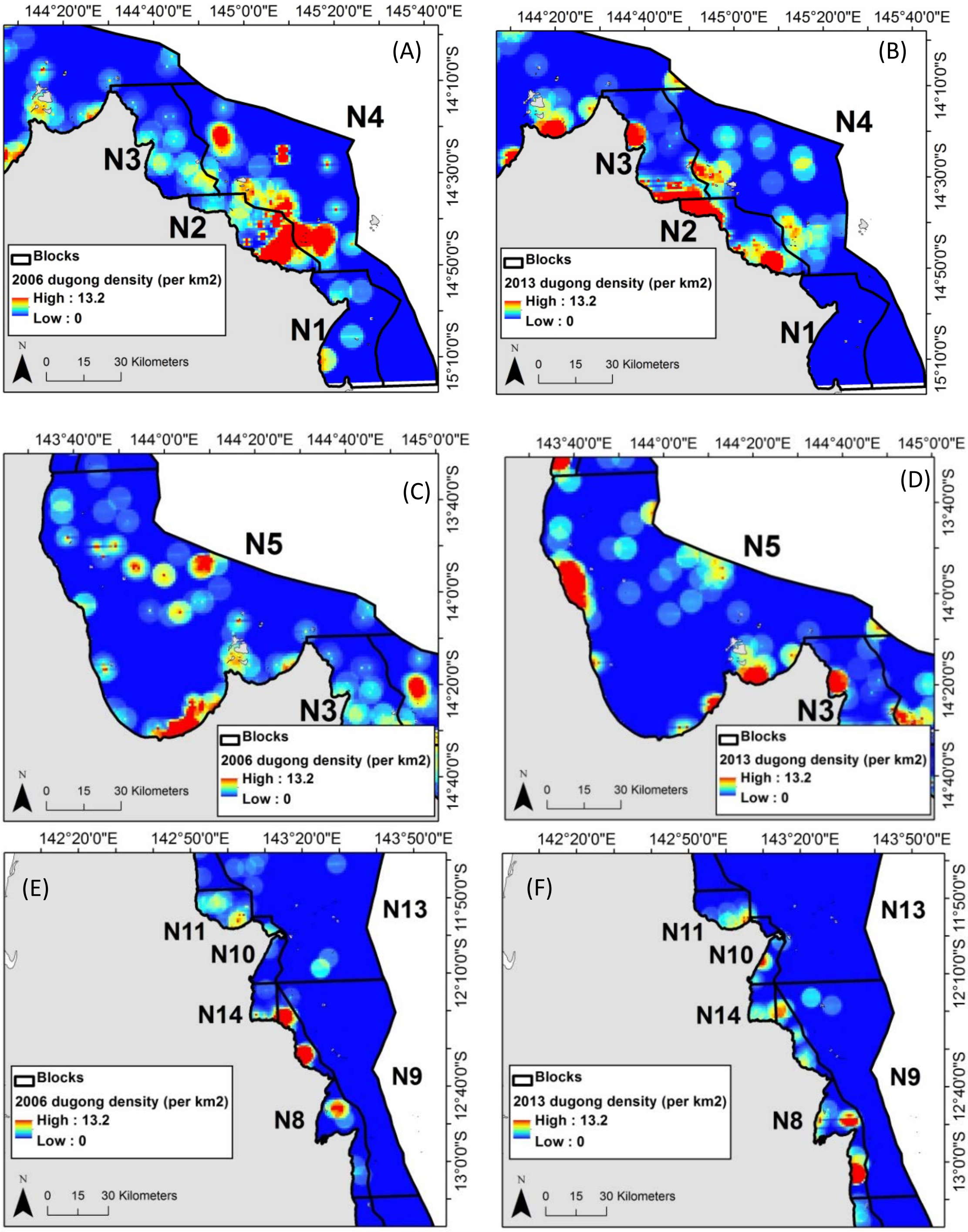

Figure 31 – Spatially-explicit model of dugong relative density in the northern Great Barrier Reef Blocks N1-N4 (A and B); Block N5 (C and D); and Blocks N8, N11, and N14 (E and F) conducted in 2006 (A, C, and E); and 2013 (B, D, and F). Data based on the Hagihara method.

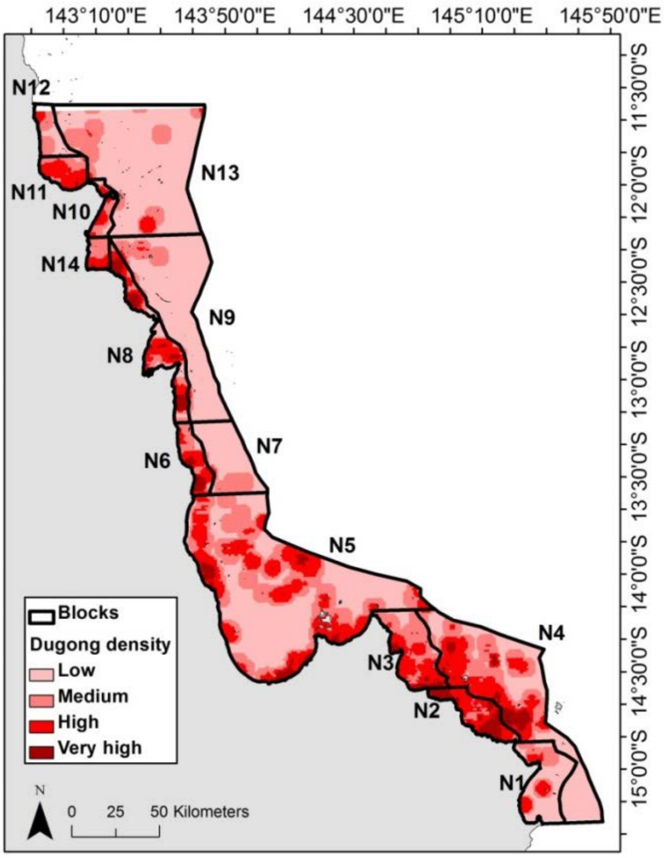

Figure 32 - Spatially-explicit model of dugong relative density in the northern Great Barrier Reef for the 2005 and 2011 survey years combined.

Table 11 – Total area (km^2) and size of dugong density classes of low, medium, high and very high relative density predicted by the spatially explicit model (Figure 32) in different blocks in the northern Great Barrier Reef (nGBR) covered by the 2006 and 2013 aerial survey.

	Size of relative dugong density class (in km^2)				**Total Area (km^2)**
Block	**Low**	**Medium**	**High**	**Very high**	
N1	588	252	152	0	992
N2	0	73	310	274	657
N3	81	439	415	94	1029
N4	1447	951	893	249	3540
N5	3121	2144	1661	246	7172
N6	31	152	179	82	444
N7	783	259	20	0	1062
N8	154	222	358	191	925
N9	2495	358	45	0	2898
N10	41	124	92	2	259
N11	13	137	259	11	420
N12	150	161	32	0	343
N13	3440	724	100	0	4264
N14	4	120	78	11	213
Entire nGBR	**12348 (51%)**	**6116 (25%)**	**4594 (19%)**	**1160 (5%)**	**24218 (100%)**

3.4.4 Sustainable levels of human-caused mortality

After the Gulf Carpentaria, the northern Great Barrier Reef Region consistently had the second highest population size estimates of all regions considered in this report. Consequently, the estimated sustainable levels of dugong mortalities from anthropogenic sources in that Region were much higher than in most of the other Regions. PBR estimates (assuming the population growth rate is in the middle of the range; R_{max} = 0.03, other values presented in Appendix 3) for the Pollock method were 56 dugongs in 2006 and 43 dugongs in 2013, while estimates for the Hagihara method were 43 and 29 dugongs, in 2006 and 2013, respectively (Table 12).

Table 12 – Estimated sustainable levels of mortalities from anthropogenic sources for dugongs in the northern Great Barrier Reef in 2006, and 2013 using the Potential Biological Removal method (Wade 1998).

Year	Methodology	RF	N	SE	CV	N_{min}	PBR		
							R_{max}= 0.01	R_{max}= 0.03	R_{max}= 0.05
2006	Pollock method	0.5	8812	1769	0.201	7454	19	56	93
	Hagihara method	0.5	6787	1281	0.189	5798	14	43	72
2013	Pollock method	0.5	6558	1141	0.174	5671	14	43	71
	Hagihara method	0.5	4517	789	0.175	3904	10	29	49

RF = recovery factor; N = dugong population estimate; SE = standard error; N_{min} = the 20th percentile of a log-normal distribution based on N; PBR = potential biological removal; R_{max} = maximum rate of increase

3.5 Gulf of Carpentaria

3.5.1 Population estimates

In 2006, only two Blocks along the Queensland coastline of the Gulf of Carpentaria were surveyed (Blocks QLD 5 and 6), with one of them (Block QLD 6) surveyed following a zig zag transect that did not allow population estimates to be calculated. As a result, the 2006 survey has been excluded from the following analyses.

In 2007, the estimated size of the dugong population in the Gulf of Carpentaria using the Hagihara method was only 76% of the Pollock estimate (9438 ± 1419 dugongs and 12438 ± 1951 dugongs, respectively, Table 13 and Figure 33). All blocks except NT7 resulted in lower dugong population estimates using the Hagihara method. The largest difference was found in Block QLD2 (difference of 968 dugongs). Although 47% of all dugong sightings in Block QLD2 (64 out of 135 sightings) were sighted under ECC 4 (Figure 34, bottom left), only 7% of the sightings were from waters 5-<25m deep, for which the depth-specific availability probabilities using the Hagihara method were lower than the constant probability using the Pollock method (Figure 2). A large proportion of area in this block was shallow and 77% of sightings (105 out of 135) were in water < 1.5 m deep where dugong sightings for all three ECC (2, 3, and 4) were not corrected with depth-specific availability probabilities.

The population size estimates for Block NT7 were larger for the Hagihara method than for the Pollock method (456 ± 196 and 389 ± 174 dugongs, respectively; Table 13). This result was caused by

63% of all dugong sightings occurring in sightability class 12 (ECC 4 and water depth 5 to <25 m deep; Figure 34 bottom right), for which the depth-corrected availability detection probability was lower than the constant probability.

Table 13 – Relative dugong abundance (± standard error) in the Gulf of Carpentaria for 2006, and 2007 based on the Pollock and Hagihara methods.

Block	2006 Pollock method	2006 Hagihara method	2007 Pollock method	2007 Hagihara method
NT1[1]	ns	ns	556 (± 376)	302 (± 193)
NT2	ns	ns	1702 (± 936)	903 (± 468)
NT3	ns	ns	612 (± 281)	343 (± 152)
NT4	ns	ns	555 (± 251)	401 (± 179)
NT5	ns	ns	994* (± 372)	1026* (± 404)
NT6	ns	ns	534 (± 165)	526 (± 192)
NT7	ns	ns	389 (± 174)	456 (± 196)
NT total			5343 (± 1164)	3957 (± 742)
QLD1[1]	ns	ns	1340 (± 749)	1232 (± 666)
QLD2	ns	ns	4304 (± 1223)	3336 (± 944)
QLD3	ns	ns	434 (± 356)	274 (± 199)
QLD4	ns	ns	1017 (± 516)	639 (± 299)
QLD5	55 (± 24)	283 (± 93)	Tfs	tfs
QLD6	zzt	zzt	Tfs	tfs
QLD total	55 (± 24)	283 (± 93)	7095 (± 1565)	5481 (± 1210)
Total	**55 (± 24)**	**283 (± 93)**	**12438 (± 1951)**	**9438 (± 1419)**
Herds sighted			* 13 dugongs	

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

[1]QLD = Queensland; NT= Northern Territory

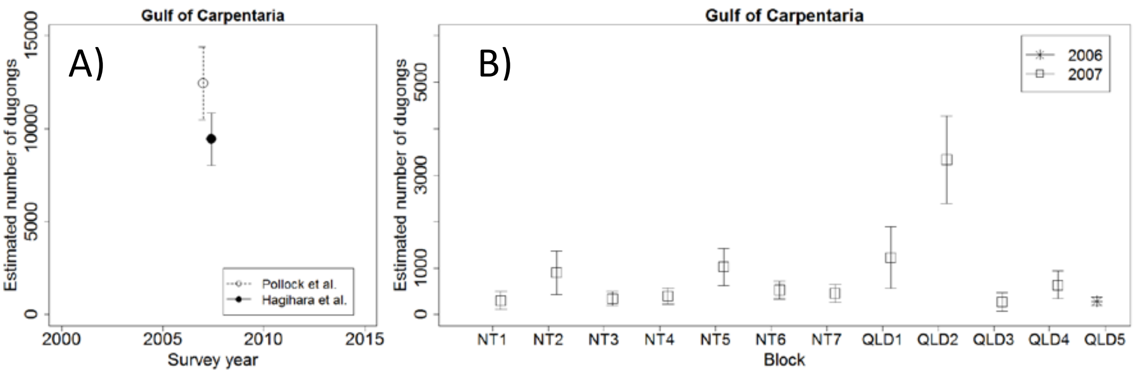

Figure 33 – Population estimates from surveys conducted in 2006, and 2007 based on A) Pollock method (open circles) and Hagihara method (closed circles) for all Gulf of Carpentaria blocks combined and B) Hagihara method only, blocks plotted separately for each year.

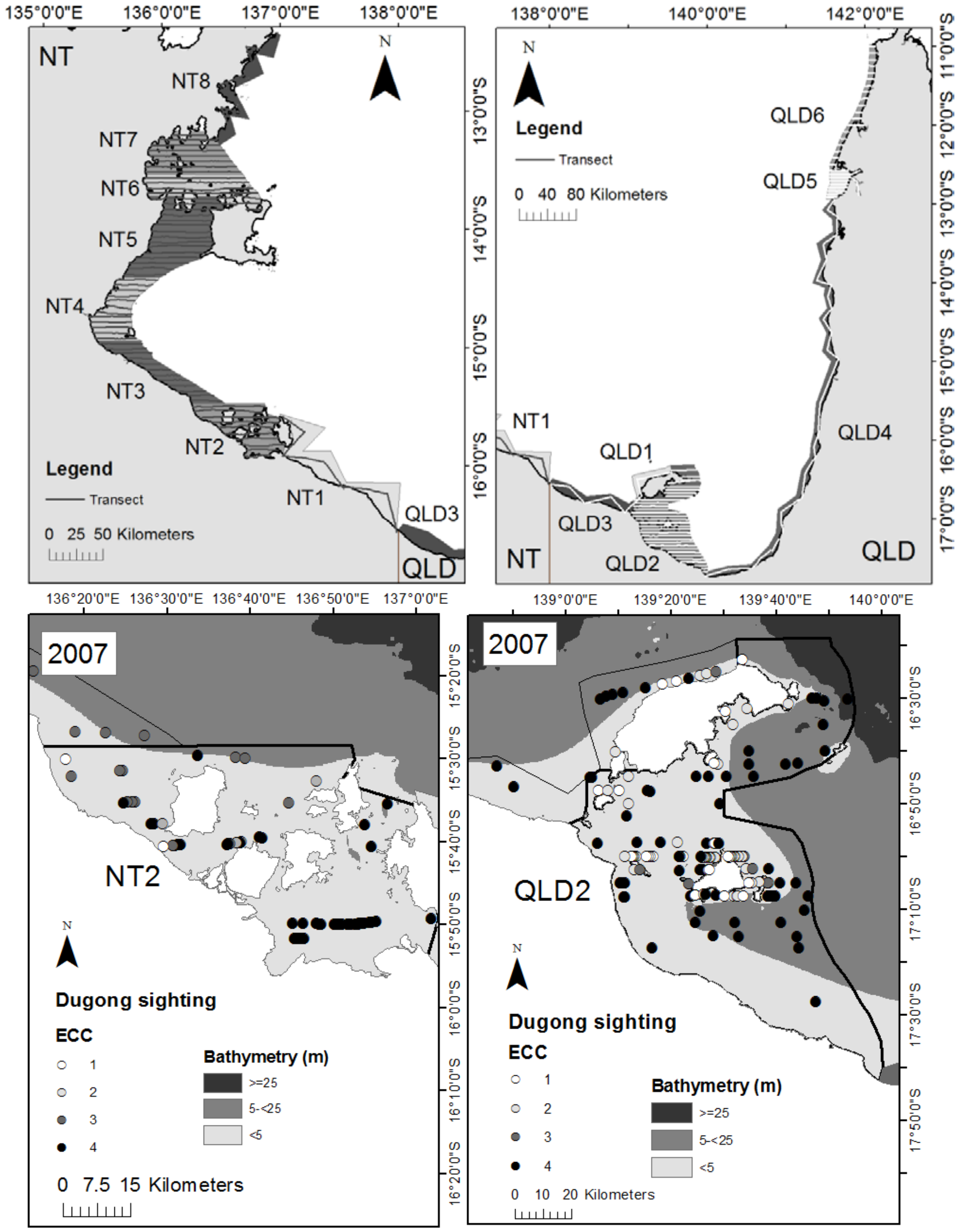

Figure 34 – Survey blocks in the Northern Territory (top left) and Queensland (top right) and distribution of dugong sightings in the Gulf of Carpentaria Region, Blocks NT2 (Sir Edward Pellew Islands, bottom left) and QLD2 (south-eastern Wellesley Islands, bottom right) in 2007, with respect to bathymetry and environmental conditions (ECC). In 2006, only two QLD blocks were surveyed (QLD 5 and QLD6). Each dot represents a sighting of a dugong group.

3.5.2 Dugong density

Dugong population sizes estimates were available for only one survey year (Figure 35; in 2006 only two Blocks were surveyed). Therefore, a between Years comparison was not possible and only between blocks densities could be compared.

A zero-inflated negative binomial model with Block as a main factor was significantly superior to a null model. The result indicates that dugong density significantly differed among blocks. The highest density block in 2007 was QLD1 (mean density of 1.28 dugongs/km^2, Figure 36). Block QLD1 (western side of Mornington Island) had a significantly higher dugong density than any of the other blocks. The second and the third highest density blocks were NT2 (Sir Edward Pellow Islands and QLD2 (south-eastern Wellesley Islands). Tables of pair-wise comparisons and the coefficient of the statistical analysis are provided in Appendices 1 and 2.

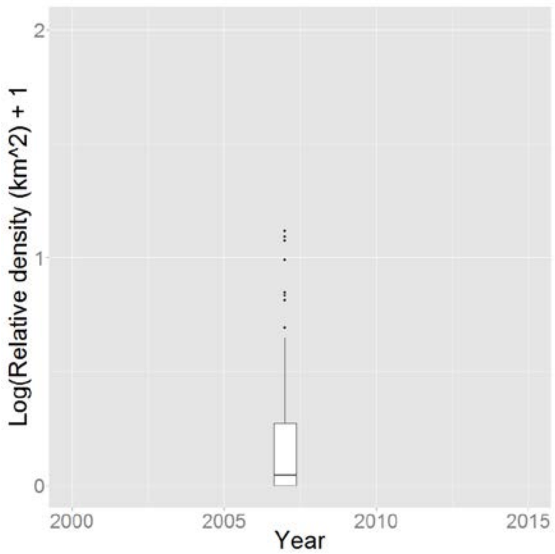

Figure 35 - Relative dugong density on natural logarithm (base 10) in the Gulf of Carpentaria in 2007. The figure includes all data generated using the Hagihara method. Error bars represent 95% confidence interval.

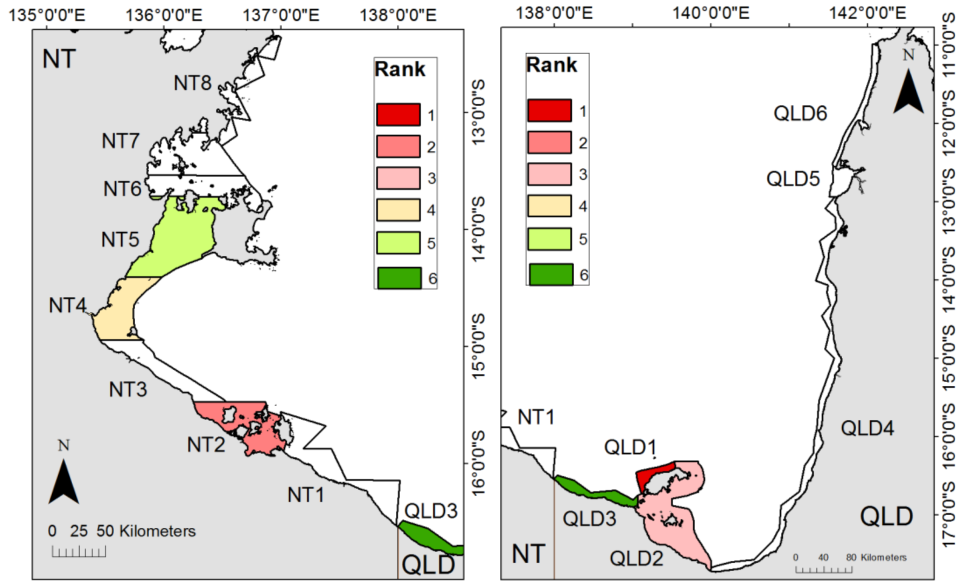

Figure 36 – Ranking of the blocks supporting high densities of dugongs in 2007 in the Gulf of Carpentaria. The ranking was based on mean dugong density from each block.

3.5.3 Spatial models

The spatially-explicit dugong relative density model for the Gulf of Carpentaria shows that along the Northern Territory coastline, areas of high and very high dugong densities are frequent, with Blocks NT2-NT7 showing large areas of high and very high dugong density (Table 14). Along the Queensland coast, areas of high and very high dugong density occur primarily in Blocks QLD 1 and 2 (around the Wellesley Islands, Figure 37).

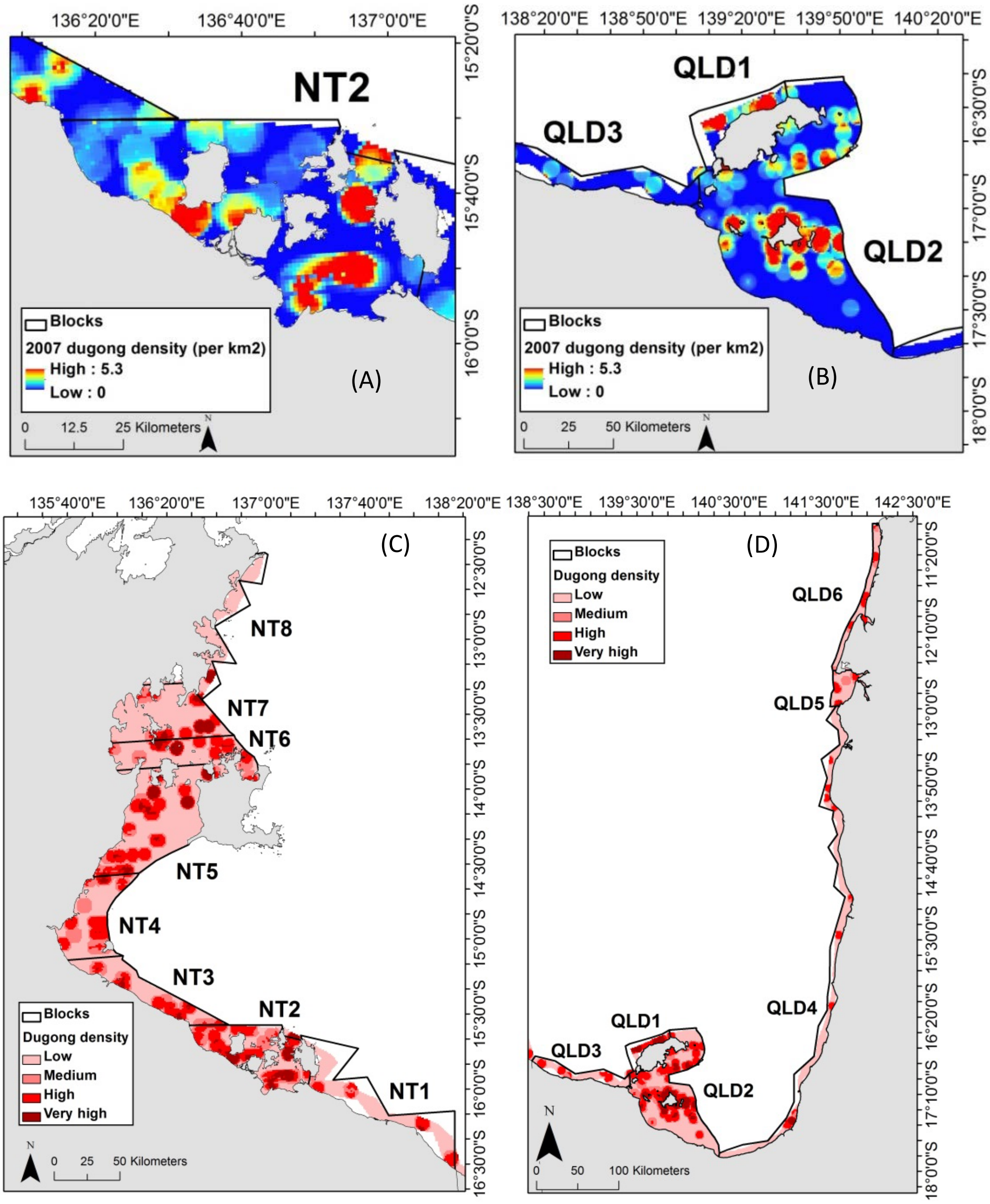

Figure 37 – Spatially-explicit model of dugong relative density in 2007 in the Gulf of Carpentaria Region Block NT2 (A); and Blocks QLD1 and 2 (B); and for the entire Northern Territory coastline (C) and Queensland coastline (D) for 2006 and 2007 combined. Densities generated using the Hagihara method.

Table 14 – Total area (km^2) and size of dugong density classes of low, medium, high and very high relative density predicted by the spatially explicit model (Figure 37) in different blocks in the Gulf of Carpentaria (GoC) covered by the 2006 and 2007 aerial survey.

Block	Size of relative dugong density class (in km^2)				Total Area (km^2)
	Low	Medium	High	Very high	
NT1	1108	150	231	16	1505
NT2	559	474	739	310	2082
NT3	815	292	384	61	1552
NT4	898	543	486	36	1963
NT5	2158	480	854	313	3805
NT6	1022	409	468	135	2034
NT7	1737	252	280	195	2464
NT8	912	13	11	62	998
QLD1	62	31	141	197	431
QLD2	3069	1123	1950	803	6945
QLD3	668	158	297	9	1132
QLD4	3361	206	413	88	4068
QLD5	677	237	183	29	1126
QLD6	919	185	293	32	1429
Entire GoC	**17969 (57%)**	**4553 (15%)**	**6730 (21%)**	**2268 (7%)**	**31534 (100%)**

3.5.4 Sustainable levels of human-caused mortality

Dugong population size estimates for the Gulf of Carpentaria in 2007 were high relative to the other survey areas: 12438 (±1951) dugongs (Pollock method); and 9438 (± 1419) dugongs (Hagihara method). Consequently, estimates for the total sustainable level of anthropogenic mortalities for the dugong population (assuming the population growth rate is in the middle of the range; R_{max} = 0.03, other values presented in Appendix 3) were also relatively high: 82(Pollock) and 62 (Hagihara) dugongs for both methods (Table 15).

Table 15 – Estimated sustainable levels of mortalities from anthropogenic sources for dugongs in the Gulf of Carpentaria in 2007 using the Potential Biological Removal method (Wade 1998).

Year	Methodology	RF	N	SE	CV	N_{min}	PBR R_{max}= 0.01	PBR R_{max}= 0.03	PBR R_{max}= 0.05
2007	Pollock method	0.5	12438	1951	0.157	10908	27	82	136
	Hagihara method	0.5	9438	1419	0.150	8322	21	62	104

RF = recovery factor; N = dugong population estimate; SE = standard error; N_{min} = the 20th percentile of a log-normal distribution based on N; PBR = potential biological removal; R_{max} = maximum rate of increase

4 DISCUSSION

4.1 Improved relative abundance estimations

Both environmental conditions and animal behaviour are typically heterogeneous across wildlife surveys and accounting for these factors should improve survey methodologies and lead to more accurate population estimates. Few studies account for heterogeneity in diving behaviour (e.g., Schweder *et al*. 1991a,b; Laake *et al*. 1997; Edwards *et al*. 2007), and fewer studies have examined the effect of both heterogeneous environmental and diving behaviour on availability bias (e.g. Thomson *et al.* 2012; Hagihara *et al*. 2014; Fuentes *et al*. 2015).

Using spatially heterogeneous corrections for availability bias should assist in correcting for shifts in the spatial distribution of a target population within a survey area between surveys (Marsh 1995). For coastal species such as dugongs, both the environmental conditions (especially water turbidity) and the depth of water can vary greatly even within a single transect, particularly if the transect is across a depth gradient (as is usual in coastal surveys to increase the precision of the population estimate). The Pollock method attempted to correct for differences in environmental conditions between surveys but did not account for changes in availability bias resulting from shifts in dugong distribution across the depth gradient between surveys (*e.g.*, Marsh *et al.* 2011; Sobtzick *et al.* 2012). Thus the Hagihara method which accounts for the heterogeneity of dugong availability bias with depth as well as environmental conditions should provide more accurate population estimates than the Pollock method.

A disadvantage of using both the Hagihara and Pollock methods is that the additional data required to implement them has been collected only from 2002. Thus analyses of the overall times series of dugong aerial surveys, which for some regions date back to the 1980s, will have to continue to rely on the Marsh and Sinclair method as illustrated by our analysis of the status of the dugong in Torres Strait (Appendix 4).

4.2 Comparison of methods

The population estimates obtained using the Hagihara method were generally (but not always) lower than those obtained using the Pollock method (Table 16) for reasons detailed in the results section of this report. However, the precision of the estimates tends to be similar (Table 16). As expected, the results obtained using the two methods were closest for Moreton Bay where most of the dugongs were sighted in large herds for which we attempted to obtain total counts without correcting for availability or perception bias and in clear water where all dugong are potentially available and so the correction for availability bias is the same for both methods.

Table 16 - Comparison of the dugong population estimates obtained using the Pollock and Hagihara methods for the surveys considered in this report.

Survey year	Ratio $\hat{N}$ Hagihara method /Pollock method[1]	CV[2] Pollock method	CV Hagihara method
	Moreton Bay		
2005	1.073	0.142	0.214
2011	0.994	0.223	0.152
2013	1.377	0.289	0.238
	Hervey Bay		
2005	0.668	0.261	0.233
2006[3]	1.384	0.382	0.377
2011	0.709	0.284	0.305
	Southern GBR[4]		
2005	0.757	0.201	0.237
2011	0.883	0.350	0.415
	Northern GBR		
2006	0.770	0.201	0.189
2013	0.689	0.174	0.175
	Gulf of Carpentaria[5]		
2007	0.759	0.157	0.150

[1]Mean population estimate Hagihara (numerator); mean population estimate Pollock (denominator)
[2] Coefficient of Variation (SE/mean) of population estimate
[3]Incomplete survey but main dugong areas covered
[4] GBR =Great Barrier Reef
[5]2006 survey of Gulf of Carpentaria not included because of limited coverage and few dugong sightings

There was no systematic difference in the precision (CV) of the population estimates obtained using the Pollock and Hagihara methods (Table 16). The precision of the mean population estimates tended to be very similar indicating that the power to detect trends should not be reduced by using the Hagihara method, despite its using 13 rather than eight sightability classes. The consistency of the population estimates across surveys (Table 17) is also similar using the two methods. Thus the chief advantage of the Hagihara method over the Pollock method should be the increase in the accuracy of the population estimates.

Table 17- Comparison of the consistency of the population estimates obtained using the Pollock and Hagihara methods.

Region	Pollock method[1]	Hagihara method[1]
Moreton Bay	1.659	1.675
Hervey Bay	1.024	1.036
Southern GBR [2]	3.387	2.901
Northern GBR	1.344	1.503

[1]Ratio of largest mean population estimate (numerator) to smallest mean population estimate (denominator) e.g. for Moreton Bay ratio of 2011 mean to 2005 mean
[2] GBR =Great Barrier Reef

4.3 Limitations of the Hagihara methodology

As explained above the Hagihara method should improve the accuracy of dugong population estimates over previous methodologies. However, we caution about these estimates being considered to be absolute estimates for several reasons:

1. The uncertainties associated with the corrections for availability bias resulting from the challenges associated with determining the detection zone (see Table 1):
    a. The resolution of the TDRs used to study dugong diving (depth resolution of ± 0.5 m) and in the dugong secchi disk experiment (depth resolution of ± 0.1 m);
    b. The difficulties in defining a dive for shallow diving animals and the inaccuracies inherent in the dive-depth profiles of shallow diving bottom feeding animals such as dugongs in which the peduncle-mounted TDR may be up to 2.5 m from the bottom as a result of the variable angle of the animal's body to the bottom due to changes in body angle (Hagihara *et al.* 2011, 2014 and Hagihara 2015);
    c. The limitations caused by the TDR records of dugong coming from only 16 dugongs and from two locations (Moreton Bay and Shoalwater Bay, of which 13 dugongs were from only one location (Moreton Bay) and our resultant assumption that it was appropriate to assume that the dive patterns of dugongs from other coastal environments (with the exception of Torres Strait as explained above).
    d. The uncertainty associated with the availability probabilities (see Figure 2;)
    e. The simplification in the record of environmental conditions resulting from using Environmental Condition Classes (see Table 1) ;
    f. Likely observer differences in the recording of Environmental Condition Classes;
2. Our failure to estimate dugong abundance in areas where there were no animals sighted (which is theoretically possible but very difficult; Martin *et al.* 2014).

These limitations mean that the population estimates should be regarded as standardised relative estimates rather than absolute estimates of dugong population size and density. The sustainable anthropogenic mortality calculated using the PBR method above should be regarded as approximate. However, the PBR method is conservative and the estimates are likely underestimates.

4.4 Improved spatial models

The outputs of this report's spatially-explicit models and the models using the Grech and Marsh (2007) approach differ in both their resolution and the spatial extent of high and very high dugong density areas. The spatially-explicit models of Grech *et al.* (2011) and Sobtzick *et al*. (2012 and 2014) use aerial survey data from all years, beginning in 1985. Aerial surveys conducted before 2005 did not record the actual flight path, and the correspondence of the flightpath with the planned transects was unknown. Along with the inevitable minor changes in the altitude of the aircraft along a transect, this lack of information on the actual flight path affected the accuracy of locations of dugong observations prior to 2005. Grech and Marsh (2007) assumed the error in dugong observations prior to 2005 was up to 2 km. All aerial surveys conducted after 2005 used GPS units to record transects, reducing the error associated with dugong observations. However, to enable the incorporation of aerial survey data prior to 2005, Grech and Marsh (2007) modelled the spatial distribution of dugongs with a resolution of 2 km. This report uses data from surveys conducted after 2007 using a 1 km resolution to account for changes in aircraft altitude and the area beneath the aircraft. A 1 km resolution enables finer-scale interpretation and understanding of dugong distribution across the survey region, and is the recommended scale to inform systematic approaches to conservation planning (Andelman and Willig, 2002).

The outputs of this report's spatially-explicit models predict a smaller area of very high and high dugong density when compared to the outputs of models using the Grech and Marsh (2007) approach. The outputs of this report show a clumped distribution pattern at important dugong habitats, whereas the outputs of Grech and Marsh (2007) are smoothed and spread over a larger area. The two modelling approaches produce differing estimates of areas of very high, high, medium and low dugong density within each survey region because: (1) they do not share the same spatial resolution; (2) the search radius (5000 m) used in this report was smaller than the maximum search radius used by Grech *et al.* (2011) (12,000 m); and (3) this report used fewer aerial survey years as the input to the model. An advantage of the models produced using the Grech and Marsh (2007) approach is that they incorporate all survey years, thus accounting for temporal changes in the distribution and abundance of dugongs over > 20 years. However, the outputs of this report's spatially-explicit models predict a higher density of dugongs within individual grid cells as a result of incorporating the revised availability probabilities. The estimates of dugong density in this report are therefore more accurate than the estimates of models that use the Grech and Marsh (2007) approach as they account for changes in the availability of dugongs to observers with depth.

4.5 Insights into the distribution and abundance of dugongs using the Hagihara method

4.5.1 Relative importance of survey regions to dugongs

Cross-regional comparisons of dugong population size and area of high and very high density habitat emphasises the importance of the remote regions of the Gulf of Carpentaria (where dugong management initiatives have not been developed and monitoring has been sporadic) and the northern Great Barrier Reef (where the 2003 rezoning of the Great Barrier Reef Marine Park was designed to protection dugong habitats from fishing (Dobbs *et al.* 2008)). Nonetheless, the Great Barrier Reef Marine Park provides limited protection from land-based activities (which are limited in this region at present) or Indigenous hunting (which is restricted to the spatially-restricted areas accessible from the scattered Aboriginal communities in the Region for cultural and socio-economic reasons). The status of the dugong in the southern Great Barrier Reef Region is an ongoing cause for concern (GBR Outlook Report 2014).

The Hervey Bay and Moreton Bay dugong populations are clearly of regional significance (Table 18). The major dugong habitat on the Eastern Banks in Moreton Bay is less prone to the impact of extreme weather events than the other Regions considered in this report because it is physically separated from the main terrestrial interface with the Queensland coast and flushed with oceanic water on a daily basis (Lyonns *et al.* 2013 and Appendix 5) and cyclones are rare at this latitude.

Table 18 - Relative importance of the aerial survey regions to dugongs based: (1) on the area of high and very high density dugong habitat (km^2) based on the spatial models; and (2) the most recent population estimates for each survey region.

Region	Area high and very high density dugong habitat km^2	Most recent population estimate ± SE (year)
Moreton Bay	560	759±181 (2013)
Hervey Bay	1534	1438±438 (2012)
Southern GBR[1]	119	537±223 (2011)
Northern GBR	5754	4517±789 (2013)
Gulf of Carpentaria	8998	9438±1419 (2007)

[1]the values quoted here for 2011 do not reflect normal conditions see text

4.5.2 Temporal changes across surveys

The only significant change in dugong numbers within a survey Region was the decline in the southern Great Barrier Reef region between 2005 and 2011 (Table 19). Using the methodology of Marsh and Sinclair (1989a), Sobtzick *et al*. (2012) estimated that size of the dugong population in the Southern Great Barrier Reef Region in November 2011 was the lowest since surveys began in 1986. This decline is attributable to the status of the seagrass beds in the region at the time of the survey. The seagrass habitats of the southern Great Barrier Reef prior had been in poor condition for several years prior to 2011 (McKenzie *et al.* 2014; Rasheed *et al*. 2014) and the severe weather events affecting the urban coast of Queensland in the summer of 2010/11 included the strongest La Niña weather pattern since 1973, major floods and Tropical Cyclones Tasha, Anthony and Yasi. All these extreme weather events impacted the major dugong habitats on the urban coast of Queensland (from Cooktown to the New South Wales border) to varying degrees. No dugong calves were sighted in the southern Great Barrier Region in the 2011 survey (Sobtzick *et al.* 2012 and Appendix 5) and the dugong mortality recorded by the Queensland Marine Wildlife Stranding Network was the highest since records began in 1996 (Meager and Limpus, 2014).

In contrast, the extreme weather of 2010/2011 did not have the same effect on the sizes of the Hervey Bay and Moreton Bay dugong populations (Table 19) or the proportions of dependent calves, both of which were within normal range (Appendix 5). These regional differences likely reflect the recent history of seagrass condition in the region (McKenzie *et al.* 2014; Rasheed *et al.* 2014); as well as the location, species composition and depth distribution of the seagrass communities and the nature and timing of the extreme weather events (Sobtzick *et al*. 2012).

Table 19 - Significant difference between dugong densities (Hagihara method) across years within each survey region.

Region (survey years)	Years	Blocks	Interaction
Moreton Bay (2005,2011, 2013)	No	Blocks 1 to 6 < Block 4	Yes
Hervey Bay (2005, 2011)	No	Blocks 3 and 4 < Blocks 1 and 2	No
Southern GBR[1] (2005, 2011)	Yes, 2011 <2005	Blocks S3, C4, C8, and C11 < Blocks S5 and C10	No
Northern GBR (2006, 2013)	No	All other Blocks < Block N2	Yes
Gulf of Carpentaria (2007)	N/A[2]	All other blocks < Block QLD1	N/A

[1] GBR =Great Barrier Reef
[2]Not available because data from only one complete survey available for analysis

4.5.3 Changes in dugong distribution

Statistically significant changes in dugong distribution were detected across surveys (interaction of Years and Bocks) in both the Moreton Bay and northern Great Barrier Reef Regions (Table 19). In Moreton Bay, this interaction can be attributed to the seasonal difference between the 2013 survey which was conducted in winter and the 2005 and 2011 summer surveys. The water temperature in parts of Moreton Bay is close to preferred thermal minimum for sirenians in winter (Marsh *et al*. 2011) and dugongs access the warmer oceanic water for thermal refuge as shown by dugong tracking studies (Preen 1992, Sheppard *et al.* 2006; Daniel Zeh unpublished). Gales *et al.* (2004) and Holley *et al.* 2006) also documented changes in dugong distribution patterns in Shark Bay at the southern limit to the dugong's range in Western Australia between summer and winter.

However, the differences in dugong distribution between surveys within Regions north of Moreton Bay described in this report cannot be attributed to seasonal differences because all these surveys were conducted in summer, generally in November-December. These differences likely reflect temporal differences in the status of the seagrass beds resulting from environmental factors, especially storms and floods (McKenzie *et al.* 2014; Rasheed *et al.* 2014) and possibly rotational grazing by dugongs (see Marsh *et al*. 2011)

5. Conclusions

We consider that the approach developed by Hagihara *et al*. (in prep, see Appendix 6) and referred to in this report as the Hagihara method and the new method used to produce spatial models should be significant improvements over the previous methodologies used to study dugong distribution and abundance (Marsh and Sinclair 1989a; Pollock *et al*. 2006; Grech and Marsh 2007; Grech *et al.* 2011) because of the better accuracy and spatial resolution. In addition, our revised approaches should be applicable to many boat- and aerial-based surveys of aquatic wildlife, especially coastal or riverine species. The technique of estimating detection zones for various environmental conditions, using animal replicas as Secchi Disks is potentially transferable to other medium-sized aquatic species residing in turbid waters (manatees, dolphins, turtles, and sharks). We have already used the methodology to analyse data on turtle sighting from the 2013 dugong survey of Torres Strait (Fuentes *et al.* 2015). Nonetheless, the Marsh and Sinclair (1989a) method for estimating dugong density and the Grech and Marsh (2007) method for producing spatial models of dugong distribution and abundance will likely still be used for studies of the entire dugong survey time series (e.g. Appendix 4) because the data required by the new approaches were not collected prior to 2002.

Despite a commitment of some management agencies (particularly the Great Barrier Reef Marine Park Authority) to conduct dugong surveys every five years, dugong aerial surveys are largely carried out on a largely *ad hoc* basis as funding permits. The meta-analysis presented here reinforces the need for a dugong monitoring program to be funded on an ongoing basis and co-ordinated across jurisdictions.

REFERENCES

Andelman, S.J., and M.R. Willig. 2002. Alternative configurations of conservation reserves for Paraguayan bats: consideration of spatial scale. *Conservation Biology*, **16**:1352–1363.

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

Dobbs, K., Fernandes, L., Slegers, S., Jago, B., Thompson, L., Hall, J., Day, J., Cameron, D., Tanzer, J., Macdonald, F., Marsh, H., and Coles, R. 2008. Incorporating dugong habitats into the marine protected area design for the Great Barrier Reef Marine Park, Queensland, Australia. *Ocean & Coastal Management*, **51**(4): 368-375.

Edwards, H.H., Pollock, K.H., Ackerman, B.B., John E, R., III, and Powell, J.A. 2007. Estimation of detection probability in manatee aerial surveys at a winter aggregation site. *Journal of Wildlife Managemen*t, **71**: 2052-2060.

Fuentes, M.M.P.B., Bell, I., Hagihara, R., Hamann, M., Hazel, J., Huth, A., Seminoff, J., Sobtzick, S., and 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.

Gales, N., R. D. McCauley, J. Lanyon and D. Holley. 2004. Change in abundance of dugongs in Shark Bay, Ningaloo and Exmouth Gulf, Western Australia: evidence for large-scale migration. *Wildlife Research*, **31**:283-290.

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

GBRMPA. 2014. Great Barrier Reef Outlook Report 2014. http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2855

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

Grech, A., Sheppard, J., and Marsh, H., 2011. Informing species conservation at multiple scales using data collected for marine mammal stock assessments. *PLoS One* **6**, e17993.

Gredzens, C., Marsh, H., Fuentes, M.P.B., Limpus, C.J., Shimada, T., and Hamann, M., 2014. Satellite tracking of sympatric marine megafauna can inform the biological basis for species co-management. *PLoS One* **9**, e98944.

Hagihara, R. 2015. Linking wildlife tracking data with environmental features to improve understanding of dugong diving ecology and abundance. PhD thesis. The College of Marine and Environmental Sciences, James Cook University.

Hagihara, R., Jones, R., Sheppard, J., Hodgson, A., Marsh, H., 2011. Minimizing errors in the analysis of dive recordings from shallow-diving animals. *Journal of Experimental Marine Biology and Ecology* **399**: 173-181

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

Holley, D. K., I. R. Lawler, and N. J. Gales. 2006. Summer survey of dugong distribution and abundance in Shark Bay reveals additional key habitat area. *Wildlife Research*, **33**:243-250.

Hooker, S.K. and Gerber, L.R. 2004. Marine reserves as a tool for ecosystem-based management: the potential importance of megafauna. *BioScience*, **54**:27-39.

IUCN, 2006. The IUCN Red List of Threatened Species. http://www.iucnredlist.org/

Laake, J.L., Calambokidis, J., Osmek, S.D., and Rugh, D.J., 1997. Probability of detecting harbor porpoise from aerial surveys: Estimating g(0). *The Journal of Wildlife Management*, **61**: 63-75.

Lambert, D. 1992. Zero-inflated poisson regression with an application to defects in manufacturing. *Technometrics*, **34**: 1-14

Long, B.G., Poiner, I.R., 1997. Seagrass communities of Torres Strait, Northern Australia, Marine Research, CSIRO.

Lyons, M.B., Phinn, S.R., and Roelfsema, C.M., 2012. Long term land cover and seagrass mapping using Landsat and object-based image analysis from 1972 to 2010 in the coastal environment of South East Queensland, Australia. *ISPRS Journal of Photogrammetry and Remote Sensing*, **71**: 34-46.

Lyons MB, Roelfsema CM, and Phinn SR. 2013. Towards understanding temporal and spatial dynamics of seagrass landscapes using time-series remote sensing. *Estuarine, Coastal and Shelf Science*.**120**(0):42-53.

Marsh, H., 1995. The limits of detectable change. In: Grigg, G.C., Hale, P.T., Lunney, D. (Eds.), Conservation through sustainable use of wildlife. Centre for Conservation Biology, The University of Queensland, pp. 122-130.

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

Marsh, H. and 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. and Saalfeld, W.K., 1990. The Distribution and abundance of dugongs in the Great Barrier Reef Marine Park South of Cape Bedford. *Australian Wildlife Research*, **17**: 511-524.

Marsh, H. and I. Lawler. 1992. The status of dugongs, sea turtles and dolphins in the Torres Strait Region. Report to the Australian Fish Management Authority. Environmental Studies Unit, James Cook University of North Queensland, Townsville.

Marsh, H., Harris, A.N.M., and Lawler, I.R., 1997. The sustainability of the Indigenous dugong fishery in Torres Strait, Australia/Papua New Guinea. *Conservation Biology*, **11**: 1375-1386.

Marsh, H., H. Penrose, C. Eros, and J. Hugues, 2002. The dugong (*Dugong dugon*) status reports and action plans for countries and territories in its range. Early warning and Assessment Reports. Nairobi: United Nations Environment Programme.

Marsh, H., Lawler, I.R., Kwan, D., Delean, S., Pollock, K., and Alldredge, M., 2004. Aerial surveys and the potential biological removal technique indicate that the Torres Strait dugong fishery is unsustainable. *Animal Conservation*, **7**: 435-443.

Marsh, H., O'Shea, T.J., and Reyholds III, J.E., 2011. Ecology and conservation of the sirenia, Conservation Biology 18. Cambridge University Press, Cambridge.

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**, p. e91683

McKenzie LJ, Collier C, Waycott M. 2014. Reef Rescue Marine Monitoring Program - Inshore seagrass. Annual Report for the sampling period July 2011- 31st May 2012. James Cook University, Cairns TropWATER, 2014.

Meager JJ, Limpus C. 2014. Mortality of Inshore Marine Mammals in Eastern Australia Is Predicted by Freshwater Discharge and Air Temperature. *PLoS ONE*. **9**(4):e94849.

Phinn, S., Roelfsema, C., Dekker, A., Brando, V., and Anstee, J., 2008. Mapping seagrass species, cover and biomass in shallow waters: An assessment of satellite multi-spectral and airborne hyper-spectral imaging systems in Moreton Bay (Australia). *Remote Sensing of Environment*, **112**: 3413-3425.

Pollock, K.H., Marsh, H.D., Lawler, I.R., and 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.
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 MA, McKenna SA, Carter AB, and Coles RG. 2014. Contrasting recovery of shallow and deep water seagrass communities following climate associated losses in tropical north Queensland, Australia. *Marine Pollution Bulletin*. **83**(2):491-9.
Schweder, T., Høst, G., and Øien, N., 1991a. A note on the bias in capture-recapture type estimates of g(0) due to the fact that whales are diving. *Report of the International Whaling Commission*, **41**: 397-399.
Schweder, T., Øien, N., and Høst, G., 1991b. Estimates of the detection probability for shipboard surveys of northeastern Atlantic minke whales, based on a parallel ship experiment. *Report of the International Whaling Commission*, **41**: 417-432.
Sheppard, J.K., Preen, A.R., Marsh, H., Lawler, I.R., Whiting, S.D., and 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.
Skaug H., Fournier D., Bolker B., Magnusson A., and Nielsen A. 2014. Generalized Linear Mixed Models using AD Model Builder. R package version 0.8.0.
Sobtzick, S., Hagihara, R., Grech, G., and 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 2010–2011, James Cook University.
Sobtzick, S., Penrose, H., Hagihara, R., Grech, A., Cleguer, C., and Marsh, H., 2014. An assessment of the distribution and abundance of dugongs in the Northern Great Barrier Reef and Torres Strait, The Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), James Cook University, Townsville.
Taylor, H.A. and Rasheed, M.A., 2011. Deepwater seagrass dynamics in the Torres Strait Dugong Sanctuary. Interim Report March & November 2010, Fisheries Queensland, Cairns, Queensland.
Thomson, J.A., Cooper, A.B., Burkholder, D.A., Heithaus, M.R., and Dill, L.M., 2012. Heterogeneous patterns of availability for detection during visual surveys: spatiotemporal variation in sea turtle dive–surfacing behaviour on a feeding ground. *Methods in Ecology and Evolution*, **3**: 378-387.
Wade, P. R. 1998. Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science*, **14**:1-37.
White, G. C., K. P. Burnham. 1999. Program MARK: survival estimation from populations of marked animals. *Bird study*, **46** (Supplement):120-139.

Appendix 1 – Coefficients from zero-inflated models with Negative Binomial distribution produced in glmmADMB from dugong relative density from aerial surveys

	Estimate	Std. Error	z value	Pr(>|z|)	Sig.
Moreton Bay in 2005, 2011, and 2013					
Between years					
(Intercept)	-0.507	0.362	-1.40	0.16	
year2011	0.593	0.492	1.21	0.23	
year2013	0.364	0.491	0.74	0.46	
Between blocks					
(Intercept)	0.868	0.272	3.19	0.001	**
Block 2	-2.197	0.496	-4.43	<0.001	***
Block 3	-4.980	0.698	-7.14	<0.001	***
Block 4	-3.484	0.773	-4.51	<0.001	***
Block 5	-1.906	0.534	-3.57	<0.001	***
Block 6	-1.962	0.451	-4.35	<0.001	***
Hervey Bay in 2005, and 2011					
Between years					
(Intercept)	-0.430	0.323	-1.33	0.18	
year2011	-0.136	0.352	-0.39	0.70	
Between blocks					
(Intercept)	-0.199	0.206	-0.96	0.335	
Block 2	-0.137	0.364	-0.38	0.706	
Block 3	-1.708	0.447	-3.82	0.001	***
Block 4	-2.795	0.497	-5.63	<0.001	***
Block 5	-18.395	1131.6	-0.02	0.987	
Block 6	-22.468	7341.8	0.00	0.998	
southern Great Barrier Reef in 2005, and 2011					
Between years					
(Intercept)	-0.397	0.516	-0.77	0.44	
year2011	-1.683	0.374	-4.50	<0.001	***
Between blocks					
(Intercept)	0.027	0.394	0.07	0.945	
Block S3	-2.344	0.476	-4.92	<0.001	***
Block C4	-2.062	0.598	-3.45	<0.001	***
Block C6	-0.392	0.618	-0.63	0.526	
Block C8	-1.475	0.558	-2.64	0.008	**
Block C10	-0.111	0.535	-0.21	0.835	
Block C11	-1.647	0.616	-2.68	0.007	**

northern Great Barrier Reef in 2006, and 2013					
Between years					
(Intercept)	-0.762	0.153	-4.96	0.001	***
year2013	-0.225	0.220	-1.02	0.31	
Between blocks					
(Intercept)	0.654	0.307	2.13	0.033	*
3	-1.324	0.404	-3.28	0.001	**
4	-1.864	0.380	-4.90	<0.001	***
5	-1.831	0.386	-4.74	<0.001	***
6	-1.175	0.498	-2.36	0.018	*
8	-0.854	0.394	-2.17	0.030	*
11	-1.401	0.453	-3.09	0.002	**
13	-4.033	0.466	-8.65	<0.001	***
Gulf of Carpentaria in 2007					
Between blocks					
(Intercept)	0.427	0.151	2.83	0.005	**
NT1	-2.589	0.350	-7.39	<0.001	***
NT2	-2.081	0.227	-9.19	<0.001	***
NT3	-1.977	0.234	-8.43	<0.001	***
NT4	-2.018	0.225	-8.98	<0.001	***
NT5	-2.076	0.199	-10.42	<0.001	***
NT6	-1.783	0.208	-8.59	<0.001	***
NT7	-2.084	0.212	-9.83	<0.001	***
QLD2	-1.522	0.168	-9.05	<0.001	***
QLD3	-2.132	0.366	-5.83	<0.001	***
QLD4	-2.641	0.237	-11.15	<0.001	***
QLD5	-3.976	0.597	-6.66	<0.001	***
QLD6	-2.466	0.366	-6.74	<0.001	***

Significance codes: *<0.05, **<0.01, ***<0.001

Appendix 2 - Pair-wise comparison of relative dugong density in different Regions

(A) Moreton Bay

Between years			
Year	2005	2011	2013
2005			
2011			
2013			

Between blocks						
Block	1	2	3	4	5	6
1		↓***		↑***		
2	↑***			↑***	↑***	↑***
3				↑***		
4	↓***	↓***	↓***		↓***	↓***
5		↓***		↑***		
6		↓***		↑***		

Significance codes: *<0.05, **<0.01, ***<0.001

Example to aid interpretation: Block 4 had significantly higher dugong density than any other block.

(B) Hervey Bay

Between years		
Year	2005	2011
2005		
2011		

Between blocks						
Block	1	2	3	4	5	6
1			↓***	↓***	n/a	n/a
2			↓**	↓***	n/a	n/a
3	↑***	↑**			n/a	n/a
4	↑***	↑***			n/a	n/a
5	n/a	n/a	n/a	n/a		n/a
6	n/a	n/a	n/a	n/a	n/a	

Significance codes: *<0.05, **<0.01, ***<0.001; n/a: insufficient data to compare significant difference

Example to aid interpretation: Block 1 had significantly higher dugong density than Blocks 3 and 4.

Note: pair-wise comparisons of Blocks 5 and 6 with other blocks could not be made, as Block 5 had no dugong sightings, and Block 6 was flown following zig-zag transects.

(C) southern Great Barrier Reef

Between years							
Year	2005	2011					
2005		↓***					
2011	↑***						
Between blocks							
Block	S3	S5	C4	C6	C8	C10	C11
S3		↑***		↑**		↑***	
S5	↓***		↓***		↓**		↓**
C4		↑***		↑*		↑**	
C6	↓**		↓*				
C8		↑**				↑*	
C10	↓***		↓**		↓*		↓*
C11		↑**				↑*	

Significance codes: *<0.05, **<0.01, ***<0.001

Example to aid interpretation: 2011 had significantly lower dugong density than 2005.

(D) northern Great Barrier Reef

Between years									
Year	2006	2013							
2006									
2013									
Between blocks									
Block	2	3	4	5	6	8	11	13	14
2		↓**	↓***	↓***	↓*	↓*	↓**	↓***	↓***
3	↑**							↓***	
4	↑***					↑**		↓***	
5	↑***					↑**		↓***	
6	↑*							↓***	
8	↑*		↓**	↓**				↓***	
11	↑**							↓***	
13	↑***	↑***	↑***	↑***	↑***	↑***	↑***		↑***
14	↑***							↓***	

Significance codes: *<0.05, **<0.01, ***<0.001

Example to aid interpretation: The Block 2 had significantly higher dugong density than any other blocks.

For the ‘between blocks’ comparisons, Blocks 1, 7, 9, 10, 12 and 15 were removed due to insufficient data.

(E) Gulf of Carpentaria

	Between blocks												
Block	NT[1]1	NT2	NT3	NT4	NT5	NT6	NT7	QLD[1]1	QLD2	QLD3	QLD4	QLD5	QLD6
NT1						↑*		↑***	↑**			↓*	
NT2								↑***	↑**		↓*	↓**	
NT3								↑***	↑*		↓**	↓***	
NT4								↑***	↑**		↓*	↓**	
NT5								↑***	↑***		↓*	↓**	
NT6	↓*							↑***			↓***	↓***	
NT7								↑***	↑***		↓*	↓**	
QLD1	↓***	↓***	↓***	↓***	↓***	↓***	↓***		↓***	↓***	↓***	↓***	↓***
QLD2	↓**	↓**	↓*	↓**	↓***		↓***	↑***			↓***	↓***	↓**
QLD3								↑***				↓**	
QLD4		↑*	↑**	↑*	↑*	↑***	↑*	↑***	↑***			↓*	
QLD5	↑*	↑**	↑***	↑**	↑**	↑***	↑**	↑***	↑***	↑**	↑*		↑*
QLD6								↑***	↑**			↓*	

[1]NT=Northern Territory; QLD=Queensland

Significance codes: *<0.05, **<0.01, ***<0.001

Example to aid interpretation: Block QLD1 had significantly higher dugong density than any other block.

Appendix 3 - Estimated sustainable levels of mortalities from anthropogenic sources for dugongs in different Regions and Years

(A) in Moreton Bay in 2005, 2011, and 2013, and in Hervey Bay in 2005, 2006, and 2013 using the Potential Biological Removal method (Wade 1998) and different Recovery Factors (RF) and maximum rates of population increase (R_{max}).

Year	Methodology	N	SE	CV	N_{min}	RF	PBR R_{max}= 0.01	PBR R_{max}= 0.03	PBR R_{max}= 0.05
Moreton Bay									
2005	Pollock method	422	60	0.142	375	0.1	0	1	1
						0.5	1	3	5
						1.0	2	6	9
	Hagihara method	453	97	0.214	379	0.1	0	1	1
						0.5	1	3	5
						1.0	2	6	9
2011	Pollock method	700	156	0.223	582	0.1	0	1	1
						0.5	1	4	7
						1.0	3	9	15
	Hagihara method	696	106	0.152	613	0.1	0	1	2
						0.5	2	5	8
						1.0	3	9	15
2013	Pollock method	551	159	0.289	434	0.1	0	1	1
						0.5	1	3	5
						1.0	2	7	11
	Hagihara method	759	181	0.238	623	0.1	0	1	2
						0.5	2	5	8
						1.0	3	9	16
Hervey Bay									
2005	Pollock method	2077	543	0.261	1673	0.1	1	3	4
						0.5	4	13	21
						1.0	8	25	42
	Hagihara method	1388	323	0.233	1144	0.1	1	2	3
						0.5	3	9	14
						1.0	6	17	29
2006	Pollock method	1044	399	0.382	765	0.1	0	1	2
						0.5	2	6	10
						1.0	4	11	19
	Hagihara method	1445	545	0.377	1063	0.1	1	2	3
						0.5	3	8	13
						1.0	5	16	27
2013	Pollock method	2029	576	0.284	1605	0.1	1	2	4
						0.5	4	12	20
						1.0	8	24	40
	Hagihara method	1438	438	0.305	1119	0.1	1	2	3
						0.5	3	8	14
						1.0	6	17	28

Appendix 3 cont'

(B) In the southern Great Barrier Reef in 2005, and 2011; in the northern Great Barrier Reef in 2006, and 2013, and in the Gulf of Carpentaria in 2007 using the Potential Biological Removal method (Wade 1998) and different Recovery Factors (RF) and maximum rates of population increase (R_{max}).

Year	Methodology	N	SE	CV	N_{min}	RF	PBR R_{max}= 0.01	PBR R_{max}= 0.03	PBR R_{max}= 0.05
southern Great Barrier Reef									
2005	Pollock method	2059	413	0.201	1742	0.1	1	3	4
						0.5	4	13	22
						1.0	9	26	44
	Hagihara method	1610	382	0.237	1322	0.1	1	2	3
						0.5	3	10	17
						1.0	7	20	33
2011	Pollock method	608	213	0.350	457	0.1	0	1	1
						0.5	1	3	6
						1.0	2	7	11
	Hagihara method	537	223	0.415	384	0.1	0	1	1
						0.5	1	3	5
						1.0	2	6	10
northern Great Barrier Reef									
2006	Pollock method	8812	1769	0.201	7454	0.1	4	11	19
						0.5	19	56	93
						1.0	37	112	186
	Hagihara method	6787	1281	0.189	5798	0.1	3	9	14
						0.5	14	43	72
						1.0	29	87	145
2013	Pollock method	6558	1141	0.174	5671	0.1	3	9	14
						0.5	14	43	71
						1.0	28	85	142
	Hagihara method	4517	789	0.175	3904	0.1	2	6	10
						0.5	10	29	49
						1.0	20	59	98
Gulf of Carpentaria									
2007	Pollock method	12438	1951	0.157	10908	0.1	5	16	27
						0.5	27	82	136
						1.0	55	164	273
	Hagihara method	9438	1419	0.150	8322	0.1	7	12	21
						0.5	21	62	104
						1.0	42	125	208

N = dugong population estimate; SE = standard error; N_{min} = the 20^{th} percentile of a log-normal distribution based on N; PBR = potential biological removal

Appendix 4 - Marsh *et al*. draft paper for submission to *Biological Conservation*

Re-evaluation of the sustainability of an indigenous marine mammal harvest using several lines of evidence.

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ABSTRACT
People in 114 countries have consumed meat from at least 87 species of marine mammals since 1990. However, it is difficult to establish whether most harvests are sustainable because of the paucity of limited information on marine mammal populations and harvest numbers. Dugongs have been harvested by the indigenous peoples of Torres Strait between Australia and Papua New Guinea, for at least 4000 years; the harvest has been substantial for at least the last 400 – 500 years. We use several lines of evidence to re-evaluate the sustainability of this harvest in the absence of robust data on the absolute size of this dugong population and the number harvested. A time series of systematic aerial surveys since 1987 has not detected a decline in dugong relative density or Area of Occupancy in Torres Strait. Relative density was significantly higher in 2013 than in any other survey year and the Area of Occupancy shows a slight upward trend over time. The proportion of calves in 2013 was the highest ever recorded. Dugongs are caught in only 4.2% of the 7,011 km^2 of the high to very high dugong density habitat as the result of input controls on the harvest, a large statutory Dugong Sanctuary, the low socio-economic status of the hunters and the ban on selling the meat. Nonetheless, many in the wider Australian community disapprove of this harvest and demand that hunting be banned. Enhancing culturally-appropriate spatial controls may be a more practical approach to managing this harvest than a more data-demanding Total Allowable Catch approach and may also be appropriate for some other indigenous harvests of marine mammals.

INTRODUCTION

Disputes between opposing groups advocating sustainable use and complete protection make the human consumption of marine mammals a globally and locally contentious issue. Despite this controversy, Robards and Reeves (2011) documented the human consumption of one or more of at least 87 marine mammal species in 114 countries since 1990. Consumption of marine mammals is a significant source of food and cultural well-being for indigenous people in many countries, including several developed countries such as Australia (Robards and Reeves 2011).

Evaluating the sustainability of subsistence marine mammal harvests is a non-trivial task. Robust data on population size and catch are often unavailable. Determining the status and trend of a marine mammal population is technically challenging (Taylor et al. 2007) and modelling solutions have been used to trigger management interventions. Two such approaches are Population Viability Analysis (Bessinger and Westphail 1998) and Potential Biological Removal (Wade 1998). Both these approaches require estimates of the size of the source population and the number of animals harvested as well as knowledge of the life history of the target species. Uncertainty about such parameters is typically addressed through scenario modelling.

Torres Strait (Figure 1a), the remote region between Australia and Papua New Guinea is the most important dugong habitat in the world (Marsh et al. 2011a). At the time of the first European contact, the Torres Strait population was estimated at 4000 – 5000 people (Beckett 1987). Disease then reduced the population to as few as 2000 (Beckett 1987). The most recent census indicates that there were about 6,000 indigenous people living on the Australian islands of Torres Strait in 2011 (OESR 2013). Dugongs have been harvested by the indigenous inhabitants of Torres Strait for at least 4000 years (Crouch et al. 2007), and possibly 7000 years (Wright 2011). Archaeological evidence indicates that the harvest has been substantial for at least 400 – 500 years (McNiven and Bedingfield 2008). Like many other marine mammal harvests (Robards and Reeves 2011), dugong hunting in Australia is extremely controversial and has been an issue in recent national and state elections (Delisle et al. 2014), despite the legality of the hunting rights of Torres Strait Islanders.

Like all other Traditional Owners[1] in northern Australia, Torres Strait Islanders have the right to hunt dugongs in their sea country under the Australian Native Title Act (e.g. *Native Title Act* 1993). Environmental laws (e.g. the Australian *Environment Protection and Biodiversity Conservation Act* 1999 (*EPBC Act*); and the Queensland (State) *Nature Conservation Act* 1992) do not affect their Native Title rights. Dugong hunting in Torres Strait is also classified as a traditional fishery guaranteed by the Torres Strait Treaty between Australia and Papua New Guinea (Havemann and Smith 2007) and is regulated by Australian and State (Queensland) fisheries laws (the *Torres Strait Fisheries Act* 1984 Commonwealth and the *Torres Strait Fisheries Act* 1984 Qld). There are some input controls. Hunting from vessels longer than 6 metres is illegal. Animals can only be hunted using a traditional spear ('wap') and by custom, only males can hunt. Hunting is banned from the Dugong Sanctuary, a > 13,000 km^2 (Figure 1a) region in western Torres Strait. These regulations are supplemented by another restriction - it is illegal to sell the meat.

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[1] Traditional Owners are Aboriginal or Torres Strait Islander people that are directly descended from the original Aboriginal or Torres Strait Islander inhabitants of a culturally defined area.

In recent years, community-based management for dugongs (and green turtles) has been strengthened in Torres Strait by the Australian Government investing millions of dollars in indigenous ranger programs. Fifteen communities have developed Turtle and Dugong Hunting Management Plans (Marsh et al. 2011a). Nonetheless, controversy over Indigenous hunting continues in the wider Australian community. This controversy has been fuelled by scientific evidence. Heinsohn et al. (2004) predicted severe and imminent reductions in dugong numbers and median times for quasi-extinction ranging from 42 -123 years using: (1) Population Viability Analysis and published estimates on dugong life history and population sizes from systematic aerial surveys conducted from 1987 to 2001 (Marsh et al. 1997, 2004), and (2) simulated hunting rates ranging from 250 to 1000 dugongs per year. Using the same life history and aerial survey data, and the Potential Biological Removal method (Wade 1998), Marsh et al. (2004) also concluded that the current harvest must be unsustainable by estimating the annual sustainable anthropogenic mortality from all causes, which was much smaller than the incomplete harvest estimates then available.

We now know that the aerial survey population estimates did not include all the dugong habitat in Torres Strait. Taylor and Rasheed (2010) discovered the largest recorded single continuous seagrass meadow in Australia to the west of the aerial survey area in 2010. When the aerial survey area was extended in response to this finding, the extension was estimated to support more than 1000 dugongs (Marsh et al. 2011b). In addition, Hagihara et al. (2014) reported that the availability of dugongs to aerial observers depends not only on environmental conditions (Pollock et al. 2006) but also bathymetry, a factor that had not been included in the aerial survey estimates. Dugongs in waters 5-25 metres deep (the depths where >90% of dugongs are sighted in Torres Strait, Sobtzick et al. 2014) are less available to aerial observers than animals in shallower or deeper waters.

Thus we consider that the data on dugong numbers from aerial surveys are not robust enough to repeat the modelling done by Heinsohn et al. (2004) and Marsh et al. (2004). The data on dugong diving required to estimate dugong numbers more accurately are not yet available for Torres Strait, where both the bathymetry and seagrass communities are very different from the area where Hagihara et al. (2014)'s data were collected making extrapolation inappropriate. Contemporary data on the dugong harvest are not available and catch per unit effort data will be particularly difficult to obtain because unsuccessful hunts are not typically reported by hunters (Grayson 2011). Thus we anticipate that it will not be possible to develop scientifically defensible estimates of a sustainable catch for at least several years.

Accordingly, we take an alternative approach to evaluate the sustainability of the Torres Strait dugong harvest using several lines of evidence. We have: (1) re-analysed the standardised time series of data on dugong relative density and percentage calves (a measure of fecundity plus neonatal mortality) collected from seven aerial surveys conducted between 1987 and 2013; (2) tracked the Area of Occupancy (*sensu* IUCN 2001) of the dugong population in Torres Strait over the same period; (3) used spatial models of dugong distribution and relative density and the spatial pattern of take to calculate the proportion of high and very high density dugong habitat where dugongs are exposed to hunting, and (4) interpreted these data in the context of published data on the genetic diversity of the dugong in Torres Strait and the status of the seagrass habitat.

METHODS

Aerial surveys

Survey design

Seven aerial surveys for dugongs were conducted over central and western Torres Strait as funding permitted between 1987 and 2013 (November 1987, 1991, 1996, 2001, 2006, 2013, March 2011; Marsh et al. 1997; Marsh et al. 2004, Sobtzick et al. 2014). The blocks and transects were generally consistent over time with the following exceptions: Blocks 6, 7, 8, and 9 were flown in 2011 and 2013 only, after the largest seagrass meadow in Australia was located in this region by Taylor and Rasheed (2010). Transects in Blocks 1A, 1B, and 0 were truncated 5 nautical miles from the Papua New Guinea coast for the 2011 and 2013 surveys; we had permission to enter that country's coastal waters in the previous surveys. Eastern Torres Strait was never surveyed as there is little seagrass in that region (Sheppard et al. 2008) and dugongs are rarely sighted. Figure 1 shows a map of the region and the locations of the blocks and orientation and spacing of transects flown in November 2013, which covered a total area of 41,640 km^2.

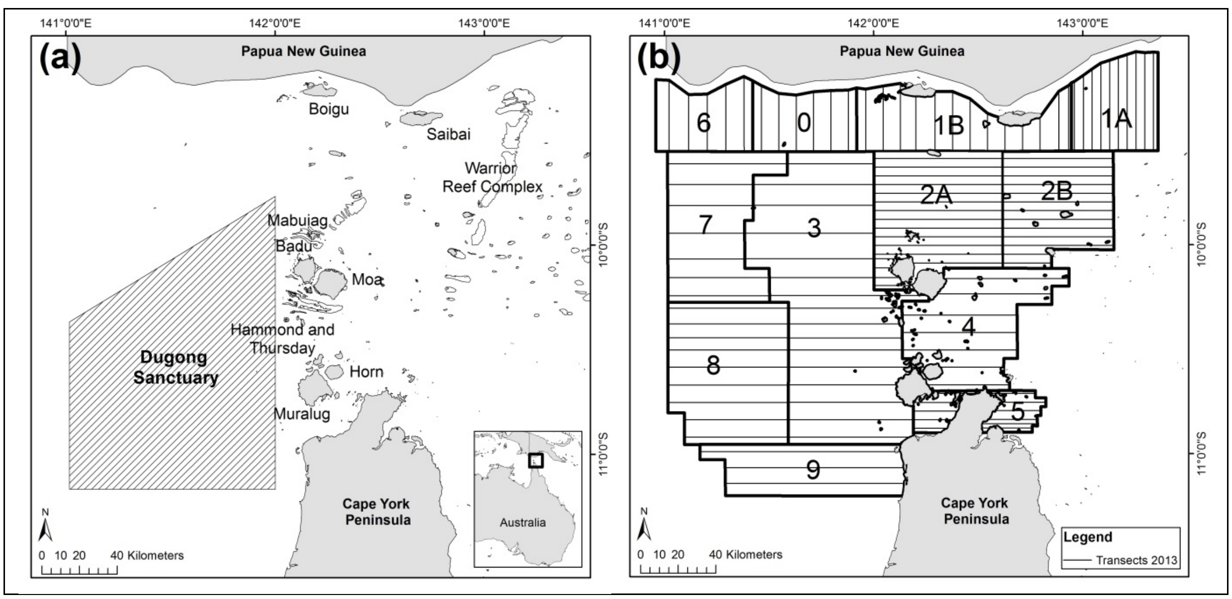

Figure 1. Central and Western Torres Strait showing: (a) locations of reefs, the Island Clusters and major hunting communities mentioned in text and the Dugong Sanctuary; and (b) the blocks and transects flown in the 2013 aerial survey.

Survey methodology

The aerial survey methodology followed the distance sampling technique detailed in Marsh and Sinclair (1989a). Transects chosen under a stratified random sampling design were flown by a 6-seat, high-wing, twin-engine Partenavia 68B as close as possible to a ground speed of 100 knots. The survey was conducted at a height of 500 feet (152 m) above sea level in 2011 and 2013 and at 450 feet (137 m) in the other surveys. The experimental work of Marsh and Sinclair (1989b) indicates that there should be no difference in dugong sightability between survey heights of 152 m 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 color bands on the artificial wing struts. Two trained tandem teams of observers on each side of the aircraft scanned their respective transect and recorded 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 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 dugongs surface cryptically and for only 1–2seconds (Anderson and Birtles 1978, Chilvers et al. 2004). 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 surveys were conducted in passing mode. For each dugong sighting, the observers recorded the total number of animals seen, number at the surface of the water, number of calves (animals less than 2/3 of the size of the cow and swimming in close proximity), position in the transect sub-strip (*e.g.,* low or medium). On the four occasions when groups of dugongs were sighted that were too large to accurately count in passing mode (usually 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. This situation occurred twice in 1991, and once in 1996, and 2006 each.

The survey leader seated next to the pilot 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). There was a strict ceiling on weather: no precipitation and sea state $\leq$3. Every few minutes during each transect, and whenever conditions changed, the survey leader recorded sea state, water transparency, and glare (none; 0<25% of field of view affected; 25<50% affected, >50% affected) on each side of the aircraft (the last was assessed by the mid-seat observers).

Survey-specific corrections for availability bias (*i.e.*, animals present in the study area but unavailable to the observers) were calculated as the proportion of dugongs sighted that were categorized as being at the surface compared with a clear, shallow-water, sandy-bottom, calm seas standard in which all dugongs were potentially available (Marsh and Sinclair (1989a). The more sophisticated technique of Pollock et al. (2006) could not be used to correct for imperfect detection over the time series because the additional data required were collected only from 2000 onwards. The sightings of the tandem observers were 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 (Marsh and Sinclair 1989a) using mark-recapture models (White and Burnham 1999).

Dugong relative density

Exploratory analysis
As there were transects on which no dugongs were sighted, zero-inflation was examined using bar-plots. Overdispersion was assessed based on dispersion statistics generated using generalized linear models assuming the data were distributed according to: (a) Poisson and (b) Negative Binomial distributions. Only the dispersion statistics of the Negative Binomial model were within acceptable levels (Zuur 2012). As the statistical analysis required at least one observation in each row of each year and block combination, the western blocks 6 to 9 (Figure 1b), surveyed only in 2011 and 2013, were excluded from the analysis. To assess the random effect of transect, transects that were flown in all seven surveys were included in the subsequent analyses (> 90% of transects flown during each survey). The inclusion of the random variable transect did not improve the model fit indicating that the random effects were minor; dugong relative density was not consistently high or low on particular transects.

Statistical model
Following this exploratory analysis, we used a zero-inflated model with a Negative Binomial distribution. The following models were used to explore temporal and spatial variation in dugong relative density based on the corrected number of animals per transect area: (1) Year or (2) Block as single explanatory categorical variables; (3) Year and Block and (4) Year, Block and their interaction. Model selection was based on Log-Likelihood. The statistical analyses were performed using R package glmmADMB (Skaug et al. 2014) in R (R Core Team 2015).

Calf counts

Logistic regression (SPlus version 8) was used to examine if the proportions of calves (response) differed among survey years. Year was treated as a continuous independent variable. As the total number of dugongs sighted differed among years, and that number is presumably correlated with the number of calves sighted, total numbers of dugongs sighted for each survey were used as weights in the logistic regression model.

Temporal changes in Area of Occupancy

Transects that were repeated in all of seven survey years were converted to a grid of 2 km x 2 km resolution *sensu* IUCN (2001) in ArcGIS (Esri). The total number of cells in which at least one dugong was sighted was calculated for each survey to investigate temporal changes in the Area of Occupancy..

Spatial modelling

The corrected dugong data (Marsh and Sinclair 1989a) from the 2011 and 2013 aerial surveys were used to develop a spatially explicit model of dugong relative density and distribution using the interpolation technique outlined in Grech et al. (2011). Dugong relative density and distribution were interpolated at the scale of 1 km x 1 km grid cells and with a search radius of

32 kilometres (Gredzens et al. 2014). Grid cells were classified into four categories based on Grech et al. (2007): Very High (> 1.0 dugongs/km^2), High (0.5 – 1.0 dugongs/km^2), Medium (0-0.5 dugongs/km^2) and Low (0 dugongs/km^2) dugong relative density.

Spatial pattern of dugong hunting effort

Hunters living in ten inhabited islands in the survey area (Figure 1a) catch most of the dugongs in Australian waters from dinghies powered by outboard motors. Hunters from the six eastern most inhabited islands catch dugongs only occasionally (Johannes and MacFarlane 1991) and were not included in our analysis of hunting effort. Dugongs are also caught by Kiwai hunters from villages along the southern coast of Papua New Guinea (PNG) (Hudson 1986). These hunters mostly use outboard-powered 'banana' boats or canoes and nets to catch dugongs (Hudson 1986; Marsh et al., 2002).

Data on the hunting patterns of Inner Island (Kaiwalagal) hunters of Hammond and Thursday Islands were obtained between 2005-2006 (Figure 1a) by Grayson (2011). Data for Mabuiag Island (Goemulgal) were collected between 1997-1999 (Kwan 2002; Marsh and Kwan, 2008). The spatial hunting patterns of the Kiwai hunters of Papua New Guinea (PNG) were inferred by from the records of hunters selling their catch at markets in Daru in PNG (where it was then legal to sell the catch) between 1978-1982 (Hudson 1986; Marsh 1996). Inner Island (Kaiwalagal) hunters recorded the distance from their home island where they caught dugongs rather than the catch location *per se*. Kwan (2002) and Hudson (1986) recorded the name of the reef where each dugong was caught for the Mabuiag Island (Goemulgal) and Kiwai hunters, respectively.

Inner Island (Kaiwalagal) hunters reported catching dugongs up to 30 km from their home islands; however, most dugongs (88%) were caught in shallow water (<5 m) relatively close (within 10 km) to the hunters' home communities (Table 1; Grayson 2011). 87% of the dugong hunting trips by Mabuiag Island (Goemulgal) hunters were to reef tops within 30 km of Mabuaig Island, and 39% of trips were within 10 km of this island (Kwan 2002; Marsh and Kwan 2008; Table 1). PNG Western Province (Kiwai) hunters mainly caught dugongs on reefs close to (< 30 km) their communities or on the Auwamaza or Warrior Reefs (Hudson 1986; Table 1). Most of the hunting on the Warrior Reefs was north of Moon Passage (around 9°S, 142°E; Hudson 1986).

Table 1: Numbers of successful hunting trips to various distances from Hammond, Thursday and Mabuaig Islands and number of dugongs caught on the Papua New Guinea coast of Torres Strait (Grayson 2011). The percentage of trips from the Kaiwalagal and Goemulgal areas and the number of individuals from the Kiwai area for which the hunting location was not recorded is also provided.

Communities	Distance between community and hunting location			% trips or number of individuals for which hunting location not recorded
	< 10km	10 – 30 km	> 30 km	
Kaiwalagal (Hammond and Thursday Islands) [a]	62	7	0	33%
Goemulgal (Mabuaig Island) [b]	56	70	18	17%
Kiwai (Papua New Guinea)[b]	127	201	95	45[c]

[a] habitat of catch unknown
[b] caught on reefs/sandbanks
[c] data to estimate % not available

A layer of the spatial extent of take at a 1 km x 1 km resolution was created in ArcGIS (Esri) using a path-distance analysis and information on the maximum distance that hunters traveled from boat ramps (30 km). We assumed that hunters in the 10 hunting communities of Torres Strait (Figure 1a) traveled the same distance to hunting areas as the Inner Island (Kaiwalagal) and Mabuiag Island (Goemulgal) hunters. In addition, we created a layer of the reefs identified as take areas by the Mabuiag Island (Goemulgal) and PNG Western Province (Kiwai) hunters (Kwan (2002), Hudson (1986)). We merged the path-distance and reef layers to create a single layer of the total spatial extent of take areas in the survey region. We removed grid cells of bathymetry < -5 m (Daniell 2008) to create a second layer of the spatial extent of take areas that assumed dugongs were caught only in shallow waters < -5 m deep, as advised by the hunters. The two take layers were overlayed with the spatial model of dugong relative density and distribution to calculate the proportion of dugong habitat exposed to hunting.

The spatial data on hunting effort favor successful hunting trips as information was recorded only when dugongs were caught. We assumed that the spatial pattern of dugong take had not changed since these data were collected. We consider this assumption is likely to be robust because of the severe socio-economic constraints on hunting due to the high fuel prices, low incomes of the hunters and the ban on the sale of dugong meat (Delisle 2013).

RESULTS

Temporal and spatial patterns in dugong relative density

Dugong relative density varied significantly with survey year and block. Dugong relative density in 2013 was significantly higher than any other survey year (Figure 2a, Appendix 1a). In 2001 and

2011, density was significantly smaller than 1991, 1996 and 2013; relative density in 1987 was also relatively low. Thus there was no evidence of a consistent temporal trend in dugong relative density.

The interaction of block and year significantly improved model fit; high density blocks shifted from one survey to another (Figure 2). Nonetheless, the model with Block as the only variable indicated that dugong relative density in Block 2A was significantly higher than any other block (Figure 2b, Appendix 1b). Dugong relative density varied more over time in other blocks, particularly Blocks 4 and 1A (Figure 2b). The coefficients of the models for Year or Block are provided in Appendix 2.

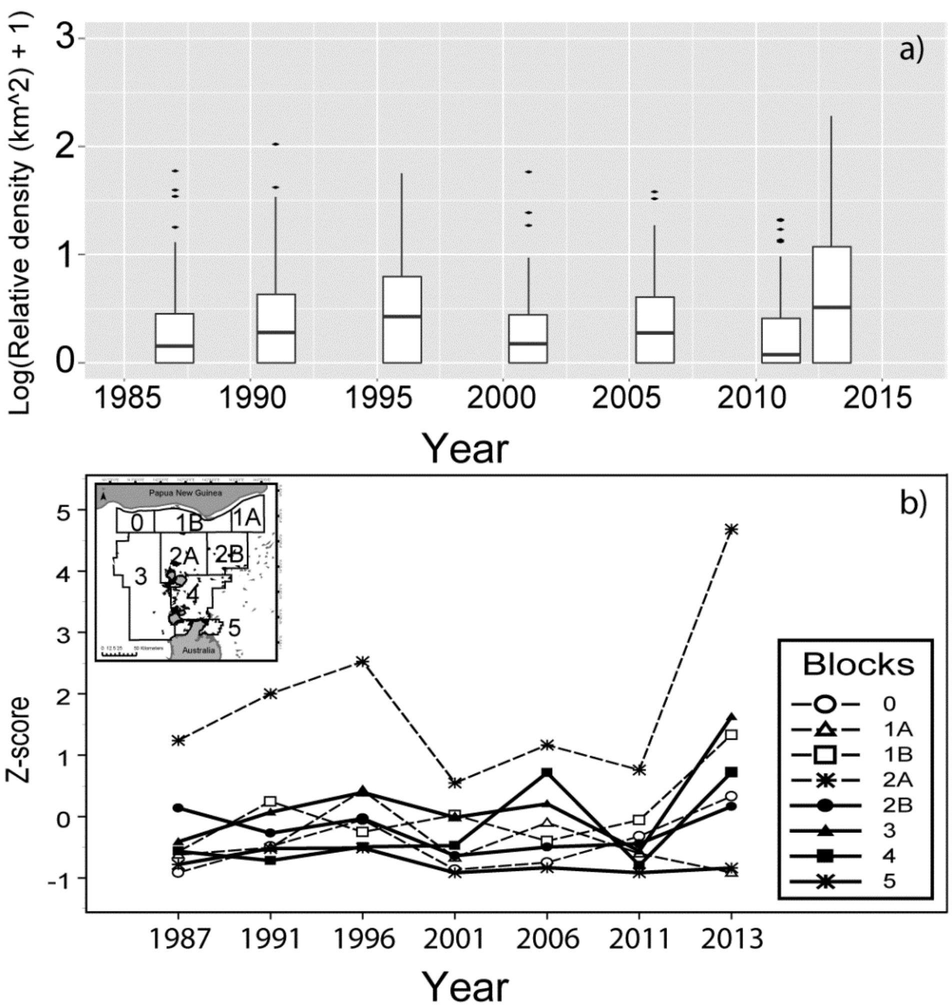

Figure 2: Dugong relative density (per km^2) in Torres Strait based on: a) log scale for aerial surveys conducted in 1987, 1991, 1996, 2001, 2006, 2011, and 2013, all blocks combined; and b) z-scores based on mean relative dugong density, blocks plotted separately. The error bars in (a) represent 95% confidence intervals

Calf counts

Ninety-two percent of sightings were of cow-calf pairs or individual animals. After 2000, the proportion of calves in Torres Strait increased (Figure 3). A logistic regression binned into two levels (pre-2000 and post-2000) showed that the proportion of calves in Torres Strait significantly increased by 22% post-2000 compared with the earlier period.

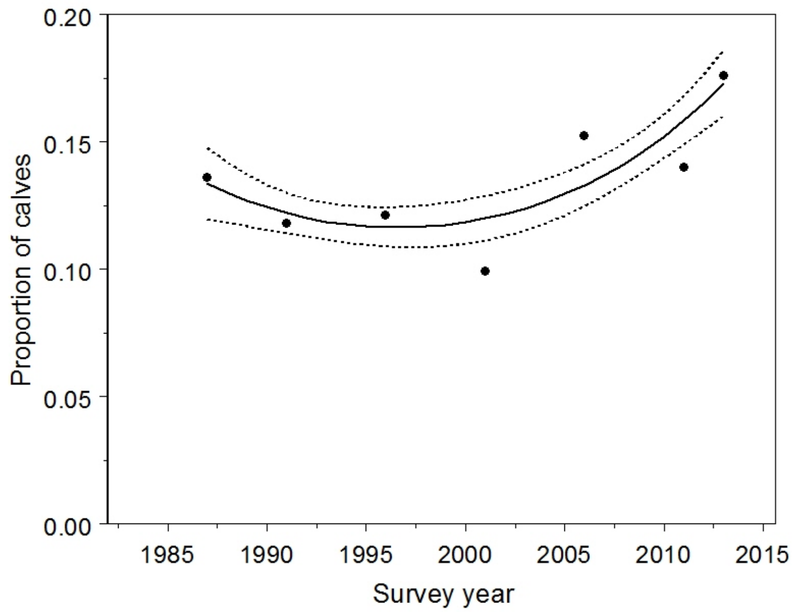

Figure 3. Proportions of calves for each aerial survey conducted in Torres Strait. The solid line represents a predicted proportion of calves, and the dotted lines indicate its standard errors based on the logistic regression model.

Changes in Area of Occupancy

The Area of Occupancy of dugongs (*sensu* IUCN 2001) ranged from 145 (1987) to 262 (1996) in the 2 km x2 km grid cells of repeated transects (Figure 4), with a slightly upward trend in the number of cells where dugongs were observed at least once over time (R^2 = 0.0555).

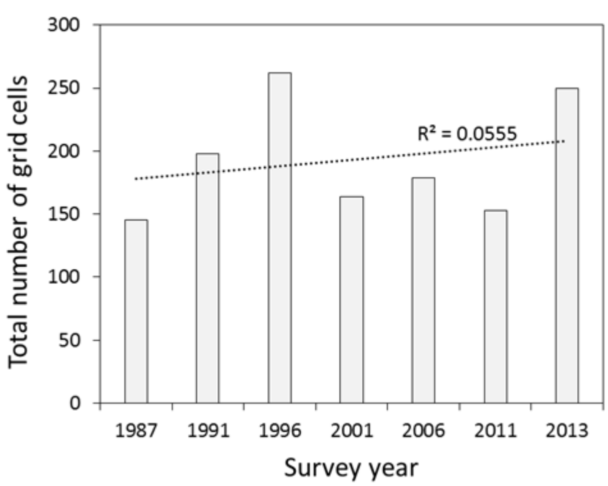

Figure 4. Area of Occupancy: The total number of grid cells of 2 km x 2 km resolution in which at least one dugong was sighted in each survey year based on the transects that were surveyed in all years.

Spatial model and patterns of hunting effort

The spatial model based on corrected data from the 2011 and 2013 surveys of Torres Strait (Figure 5a) shows that 7,011 km^2 of the survey region supports dugongs at high and very high relative density, particularly a large, central area (from south of Boigu Island to north of Badu and Moa Islands; and west of Badu and Muralug Islands, mainly Block 2A [Figure 1]).

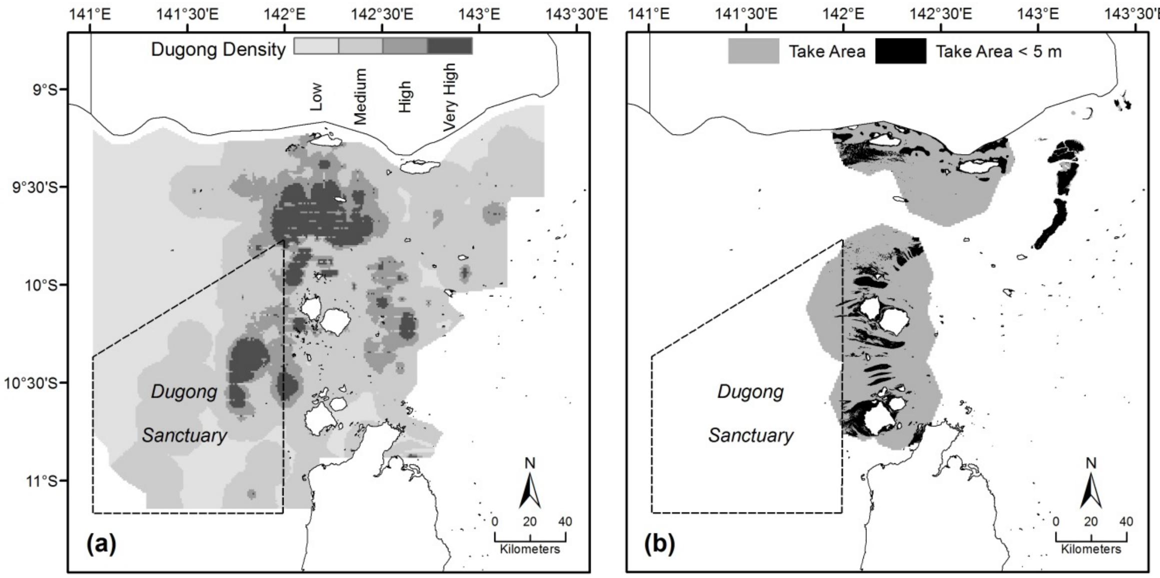

Figure 5: (a) Spatially explicit model of dugong relative density and distribution in Torres Strait based on data from the 2011 and 2013 aerial surveys; and (b) take areas assuming that dugong take is: (1) not depth limited and (2) limited to waters shallower than 5 metres.

We calculated two estimates of the spatial extent of take areas: with and without a depth limit on hunting (Figure 5b; Table 2). Assuming no depth restriction (which does not represent the actual situation), our model indicates that hunting mainly occurs in 30.9 % of the very high density areas and 42.7 % of the high density areas. However, limiting take to waters $\leq$ 5m deep (which we consider to be more realistic), indicates that hunting occurs in 2.0 % of the very high and 5.5 % of the high density areas (Table 2).

Table 2: Overlap between take areas in Torres Strait and the spatial model of dugong relative density and distribution (Figure 5).

Dugong relative density	Area with that density (km^2)	Assuming hunting not limited by depth		Assuming hunting occurs in water ≤ 5m deep	
		Take Area (km^2)	**% Take Area**	**Take Area (km^2)**	**% Take Area**
Low	12250	550	4.5	39	0.3
Medium	21258	6087	28.6	1416	6.7
High	4383	1873	42.7	242	5.5
Very High	2628	811	30.9	53	2.0

DISCUSSION

Status of the dugong in Torres Strait

Our standardized aerial surveys conducted since 1987 have not detected a decline in dugong relative density or Area of Occupancy in Torres Strait. Rather, the aerial survey data indicate that dugong relative density in 2013 was significantly higher than in all other years. This result suggests that the current level of dugong harvest is sustainable. In addition, the Torres Strait dugong population is genetically healthy with the highest genetic diversity of any dugong population in Australia (Blair et al. 2014). The proportion of the population that was classified as calves during the 2013 aerial survey was very high (17.9%) relative to the adjacent northern Great Barrier Reef region (6%) (Sobtzick et al. 2014), presumably reflecting the excellent status of the seagrass habitat in Torres Strait (Marsh and Kwan 2008; Marsh et al. 2011a; Carter et al. 2014a,b). The area of dugong habitat that supports high or very high densities of dugongs in Torres Strait is large (7,011km^2) and hunting is largely restricted to a very low percentage of that habitat (4.2%) due to the input control on the fishery (explained above) and socio-economic reasons. The fuel costs of a successful hunting trip (total fuel costs divided by the probability of success) ranged from between $A120 and $A180; or 46% - 69% of the average weekly income of a resident of an Australian island in Torres Strait (Delisle 2013).

It is possible that dugong density in Torres Strait is being enhanced by migration from other areas such as the northern Great Barrier Reef region adjacent to Torres Strait on the east coast of Queensland. Dugongs are also hunted in the northern Great Barrier Reef region and there is some recent concern about the status of the population as a result of habitat loss from tropical cyclones (Sobtzick et al. 2014), which rarely occur in Torres Strait (Green et al. 2010). Dugongs from Torres Strait have not been genetically differentiated from those in the northern Great Barrier Reef using microsatellite or mitochondrial markers (Blair et al. 2014) suggesting that such movements occur. Although dugong movements have not been documented between the northern Great Barrier Reef and Torres Strait, dugongs are capable of moving distances equivalent to that between the two areas (Sheppard et al. 2006, Gredzens et al. 2014). Satellite tracking data are available from only six dugongs tagged in Torres Strait and genetic pedigree analysis of dugongs from South–East Queensland indicates that satellite tracking and genetic tagging tend to underestimate dugong movements (Cope et al. 2015). If large numbers of dugongs have moved between the northern Great Barrier Reef and Torres Strait, their movements are likely to have been associated with seagrass diebacks (Marsh and Kwan 2008, Marsh et al. 2011a), especially the loss of seagrass resulting from extreme weather events on the east coast of Queensland (Sobtzick et al. 2012; Rasheed et al. 2014). We have no data to test this hypothesis.

Long-term risks to dugongs in Torres Strait

As explained above, dugongs have been harvested in Torres Strait for millennia (Crouch et al. 2007; Wright 2010) and the harvest has been substantial for at least 400 – 500 years (McNiven and Beddingfield 2008). Experience with other large mammals (Johnson 2006) demonstrates that even very low levels of anthropogenic mortality can drive species to extinction if all individuals in the prey populations are exposed to mortality at some stage of their lives. This situation is most likely if: (1) animals are exposed to anthropogenic mortality in all the habitats in which they live; (2) human population size does not depend strongly on access to megafauna; and/or (3) animals in low density populations are still exposed to the risk of being killed.

The second of these conditions certainly applies to dugongs in Torres Strait waters. The human population of the region is low as explained above. The most important motives for hunting by the Australian communities are cultural (Delisle 2013). However, food security could be an issue for the Papua New Guinea villagers because that countries' Human Development Index is low (157 out of 187 countries and territories in 2013 http://hdr.undp.org/sites/all/themes/hdr_theme/country-notes/PNG.pdf.) Condition (3) also applies because dugongs and green turtles are hunted by the same people using the same vessels and equipment (Johannes and MacFarlane 1991) and many dugong and turtle hunters are also crayfishers and hunt opportunistically while fishing (Marsh et al. 1997, Kwan et al. 2006). However, the first of Johnson's (2006) conditions does not apply in Torres Strait. Significant numbers of dugongs occur in areas where indigenous hunting does not occur (Figure 5 and Table 2). The high proportion of the dugong habitat that is never hunted presumably contributes to the sustainability of dugong hunting, especially as dugongs move widely within Torres Strait where the area of seagrass is larger than anywhere else in Australia (Gredzens et al. 2014; Figure 5a).

Dugongs are long-lived and slow to mature. The greatest risks are from anthropogenic mortality (Marsh et al. 2011a). The major sources of direct anthropogenic mortality to dugongs in the Torres Strait are the unknown levels of indigenous harvest, which is substantial (Marsh et al. 2004) and some illegal poaching, including poaching by foreign fishers. Another concern is the potentially burgeoning risks to this generally pristine dugong habitat (see Halpern et al. 2008) from oil spills and damage to seagrass beds as a result of the increase in commercial shipping resulting from current and proposed port expansions along the urban Great Barrier Reef coast (e.g., Waterhouse et al. 2012; Grech et al. 2013) and at Daru, the capital of the Western Province of Papua New Guinea. Climate change (Carter et al. 2014c) and seagrass diebacks of unknown cause (Daniell et al. 2008) are additional long-term threats to the seagrass habitats of Torres Strait on which dugongs depend. Thus ongoing management is important, especially given the wider Australian community's objections to the harvest.

Implications for management of the Torres Strait dugong harvest

In the light of positive indicators of the status of the dugong in Torres Strait resulting from our analysis of the long-term survey data, we consider that the major priority for dugong management in this region should be the continued support of the culturally acceptable and scientifically robust community-based mechanisms to manage indigenous hunting. Community-based Turtle and Dugong Management Plans now strengthen the statutory management arrangements imposed by the Commonwealth *Torres Strait Fisheries Act 1984* and its regulations by reinforcing cultural practices and protocols designed to control hunting (Marsh et al*.* 2011a).

The current Turtle and Dugong Management Plans have been developed separately by each community. Gredzens et al. (2014) demonstrated using GPS satellite telemetry that the home ranges of dugongs in Torres Strait are generally much larger than those in the other areas where dugongs have been tracked in Australia and Indonesia. One of six tracked dugongs crossed the international boundary between Australian and Papuan New Guinean waters. These results indicate the need for co-ordinated management of dugongs across international and regional jurisdictions.

Estimating a scientifically-defensible sustainable Total Allowable Catch for the Torres Strait dugong fishery would require robust information on the sizes of both the dugong population and the catch. As discussed above, the population estimates obtained from our aerial surveys are likely to be substantial underestimates, because of the bathymetry of Torres Strait (Hagihara et al*.*2014). It will be important to conduct the experimental work required to obtain availability correction factors appropriate to the area. Reliable estimates of the current dugong catch of each of the major hunting communities in the greater Torres Strait region administered by both Australia and Papua New Guinea will also be necessary to evaluate the likely sustainability of the dugong harvest using appropriate modelling techniques. Grayson (2011) offers important insights into how catch monitoring might be effectively implemented by transferring the reporting burden from the hunters to indigenous rangers, trained to collect longitudinal data from each hunter at regular intervals. Such techniques (Pollock et al. 1994) have been widely used to survey recreational fishers (Lyle et al. 2002; Henry and Lyle 2003). It would be important to include the Papua New Guinean villagers and the communities on the nearby Australian mainland in such an initiative.

Conclusions

Using several lines of evidence, we conclude that the indigenous fishery for dugongs in Torres Strait is likely to be sustainable. A scientifically defensible Total Allowable Catch for dugongs in Torres Strait is clearly at least several years away because: (1) the voluntary Islander reporting of the dugong catch is limited to the Australian communities and does not include effort data and (2) obtaining an accurate population estimate is so difficult. Even if the data required to implement a robust Total Allowable Catch were available, it could not be implemented using top-down rules that cannot be monitored or enforced in this remote, sparsely-populated area that spans two countries.

Further reinforcement of cultural tenure and taboos including spatial closures may be a more practical approach than conventional fisheries management, but will require cross-jurisdictional collaboration and the support of the Traditional Owners. Hunting never occurs in most of the high and very high density dugong habitat in Torres Strait (Figure 5b; Table 2). The statutory Dugong Sanctuary in western Torres Strait (Figure 5a) comprises about a third of the unhunted area; the remainder is a residual sanctuary that results from: (1) cultural protocols that dictate where hunting should occur and which are reflected in the community-based Turtle and Dugong Hunting Management Plans; (2) the *Torres Strait Fisheries Act* 1984 (C'lth) requirement that hunting must be carried out from vessels ≤ 6 m long; (3) the ban on the sale of dugong meat; and (4) the Torres Strait Islanders' double burden of low incomes and high commodity prices, especially fuel (Delisle 2013).

Our spatial model (Figure5a) could be used by Traditional Owners to inform the design of further designated hunting and no-hunting areas. We suggest that high priority be given to further discussions with communities and the PNG government about the desirability of: (1) declaring some of the high density dugong areas as no-hunting areas for an agreed period; and (2) determining how the Dugong Sanctuary might be extended.

Spatial approaches such as those recommended here may have application in the co-management of other indigenous marine mammal harvests, if that harvest is the major anthropogenic impact on the target population. In such situations, spatial information on: (1) the distribution and relative abundance of the harvested marine mammal population, and (2) the area where harvesting occurs, is much easier to obtain than data on the population sizes and trends and the number of harvested animals. Many cultures have developed restrictions about where fishing and hunting can occur to manage relationships between social groups (Foale et al. 2011). Such restrictions may now be reinforced by poverty and the cost of fuel as in Torres Strait. Encouraging hunters to use such cultural restrictions as part of the input controls on a fishery may be a practical and acceptable method of encouraging local stewardship of marine mammals in the face of public controversy and climate change.

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REFERENCES

Anderson, P. K., and Birtles, A. (1978) Behaviour and ecology of the dugong, *Dugong dugon* (Sirenia): Observations in Shoalwater and Cleveland Bays, Queensland. *Australian Wildlife Research*, **5**: 1-23.

Beckett, J. (1987). Torres Strait Islanders: custom and colonialism. Cambridge, UK, Cambridge University Press.

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

Beissinger, S. R., and Westphal, M. I. (1998). On the use of demographic models of population viability analysis in endangered species management. *Journal of Wildlife Management* **62**: 821-841.

Carter A.B., Taylor H.A., McKenna S.A. and Rasheed M.A. (2014a). Long-term Seagrass Monitoring in the Port of Thursday Island: March 2014, James Cook University Publication, Centre for Tropical Water & Aquatic Ecosystem Research report no.14/24, Cairns, 29 pp.

Carter A.B., Taylor H.A., and Rasheed M.A. (2014b) Torres Strait Dugong Sanctuary – Deepwater Seagrass Monitoring 2010 – 2014", JCU Publication, Report no. 14/21, Centre for Tropical Water & Aquatic Ecosystem Research, Cairns, 22 pp.

Carter A.B., Taylor H.A., McKenna S.A, York P.Y. and Rasheed M.A. (2014c). The effects of climate on seagrass in the Torres Strait – 2011-2014 Report. JCU Publication 14/48, Centre for Tropical Water & Aquatic Ecosystem Research, Cairns, 36 pp.

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

Cope R.C., Pollett P.K., Lanyon J.M., 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.

Crouch J., McNiven I.J. , Rowe B. D. C., and Weisle, M, (2007). Berberass: marine resource specialisation and environmental change in Torres Strait over the past 4000 years. *Archaeology in Oceania* **42**: 49-64.

Daniell J. (2008) Development of a bathymetric grid for the Gulf of Papua and adjacent areas: A note describing its development. *Journal of Geophysical Research: Earth Surface.* 113(F01S15): DOI: 10.1029/2006JF000673

Delisle A. (2013) A socio-economic investigation of the Torres Strait Indigenous dugong and turtle fisheries. PhD Thesis, James Cook University, Townsville Queensland Australia.

Delisle A., Watkin Lui F., Stoeckl N., and Marsh H. (2014) The sharing and consumption of dugong and turtle meat outside Torres Strait: management strategies and options. Final Report to the Australian Marine Mammal Centre (Project # 11/6). James Cook University, Townsville.

Foale S., Cohen P., Januchowski-Hartley S., Wenger A., and Macintyre M. 2011. Tenure and taboos: origins and implications for fisheries in the Pacific. *Fish and Fisheries*: **12**: 357 – 369.

Grayson J. (2011) Characteristics of traditional dugong and green turtle fisheries in the Torres Strait: opportunities for management. PhD Thesis, James Cook University, Townsville Queensland Australia.

Grech A., Sheppard J., Marsh H. (2011) Informing species conservation at multiple scales using data collected for marine mammal stock assessments. *PLoS ONE*, E 6(3): e17993. doi:10.1371/journal.pone.0017993

Grech A, Bos M., Brodie J., Coles R., Dale A., Gilbert R., Hamann M., Marsh H., Neil K., Pressey R.L., Rasheed M.A., Sheaves M., and Smith A. (2013). Guiding principles for the improved governance of port and shipping impacts in the Great Barrier Reef. *Marine Pollution Bulletin,* 75: 8 - 20.

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

Green D., Alexander L., McLnnes K., Church J., Nicholls N., White N. (2010). An assessment of climate change impacts and adaptation for the Torres Strait Islands, Australia. *Climatic Change,* **102**: 405-433.

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

Halpern B.S., Walbridge S., Selkoe K. A., Kappel C. V., Micheli F., D'Agrosa C., Bruno J. F., Casey K. S., Ebert C., Fox H. E., Fujita R., Heinemann D., Lenihan H. S., Madin E. M. P., Perry M. T.,

Selig E. R., Spalding M., Steneck R., and Watson R. (2008) A global map of human impact on marine ecosystems. *Science*: **319**, 948–952.
Havemann P., and Smith R. (2007). Current legislation and policy conducive to sustainable community management of dugong and turtle Traditional fisheries in the Torres Strait TSRA Torres Strait Dugong & Marine Turtle Project Governance & Policy Review Consultancy Contract # 070918.
Havemann P., Thiriet D., Marsh H., and Jones C. (2005) Decolonising conservation? Traditional use of marine resources agreements & dugong hunting in the Great Barrier Reef World Heritage Area. *Environmental & Planning Law Journal*, **22**: 258-280.
Heinsohn R., Lacy, R.C. et al., Lindenmeyer D.B., Marsh H. Kwan D., and Lawler I.R. (2004). Unsustainable harvest of dugongs in Torres Strait and Cape York (Australia) waters: two case studies using population viability analysis. *Animal Conservation* **7**: 417-425.
Henry G. W., and Lyle J. M. (2003) The national recreational and Indigenous fishing survey. Final report to the Fisheries Research and Development Corporation, Project 99/158. NSW Fisheries Final Report Series No. 40, 188pp.
Hudson B. E. T. (1986) The hunting of dugong in Daru, Papua New Guinea, during 1978-82: community management and education initiatives. In: Haines A.K., Williams G.C., Coates D. (Eds). Torres Strait Fisheries Seminar, Port Moresby, 11-14 February 1985, Australian Government Printing Service, Canberra. pp. 77–94.
IUCN (2001) IUCN Red List Categories and Criteria: Version 3.1. IUCN Species Survival Commission. IUCN, Gland, Switserland.
Johannes R. E., and MacFarlane J. W. (1991) Traditional fishing in the Torres Strait Islands. CSIRO Division of Fisheries, Hobart, Australia. 268 pp.
Johnson C. (2006) Australia's Mammal Extinctions: A 50,000-Year History. Cambridge University Press, Cambridge, 278 pp.
Kwan, D. (2002). Towards a sustainable indigenous fishery for dugongs in Torres Strait: A contribution of empirical data analysis and process. PhD Thesis, James Cook University, Townsville Queensland Australia.
Kwan D., Marsh H., and Delean S. (2006) Factors affecting the customary hunting of a threatened marine mammal by a remote Indigenous community. *Environmental Conservation*, **33**: 164-171.
Lyle J. M., Coleman A. P. M., West L., Campbell D., and Henry, G. W. (2002) An innovative methodology for the collection of detailed and reliable data in large-scale Australian recreational fishing surveys. In: Recreational Fisheries: Ecological, Economic and Social Evaluation, Pitcher TJ & Hollingsworth, CE (eds). pp 207-226. Fisheries and Aquatic Resources Series No. 8, Blackwell Sciences, Oxford, UK.
Marsh, H. 1996. Progress towards the sustainable use of dugongs by Indigenous peoples in Queensland. Pages 139-151 in Bomford T. M. and Caughley J. eds *The Sustainable use of wildlife by Aboriginal & Torres Strait Islander people* AGPS, Canberra.
Marsh H., and Sinclair D. F. (1989a) Correcting for visibility bias in strip transect aerial surveys of aquatic fauna. *Journal of Wildlife Management* **53**:1017-1024.
Marsh H., and Sinclair D. F. (1989b) An experimental evaluation of dugong and sea turtle aerial survey techniques. *Australian Wildlife Research* **16**: 639–650.
Marsh H., Harris A. N. M., and Lawler, I. R. (1997) The sustainability of the Indigenous dugong fishery in Torres Strait, Australia/Papua New Guinea. *Conservation Biology* **11**: 1375-1386.

Marsh H., Eros C., Penrose H. and Hughes J. (2002) Dugong status report and action plans for countries and territories. UNEP Early Warning and Assessment Report Series 1. Cambridge : UNEP.

Marsh H., Lawler I. R., Kwan D., Delean S., Pollock K., and Alldredge M. (2004) Aerial surveys and the potential biological removal technique indicate that the Torres Strait dugong fishery is unsustainable. *Animal Conservation* **7**: 435-443.

Marsh H., and 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**: 2152-2159

Marsh H., O'Shea T. J., and Reynolds J.R. (2011a) The ecology and conservation of Sirenia; dugongs and manatees. Cambridge University Press, 521pp.

Marsh H., Grech A., and Hagihara R. (2011b) Aerial survey of Torres Strait to evaluate the efficacy of an enforced and possibly extended Dugong Sanctuary as one of the tools for managing the dugong fishery. Report to the Australian Marine Mammal Centre and the Torres Strait Regional Authority. 33pp.

McNiven, I.J. and Bedingfield, A. (2008) Past and present marine mammal hunting rates and abundances: Dugong (*Dugong dugon*) evidence from Dabangai Bone Mound, Torres Strait. *Journal of Archaeological Science* **35**: 505–515.

OESR (2013). Indigenous Regional Profiles Census 2011. Produced by the Office of Economic and Statistical Research in the Queensland Department of Treasury and Trade. Accessed 16 Jan 2014, http://www.oesr.qld.gov.au/regions/fitzroy/profiles/indigenous-reg-profiles-c11/index.php

Pollock K. H., Jones C. M., and Brown, T. L. (1994) Angler survey methods and their applications in fisheries management. American Fisheries Society Special Publication 56, Bethesda, Maryland.

Pollock K., Marsh H., Lawler I., and Alldredge M. (2006) Modelling availability and perception processes for strip and line transects: an application to dugong aerial surveys. *Journal of Wildlife Management* **70**: 255-262.

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

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

Robards MD and Reeves RR (2011) The global extent and character of marine mammal consumption by humans: 1970–2009. *Biological Conservation*, **144**: 2770–2786.

Sheppard J. K., Preen A. R., Marsh H., Lawler I. R., Whiting S., and 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.

Sheppard, J.K., Carter, A.B., McKenzie, L. J., Pitcher, C. Roland, and Coles, R. G. (2008) Spatial patterns of sub-tidal seagrasses and their tissue nutrients in the Torres Strait, northern Australia: implications for management. *Continental Shelf Research*, **28:** 2282-2291.

Skaug H., Fournier D., Bolker B., Magnusson A., and Nielsen A. (2014). Generalized Linear Mixed Models using AD Model Builder. R package version 0.8.0.

Sobtzick S., Hagihara R., Grech A., and 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.

Sobtzick, S., Penrose, H., Hagihara, R., Grech, A., Cleguer, C., and Marsh, H. (2014) An assessment of the distribution and abundance of dugongs in the Northern Great Barrier Reef and Torres Strait. Report No. 14/17. Report for the Department of the Environment, National Environmental Research Program (NERP). June 2014

Taylor B. L., Matinex M., Gerrodette T., and Barlow J. (2007) Lessons from monitoring trends in abundance of marine mammals. *Marine Mammal Science*, **23**: 157-175.

Taylor, H.A. and Rasheed, M.A. (2010). Torres Straits Dugong Sanctuary Seagrass Baseline Survey, March 2010. DEEDI Publication (Fisheries Queensland, Northern Fisheries Centre, Cairns), 22 pp.

Wade, P. R. (1998). Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science*: **14**: 1–37. doi: 10.1111/j.1748-7692.1998.tb00688.x

Waterhouse J., Brodie J., Wolanski E., Petus C., Higham W., and Armstrong T. (2013) Hazard assessment of water quality threats to Torres Strait marine waters and ecosystems. Technical Report. National Environmental Research Program. Tropical Ecosystems Hub 76 pp.

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

Wright, D. (2011) Mid Holocene maritime economy in the western Torres Strait. *Archaeology in Oceania* **46**: 23-27.

Zuur, S. I. (2012) Zero inflated models and generalized linear mixed models with R**.** Highland Statistics Limited.

Supporting documentation

Appendix 1: Pair-wise comparison of dugong relative density[1] across: a) survey years and b) blocks examined using the glmmADMB package.

a) Years							
	1987	1991	1996	2001	2006	2011	2013
1987							↑***
1991				↓*		↓*	↑***
1996				↓**		↓**	↑***
2001		↑*	↑**				↑***
2006							↑***
2011		↑*	↑**				↑***
2013	↓***[2]	↓***	↓***	↓***	↓***	↓***	

b) Blocks								
	0	1A	1B	2A	2B	3	4	5
0			↑*	↑***				↓**
1A			↑*	↑***				↓**
1B	↓*	↓*		↑***	↓**			↓***
2A	↓***	↓***	↓***		↓***	↓***	↓***	↓***
2B			↑**	↑***		↑**		↓***
3				↑***	↓**			↓***
4				↑***				↓***
5	↑**	↑**	↑***	↑***	↑***	↑***	↑***	

[1]estimated from corrected counts with area of transect as an offset

[2] examples to aid interpretation; 1987 had significantly lower relative density than 2013 across blocks

[3] significance codes: <0.001 =***; 0.001< 0.01 =**; 0.01≤0.05 =*

Appendix 2: Coefficients of the zero-inflated model with Negative Binomial distribution of dugong relative density[1] across a) survey years and b) blocks examined using the glmmADMB package. The reference level is Year 2013 for (a) and Block 2A for (b).

a) Years	Estimates	Std. Error	Z value	Pr(>|z|)	
(Intercept)	0.536	0.128	6.55	<0.001	***
Year 1987	-1.016	0.187	-5.43	<0.001	***
Year 1991	-0.767	0.179	-4.29	<0.001	***
Year 1996	-0.693	0.173	-4.01	<0.001	***
Year 2001	-1.231	0.185	-6.66	<0.001	***
Year 2006	-0.948	0.179	-5.29	<0.001	***
Year 2011	-1.216	0.189	-6.44	<0.001	***
b) Blocks	**Estimates**	**Std. Error**	**Z value**	**Pr(>|z|)**	
(Intercept)	0.668	0.094	7.12	<0.001	***
Block 0	-1.133	0.258	-4.39	<0.001	***
Block 1A	-1.229	0.254	-4.84	<0.001	***
Block 1B	-0.579	0.175	-3.31	<0.001	***
Block 2B	-1.196	0.153	-7.82	<0.001	***
Block 3	-0.767	0.139	-5.51	<0.001	***
Block 4	-1.024	0.202	-5.08	<0.001	***
Block 5	-2.231	0.267	-8.36	<0.001	***

[1]estimated from corrected counts with area of transect as an offset

[2] significance codes: <0.001 =***; 0.001< 0.01 =** ;0.01≤0.05 =*

Appendix 5 – Fuentes *et al.* draft paper for submission to PLOS One

Spatial and temporal variation in the effects of climatic variables on dugong calf production and neonatal survivorship

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Abstract

Knowledge of the relationship between environmental forcing and demographic parameters is important to predict responses from climatic changes and to manage populations effectively. Here we explore the relationship between climatic drivers and demographic parameters of the dugong, *Dugong dugon,* a marine herbivorous endotherm. Historical data were used to investigate how the proportion of dependent calves in a population is affected by various climatic covariates (rainfall anomaly, SOI, NINO 3.4, and tropical cyclones) at a range of spatially distinct locations in Queensland, Australia, a region with relatively high dugong density. The relationship between this demographic parameter and climatic drivers varied spatially and temporally, with climatic drivers influencing dugong calf production and neonatal survivorship at local rather than regional (ocean basin) scales. Given the variability and local scale relationships between the proportion of dependent calves in a population and climatic drivers, we recommend that the assessments of and management response to indirect climatic threats on dugongs should be at local scales.

Keywords: dugongs, climate, calf production, neonatal survivorship, population dynamics, temperature, rainfall, cyclones, Australia

Introduction

Understanding the mechanisms underpinning population dynamics is central to many ecological and evolutionary questions and to the development of effective conservation strategies (1-3). The dynamics of a population are a function of its key demographic parameters such as mortality, fecundity and migration rates (4). All these parameters are directly and/or indirectly influenced by environmental and climatic drivers (e.g., 5-7). Indirect pathways occur mainly through reductions in food and the availability of quality habitat (e.g., 8).

Interest in the relationship between demographic parameters and environmental and climatic drivers has increased as a result of concerns about the ecological impacts of climate change on individual species (e.g., 9, 10). Understanding the relationship between environmental forcing and demographic parameters is an important first step in predicting the impacts of extreme weather events and climate change (5, 11). For example, understanding the relationship between the number of breeding green turtles, *Chelonia mydas*, in Australia and the Southern Oscillation Index (SOI) has enabled the annual green turtle nesting population at key eastern Australian rookeries to be predicted with reasonable confidence based on the SOI two years before the commencement of a breeding season (8, 12). This relationship suggests that the SOI influences the proportion of sub-adult and adult females able to acquire the fat reserves necessary to breed, a proportion limited by the availability of their food, principally seagrass and algae (8). Mass nesting is generally recorded two years after major El Niño events, while extremely low nesting numbers tend to be recorded two years after major La Niña events (8). This knowledge is potentially of great value for managing green turtles in the Australian region, particularly in areas where nesting females and their eggs are harvested (12).

Environmental and climatic drivers also influence key demographic parameters of another seagrass community specialist, the dugong, *Dugong dugon* (13, 14). Dugongs occur sympatrically with green turtles in the coastal and island waters of the tropical and Indo-West Pacific (15). Extreme weather events (e.g., cyclones and flooding) have been associated with the following impacts on dugongs: mass stranding, increased movements presumably in search of food, loss of weight and fat, delayed reproduction and mortality (14, 16-19). For example, the proportion of dependent calves in the dugong population in Hervey Bay (Queensland, Australia) plummeted after two floods and a cyclone in 1992, a sequence of extreme weather events ,which caused the loss of more than 1000 km^2 of seagrass in the region (13).

Severe weather events affected the 2000 km long urban coast of Queensland, Australia in the summer of 2010/11, including the strongest La Niña weather pattern since 1973, major floods and three tropical cyclones. These events followed several years of deterioration in some seagrass communities as a result of unusually wet weather (20-22). Dugongs moved from affected areas, suffered record mortality, and a reduction in fecundity and neonatal survivorship was observed as evidenced by the proportion of dugong classified as dependent calves (15, 23-25). Aerial surveys following these extreme weather events suggested that the dugongs' responses were geographically uneven and much more evident in the Southern Great Barrier Reef region (latitudes 24° 30'S to 15^0 30' S) than in Hervey Bay (25° 17' S) or Moreton Bay (27^{0} 28'S) (24). These examples suggest that in contrast to the green turtle, the dugong's demographic parameters can be negatively impacted by key climatic drivers at local rather than regional (ocean basin) scales. The differences between the scale at which climate drivers affect green turtles and dugongs may reflect their biology, movement patterns and use of the environment.

Here we test the prediction that the relationship between climatic drivers and demographic parameters of the dugong, a marine herbivorous endotherm, may operate at more local scales than for the green turtle, a sympatric ectotherm with a more restricted foraging range than the dugong and high site fidelity (26). We use historical data to investigate how dugong calf counts are affected by various climatic covariates (rainfall anomaly, SOI, NINO 3.4, and tropical cyclones) at a range of spatially distinct locations in Queensland, Australia, an area with relatively high dugong density.

Materials and Methods

Study Region

Our study area is the eastern Queensland coast (Fig. 1) including Torres Strait, a region which supports globally significant populations of dugongs (14). We divided the coast into 5 subregions (Torres Strait, Northern and Southern Great Barrier Reef (GBR), Hervey Bay and Moreton Bay) (Fig. 1) to match the biological datasets used for this study (Table 1).

[Fig. 1] [2]

Dugong calf production and neonatal survivorship

The proportion of dugongs that were dependant calves was recorded for aerial surveys conducted in eastern Queensland since the middle of the 1970s (24, 27-31); Table 1). A calf was identified as an animal less than two thirds of the size of and swimming in close proximity to a mature dugong. Marsh et al. (14) summarise the literature on dugong reproduction. Like green turtles, dugongs apparently require significant fat stores to ovulate and conceive. Gestation is estimated to last about 14 months and calves are dependent on their mother for some 18 months, even though they start eating seagrass soon after birth. Thus the proportion of dependant calves sighted during aerial surveys is a combined index of calf production (which is expected to reflect the environmental conditions over several years) and neonatal survivorship (which is likely to be a more immediate response to seagrass loss).

[2] The figures are at the end of the paper

Table 1. Details of the aerial survey data used in this paper. For a full list of sources see 24, 28, 32, 33 .

Subregions	Year
Torres Strait **10° 29'S 142° 10' E**	1991, 1996, 2001, 2006, 2011, 2013
Northern Great Barrier Reef **11°32'S -15 ^{0}30'S**	1978, 1984, 1985, 1990, 1995, 2000, 2006, 2013
Southern Great Barrier Reef **15 ^{0}30'S-24^0 30'S**	1974, 1975, 1976, 1977, 1978, 1979, 1986, 1992, 1994, 1999, 2005, 2011
Hervey Bay **25° 17' S**	1979, 1988, 1992, 1993, 1994, 1999, 2001*, 2005, 2011
Moreton Bay **27° 28' S**	1976, 1977, 1979, 1995, 1999, 2000, 2001*, 2005, 2011

*Surveys conducted both in autumn (April) and summer (November).

The sampling effort varied spatially and temporally depending on the availability of resources (see Table 1). All aerial surveys were conducted as described by Marsh, Marsh and Sinclair or Pollock et al. (31, 34, 35). Differences between survey methodologies should not have affected the proportion of animals classified as dependent calves. Aerial surveys were conducted mostly during late spring or early summer when weather and sea states provide optimum survey conditions. However, since dugongs move during winter in response to low water temperatures at the higher latitudinal limits to the dugong's range in Moreton Bay and Hervey Bay (36) some aerial surveys at these locations were also conducted during winter (Table 1). Given the dugong's diffusely seasonal breeding cycle and protracted period of calf dependency (14, 37), seasonal differences in the timing of aerial surveys should not have affected the proportion of dugongs classified as calves.

Climatic covariates

The influences of climatic covariates on the proportion of dependent calves in a population were explored for: (1) rainfall anomaly - wet season rainfall anomaly (difference between wet season rainfall for a surveyed subregion and the 30 year average for that subregion; (2) SOI - the November to February Southern Oscillation Index (SOI); (3) NINO 3.4 - the November to February NINO 3.4 sea surface temperature index; and (4) tropical cyclones (TC). Data on the first three climatic covariates were obtained from the Australian Bureau of Meteorology (http://www.bom.gov.au/). The cyclone track data were obtained from the International Best Track Archive for Climate Stewardship (IBTrACS) dataset (38). Tropical cyclone tracks were interpolated onto a 1°× 1° grid and the region of influence of each tropical cyclone was calculated using an effective radius of 5° longitude/latitude. A tropical cyclone was included in the analysis if it came within 5° of the coastline of any of the subregions in Table 1.

Data analysis

Exploratory analysis

The data were explored for over-dispersion by overlaying the proportion of dependent calves per subregion and year with the probability from a null Binomial generalised linear model. The dataset was also explored for zero-inflation by comparing the percentage of zeroes in the data to the percentage expected from a binomial distribution with a centrality parameter equal to that estimated from the data.

Data processing

The initial exploratory data analysis suggested that data were over-dispersed (relative to a Binomial distribution), yet not zero-inflated. Hence all models were fit against a Beta-Binomial (logit) distribution. Temporal trends in the proportion of dugongs with calves were explored via a Beta-Binomial (logit-link), Bayesian penalized spline regression (39):

$$y_{ij} \sim \text{Binomial}(\pi_{ij}, n_{ij})$$
$$\pi_{ij} \sim \text{Beta}(a_{ij}, b_{ij})$$
$$a_{ij} = \theta\pi_{ij}$$
$$b_{ij} = \theta(1 - \pi_{ij})$$
$$\text{logit}(pi_{ij}) = f(t_{ij}) + f_l(t_{ij})$$

$$\begin{cases} f(t) = \beta_0 + \beta_1 t + \sum_{k=1}^{K} r_k\, z_{tk} \\ f_l(t) = \gamma_{ol}\, l_{(l>1)} + \gamma_{1l}\, tl_{(l>1)} + \sum_{k=1}^{K} s_{lk}\, z_{tk} \end{cases}$$

$$\begin{cases} \beta_0, \beta_1 & \sim N(0, \sigma^2) \\ \gamma_o, \gamma_1 & \sim N(0, \sigma_\gamma^2), l = 1, \dots, 5 \\ r_k & \sim N(0, \sigma_r^2), k = 1, \dots, K \\ s_k & \sim N(0, \sigma_s^2), l = 1, \dots, 5, k = 1, \dots, K \\ \sigma^2, \sigma_\gamma^2, \sigma_r^2, \sigma_s^2 & \sim HC(0, 25) \\ \theta & \sim U(0, 100) \end{cases}$$

where y_{ij}, n_{ij} and t_{ij} are are the number of dugongs without calves, the total number of dugongs and the year within population $_i$ and year $_j$ respectively. $f(t)$ *and* $f_l(t)$ respectively represent the overall smooth curve and the deviations of each population from this overall curve. z_{tk} represents a design matrix for the thin-plate spline with three knots (K = 3). Non-informative normal priors were specified for all model parameters and half-cauchy (scale=25). Priors were specified for variances (40).

To explore the temporal trends, 1500 samples were collected from three chains with a total of 300,000 iterations, burnin of 50,000 per chain and thinning rate of 10. Chain mixing and convergence were assessed via traceplots, autocorrelation and Gelman-Rubin diagnostics (all scale reduction factors less and 1.05).

As dugongs have a long reproductive cycle (14, 41), calf production is likely to be impacted by an accumulation of past conditions, with each climatic covariate potentially influencing calf counts with a lagged and/or instantaneous effect (15). Therefore, appropriately lagged versions of each of the focal climatic covariates, scaled to a mean of 0 and standard deviation of 1, were first selected from a range of candidates (lags ranging from zero to four years prior to survey year) via Gibbs variable selection (42).

For each climatic covariate, a model was fit containing proportion of calves crossed with each of the lagged versions of the covariate. The lagged version with the highest posterior probability was considered the most appropriate and selected for the full covariate model.

y_{ij} ~ Binomial (π_{ij}, n_{ij})
π_{ij} ~ Beta (a_{ij}, b_{ij})
$a_{ij} = \theta\pi_{ij}$
$b_{ij} = \theta(1 - \pi_{ij})$
logit (pi_{ij}) = η_{ij}
$\eta_j = \gamma_j\beta_j X_j$
$\gamma_j = \mathrm{Ind}_j - 1$

$$\begin{cases} \mathrm{Ind}_j & \sim \mathrm{Cat}(p), \text{ where } p = \frac{1}{2}, 1-\frac{1}{2} \\ \beta_j & \sim N(0, \sigma^2{}_{\mathrm{Indj}}) \\ \sigma^2{}_{\mathrm{Indj}} & \sim HC(0,25) \\ \theta & \sim U(0,100) \end{cases}$$

y_{ij}, n_{ij} and x_{ij} are respectively the number of dugongs without calves, the total number of dugongs within observation *j* of population *i* . X_j is the design matrix for the interaction of population and each lagged version of the covariate. *j* is an vector indicator in the range [0,1] indicating which set ofvariables is present in the model. Variables with posterior model probabilities exceeding 0.5 (50% of models) were considered important predictors of the proportion of dependent calves in a population and selected for the full covariate model. Selected lagged covariates along with population were thereafter fit with the same Beta-Binomial with Gibbs variable selection models as described above. All Bayesian models were fit using JAGS (43) using the R2jags (44) and coda (45) packages for R (46).

Results

Proportion of calves

The proportion of calves varied across the different locations (Table 2 and Fig. 2) ranging from 0 in Moreton Bay in 1999 and the Southern Great Barrier Reef in 2011 to 0.22 in Hervey Bay in 1988 and 1992 (Fig. 2). The average proportion of calves over all of the years in each location ranged from 0.072 in Moreton Bay to 0.139 in Torres Strait (Table 2). No strong temporal changes in the proportion of calves were observed for any of the subregions however, the proportion of calves appear to have increased in the Northern and Southern Great Barrier Reef regions in the late 1990s before declining (Fig. 2).

Table 2. Proportion of dugong calves for each subregion during the study period.

Subregion*	# years*	Average proportion of calves (range)
Torres Strait	6	0.139 (0.099 - 0.176)
Northern Great Barrier Reef	8	0.094 (0.002 - 0.128)
Southern Great Barrier Reef	12	0.079 (0 - 0.188)
Hervey Bay	9	0.104 (0.015 - 0.221)
Moreton Bay	9	0.072 (0 – 0.124)

*For details of regions and survey years refer to Table 1.

Overall time lags: best fit models for proportion of dugong calves

The time lags with the highest posterior probability for the proportion of dugong calves varied with climate covariates and subregion (Table 3, S1 Fig.). For rainfall anomaly, lags of 2 and 4 years were found to have the highest general (mean) and specific posterior probability. A lag of 4 years was selected for SOI. Lagged versions of 1, 2 and 4 years were selected for Nino 3.4 and lags of both 1 and 2 years were considered important for tropical cyclones (Table 3, S1 Fig.).

Table 3. Posterior model probabilities in Beta-Binomial regression with Gibbs variable selection for each of the lags of the five climatic covariates. Grey highlights indicate important predictors of the proportion of dugong calves and thus were selected for the full covariate model.

Model	Variable	Torres Strait	Northern Great Barrier Reef	Southern Great Barrier Reef	Hervey Bay	Moreton Bay	Mean	Maximum
Rainfall Anomaly	Population	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Lag 0	0.16	0.26	0.26	0.28	0.14	0.22	0.28
	Lag 1	0.12	0.20	0.16	0.23	0.25	0.19	0.25
	Lag 2	0.14	0.40	0.26	0.79	0.31	0.38	0.79
	Lag 3	0.15	0.15	0.31	0.31	0.46	0.27	0.46
	Lag 4	0.35	0.74	0.37	0.23	0.11	0.36	0.74
SOI	Population	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Lag 0	0.15	0.30	0.18	0.16	0.21	0.20	0.30
	Lag 1	0.13	0.16	0.16	0.16	0.18	0.16	0.18
	Lag 2	0.15	0.14	0.17	0.26	0.14	0.17	0.26
	Lag 3	0.14	0.22	0.20	0.24	0.11	0.18	0.24
	Lag 4	0.10	0.94	0.12	0.17	0.32	0.33	0.94
Nino 3.4	Population	1.00	1.00	1.00	0.99	1.00	1.00	1.00
	Lag 0	0.23	0.12	0.20	0.11	0.21	0.17	0.23
	Lag 1	0.12	0.73	0.63	0.57	0.37	0.48	0.73
	Lag 2	0.12	0.17	0.11	0.79	0.10	0.26	0.79
	Lag 3	0.13	0.23	0.32	0.43	0.10	0.24	0.43
	Lag 4	0.11	0.96	0.24	0.14	0.25	0.34	0.96
Tropical cyclones	population	0.99	1.00	1.00	1.00	1.00	1.00	1.00
	Lag 0	0.21	0.22	0.12	0.12	0.17	0.17	0.22
	Lag 1	0.16	0.14	0.29	0.99	0.22	0.36	0.99
	Lag 2	0.15	0.99	0.11	0.11	0.14	0.30	0.99
	Lag 3	0.22	0.23	0.13	0.11	0.20	0.18	0.23
	Lag 4	0.17	0.16	0.20	0.09	0.18	0.16	0.20

Spatial and temporal variation in the effect of climatic covariates on fecundity

The influence of each climatic covariate on the proportion of calves varied spatially and temporally (Figs. 3 and 4 and S1 Fig.). The proportion of calves in Torres Strait and Moreton Bay did not vary with any of the climatic covariates (Figs. 3 and 4). In the Northern Great Barrier Reef region, the proportion of calves declined as the Southern Oscillation Index (lagged to four years) increased (Fig. 4). In the Southern Great Barrier Reef, the proportion of calves declined with: (1) increasing rainfall above the long-term average (lagged to 2 years); (2) increases in Nino 3.4 (lagged to 1 year) and (3) frequency of tropical cyclones (lagged to 1 year) (Figs. 3 and 4). In Hervey Bay, the proportion of calves declined substantially with increased cyclone frequency (lagged by 1 year; Figs. 3 and 4).

Discussion

The relationship between the dugong's demographic parameters and climatic drivers is not as strong as for green turtles. In contrast to their effects on green turtles, climatic drivers influenced dugong calf production and neonatal survivorship at local rather than regional (ocean basin) scales. The differences between the scales at which climate drivers affect reproduction in green turtles and dugongs may reflect the biology, movement patterns and use of the environment of these two sympatric marine herbivores. Green turtles tend to forage at local scales and as cold blooded herbivores can presumably tolerate longer periods of starvation than dugongs, especially as they also eat algae and so are less dependent on seagrasses than dugongs (47). Dugongs forage over larger areas than green turtles and do not demonstrate the same level of site fidelity (26). As mammalian herbivores, dugongs must consume much larger quantities of seagrass than green turtles (47). Thus dugongs undertake large-scale movements between feeding habitats (36), especially in association with episodic habitat disturbance from cyclones and floods (48, 49). These patterns likely make the links between environmental and climatic drivers and demographic parameters of dugongs less direct than those observed for green turtles (e.g., 12).

Dugong mortality shows a similar pattern. The relationships between dugong mortality and climatic drivers (e.g., freshwater discharge, air and sea surface temperature) across the urban Queensland coast (> 2000 km of coastline from Cairns 16 ^{o} 55' S to the NSW border 28^{o} 10' S; Fig. 1) was modelled by Meager and Limpus (5)). Across this region, dugong mortality was predicted by sustained periods of elevated freshwater discharge and low air temperatures (5), however, there was some variation when analyses were conducted for specific latitudinal areas (e.g., Townsville, Moreton Bay and Hervey Bay). This result also indicates that climatic drivers affect dugong demography at local rather than regional scales. These results suggest that: (1) research on the influence of climatic drivers on the demography of the dugong needs to be conducted at local rather than ocean basin scales and (2) predictive models of the impacts of extreme weather events and climate change on these animals also need to be developed at local scales.

Variation in the effect of climatic covariates on the proportion of dependent calves in a population

The best predictors of the effect of each of the climatic variables, we studied, on the proportion of dependent calves in a dugong population was always lagged by at least one year, indicating that they are impacted by an accumulation of past conditions. This result presumably reflects the need for dugongs to be in good condition prior to and during the prolonged periods of pregnancy and lactation (19). Thus, dugong calf counts are influenced by the condition of the mother 2-3 years prior to the survey as well as the availability of seagrass to mothers and calves and the direct impacts of storms on dugongs (13, 14, 16, 17) and their seagrass habitats (13, 20, 21). Thus, in areas with lower levels of exposure to extreme weather events such as cyclones, dugong calf production and neonatal survivorship are less likely to be influenced by climatic drivers than in the cyclone belt. The proportion of dependent calves in the Torres Strait and Moreton Bay dugong populations were not associated with any of the climatic covariates explored here. The major dugong habitat for dugongs in Moreton Bay is in the eastern bay, an environment that is physically separated from the main terrestrial interface with the Queensland coast, flushed with oceanic water on a daily basis (50) and where cyclones are rare. In contrast, the seagrass beds in the other coastal locations we studied (e.g., Great Barrier Reef, Hervey Bay) are influenced by flooding events and subject to more frequent cyclones (5, 13, 20). Torres Strait lies north of the main cyclone belt of the Great Barrier Reef, and is thus less prone to cyclones than the Great Barrier Reef coast (51-53).

Nonetheless, there is evidence of the severe effect of a major seagrass 'dieback' from unknown causes on dugong recruitment in Torres Strait in the 1970s (see 19). Seagrass 'diebacks', extensive mortality of seagrasses occurring over a short period (days to months) (54), are usually caused by light deprivation resulting from sediment resuspension associated with natural events such as cyclones, and/or prolonged periods of monsoon winds (13, 55), or a combination of environmental factors (56, 57). Since cyclones are uncommon in Torres Strait (only two cyclones crossed Torres Strait from 1970-71 to 1979-80, (58) the seagrass dieback in the 1970s is likely to have been influenced by other conditions (59).

The influence of extreme weather events on the proportion of dependent calves in a dugong population is more obvious in Hervey Bay and the Great Barrier Reef region where this parameter was associated with the number of tropical cyclones (negative effect, lagged by 1 year and 2 years, respectively). For example, 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 (13). The impact of extreme weather events, flooding and storms on dugongs is variable. Responses to the extreme weather events in 2010/11 in the eastern Queensland coast, Australia, including the strongest La Niña weather pattern since 1973, major floods and three cyclones, were geographically uneven, with impacts more evident in the Southern Great Barrier Reef than in Hervey Bay or Moreton Bay (24). No calves were seen in the Southern Great Barrier Reef during an aerial survey in late 2011, whereas the proportion of calves in Hervey Bay and Moreton Bay were within normal range (24). These regional differences likely reflect the recent history of seagrass condition in the region (seagrass was in poor condition in the southern Great Barrier Reef prior to the extreme weather events of 2011(20, 22), as well as the species composition and depth distribution of the seagrass community and the nature and timing of the extreme weather events (24). We found that the proportion of dependent calves in the Southern Great Barrier Reef was associated with several climatic covariates (rainfall anomaly, tropical cyclone, and Nino 3.4), suggesting that multiple drivers were affecting the dugong's food supply a result consistent with the findings of Meager and Limpus (2014) as explained below.

Implications for management

Dugongs are long-lived slow breeding animals and the greatest influence on their population dynamics is adult survivorship (14). Hence, dugong conservation management has focused on direct threats (e.g. bycatch, Indigenous harvest, vessel strike). The indirect effects of freshwater discharge and low water temperatures on dugong mortality has been demonstrated (5). Our analysis strengthens the need for managers to consider the effects of indirect stressors (e.g., habitat degradation, food availability) which can influence population dynamics. Consideration of indirect threats from climatic processes will be even more pressing as climate change progresses and emergency responses become more necessary (60). Knowledge of the relationship between climatic drivers and demographic parameters and the lag between an event and impact coupled with predictive models strengthens the need to restrict direct impacts to increase the resilience of dugong populations to climatic drivers. Given the variability and local scale relationship between the proportion of dependent calves in a population and climatic drivers, we recommend that the assessment and management of indirect climatic threats are conducted at local scales. It is important, however to remember that environmental factors not considered here may also affect seagrass (e.g., light deprivation from sediment suspension during prolonged periods of high winds) (57) and that dugong fecundity rates, neonatal survival and mortality may also be influenced by density-dependent responses to changes in population size (19). Thus, all factors affecting a population need to be considered.

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References

1. Frick WF, Reynolds DS, Kunz TH. Influence of climate and reproductive timing on demography of little brown myotis Myotis lucifugus. Journal of Animal Ecology. 2010;79(1):128-36.
2. Gordon IJ, Hester AJ, Festa-Bianchet M. REVIEW: The management of wild large herbivores to meet economic, conservation and environmental objectives. Journal of Applied Ecology. 2004;41(6):1021-31.
3. Tuljapurkar S, Caswell H. Structured-Population Models in Marine, Terrestrial, and Freshwater System: Chapman & Hall; 1997.
4. Crouse DT, Crowder LB, Caswell H. A stage-based population model for loggerhead sea turtles and implications for conservation. Ecology. 1987;68(5):1412-23.
5. Meager JJ, Limpus C. Mortality of Inshore Marine Mammals in Eastern Australia Is Predicted by Freshwater Discharge and Air Temperature. PLoS ONE. 2014;9(4):e94849.
6. Oro D, Torres R, Rodríguez C, Drummond H. Climatic influence on demographic parameters of a tropical seabird varies with age and sex. Ecology. 2010;91(4):1205-14.
7. Stenseth NC, Mysterud A, Ottersen G, Hurrell JW, Chan K-S, Lima M. Ecological Effects of Climate Fluctuations. Science. 2002;297(5585):1292-6.
8. Limpus C, Nicholls N. ENSO Regulation of Indo-Pacific Green Turtle Populations. In: Hammer GL, Nicholls N, Mitchell C, editors. Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems. Atmospheric and Oceanographic Sciences Library. 21: Springer Netherlands; 2000. p. 399-408.
9. Winkler DW, Dunn PO, McCulloch CE. Predicting the effects of climate change on avian life-history traits. Proceedings of the National Academy of Sciences. 2002;99(21):13595-9.

10. Ludwig GX, Alatalo RV, Helle P, Lindén H, Lindström J, Siitari H. Short- and long-term population dynamical consequences of asymmetric climate change in black grouse. Proceedings of the Royal Society B: Biological Sciences. 2006;273(1597):2009-16.
11. Schumann N, Gales NJ, Harcourt RG, Arnould JPY. Impacts of climate change on Australian marine mammals. Australian Journal of Zoology. 2013;61(2):146-59.
12. Limpus CJ, Nicholls N. The Southern Oscillation Regulates the Annual Numbers of Green Turtles (Chelonia mydas) Breeding around Northern Australia. Australian Journal of Wildlife Research. 1988;15:157-61.
13. Preen A, Marsh H. Response of dugongs to large-scale loss of seagrass from Hervey Bay, Queensland, Australia. Wildlife Research. 1995;22(4):507-19.
14. Marsh H, O'Shea TJ, Reynolds III JE. Ecology and Conservation of the Sirena: Dugongs and Manatees. New York: Cambridge University Press; 2011.
15. Meager JJ, Limpus CJ. Marine wildlife stranding and mortality database annual report 2011. Brisbane: 2012.
16. Heinsohn GE, Spain AV. Effects of a tropical cyclone on littoral and sub-littoral biotic communities and on a population of Dugongs (Dugong dugon (Müller)). Biological Conservation. 1974;6(2):143-52.
17. Marsh H. Mass stranding of dugongs bya tropical cyclone in Northern Australia. Marine Mammal Science. 1989;5:78-84.
18. Preen A, Marsh H. Response of dugongs to large-scale loss of seagrass from Hervey Bay, Queensland, Australia. Widlife Research. 1995;22:507- 19.
19. Marsh H, Kwan D. 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. 2008;28(16):2152-9.
20. Rasheed MA, McKenna SA, Carter AB, Coles RG. Contrasting recovery of shallow and deep water seagrass communities following climate associated losses in tropical north Queensland, Australia. Marine Pollution Bulletin. 2014;83(2):491-9.
21. Coles RG, Rasheed MA, McKenzie LJ, Grech A, York PH, Sheaves M, et al. The Great Barrier Reef World Heritage Area seagrasses: Managing this iconic Australian ecosystem resource for the future. Estuarine, Coastal and Shelf Science. 2015;153(0):A1-A12.
22. McKenzie LJ, Collier C, Waycott M. Reef Rescue Marine Monitoring Program - Inshore seagarss. Annual Report for the sampling period July 2011- 31st May 2012. . James Cook University, Cairns TropWATER, 2014.
23. Brodie J, Waterhouse J. A critical review of environmental management of the "not so Great" Barrier Reef. Estuarine, Coastal and Shelf Science. 2012;104-105(0):1-22.
24. Sobtzick S, Hagihara R, Grech A, Marsh H. 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: 2012.
25. GBRMPA. Impacts of Tropical Cyclone Yasi on the Great Barrier Reef: A Report on the Findings of a Rapid Ecological Impact Assessment. Townsville: GBRMPA, 2011.
26. Gredzens C, Marsh H, Fuentes MMPB, Limpus CJ, Shimada T, Hamann M. Satellite tracking of sympatric marine megafauna can inform the biological basis for species co-management. PLoS ONE. 2014;9(6):doi:10.1371/journal.pone.0098944.
27. Lawler IR. Preliminary Report - Aerial survey of dugongs in Moreton Bay and Hervey Bay, April 2001. Brisbane: Queensland Parks and Wildlife Service, 2001.
28. Sobtzick S, Hagihara R, Penrose H, Grech A, Cleguer C, Marsh H. An assessment of the distribution and abundance of dugongs in the Northern Great Barrier Reef and Torres Strait.

A Report for the Department of the Environment, National Environmental Research Program (NERP). 2014 October 2014.
29. Marsh H, Lawler IR. Dugong distribution and abundance in the southern Great Barrier Reef Marine Park and Hervey Bay: Results of an aerial survey in October-December 1999. Townsville: Great Barrier Reef Marine Park Authority, 2001 Research Publication No. 70.
30. Marsh H, Saafeld WK. Distribution and abundance of dugongs in the Great Barrier Reef marine park south of Cape Bedford. Australian Wildlife Research. 1990;17:511-24.
31. Marsh H, Sinclair DF. An experimental evaluation of dugong and sea turtle aerial survey techniques. Australian Wildlife Research. 1989;16:639-50.
32. Grayson J, Marsh H, Delean S, Hagihara R. Improving knowledge of dugong life history using surrogate data. Great Barrier Reef Marine Park Author. 2008.
33. Marsh H., Grech A., R. H. Aerial survey of Torres Strait to evaluate the efficacy of an enforced and possibly extended Dugong Sanctuary as one of the tools for managing the dugong fishery. . 2011.
34. Pollock KH, Marsh H, Lawler IR, Alldredge MW. Estimating animal abundance in heterogenous environments: an application to aerial surveys for dugongs. Journal of Wildlife Management. 2006;70(1):255-62.
35. Marsh H, editor Techniques used for determining age in dugongs based on the examination of layers in hard tissues. The Dugong; 1981; James Cook University, Townsville: James Cook University of North Queensland.
36. Sheppard JK, Preen AR, Marsh H, Lawler IR, Whiting SD, Jones RE. Movement heterogeneity of dugongs, *Dugong dugon* (Müller) over large spatial scales. Journal of Experimental Marine Biology & Ecology. 2006;334:64-83.
37. Marsh H, Heinsohn G, Marsh L. Breeding Cycle, Life History and Population Dynamics of the Dugong, Dugon dugon (Sirenia: Dugongidae. Australian Journal of Zoology. 1984;32(6):767-88.
38. Knapp KR, Kruk MC, Levinson DH, Diamond HJ, Neumann CJ. The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. Bulletin of the American Meteorological Society. 2010;91:363-76.
39. Crainiceanu CM, Ruppert D, Wand MP. Bayesian Analysis for Penalized Spline Regression Using WinBUGS. Journal of Statistical Software. 2005;14:1-24.
40. Gelman A. Prior distributions for variance parameters in hierarchical models. Bayesian Analysis. 2006(3):515-33.
41. Boyd IL, Lockyer C, Marsh HD. Reproduction in marine mammals. In: Reynolds JE, Twiss JR, editors. Marine Mammals: Smithsonian Institution Press; 1999. p. 218-86.
42. Dellaportas P, Forster JJ, Ntzoufras I. On Bayesian model selection and variable selection using MCMC. Statistics and Computing 2002;1(12):27-36.
43. Plummer M, editor JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. Proceedings of the 3rd International Workshop on Distributed Statistical Computing; 2003 March 20-22; Vienna, Austria.
44. Su Y-S, Yajima M. R2jags. 2014. p. A Package for Running jags from R.
45. Plummer M, Best N, Cowles K, Vines K. CODA: Convergence Diagnosis and Output Analysis for MCMC. . R News. 2006;6:7-11.
46. A language and environment for statistical computing. R Foundation for Statistical Computing [Internet]. 2014. Available from: http://www.R-project.org/.
47. André J, Gyuris E, Lawler IR. Comparison of the diets of sympatric dugongs and green turtles on the Orman Reefs, Torres Strait, Australia. Wildlife Research. 2005;32(1):53-62.

48. Marsh H, Lawler IR. Dugong distribution and abundance in the Northern Great Barrier Reef Marine Park, November 2000. Townsville: Great Barrier Reef Marine Park Authority, 2002.
49. Marsh H, Lawler IR, Kwan DK, Delean S, Pollock KH, Alldredge M. Aerial surveys and the potential biological removal technique indicate that the Torres Strait dugong fishery is unsustainable. Animal Conservation. 2004;7:435-43.
50. Lyons MB, Roelfsema CM, Phinn SR. Towards understanding temporal and spatial dynamics of seagrass landscapes using time-series remote sensing. Estuarine, Coastal and Shelf Science. 2013;120(0):42-53.
51. Green D, Alexander L, McLnnes K, Church J, Nicholls N, White N. An assessment of climate change impacts and adaptation for the Torres Strait Islands, Australia. Climatic Change. 2010;102(3-4):405-33.
52. Fuentes MMPB, Bateman BL, Hamann M. Relationship between tropical cyclones and the distribution of sea turtle nesting grounds. Journal of Biogeography. 2011;38(10):1886-96.
53. Marcovaldi MÂ, Godfrey MH, Mrosovsky N. Estimating sex ratios of loggerhead turtles in Brazil from pivotal incubation durations. Canadian Journal of Zoology. 1997;75(5):755-70.
54. Reis EC, Soares LS, Vargas SM, Santos FR, Young RJ, Bjorndal KA, et al. Genetic composition, population structure and phylogeography of the loggerhead sea turtle: colonization hypothesis for the Brazilian rookeries. Conservation Genetics. 2010;11(4):1467-77.
55. Poiner IR, Peterken C. Seagrasses. In: Zann LP, Kailola P, editors. The State of the Marine Environment Report for Australia Technical Annex: 1. Townsville: Great Barrier Reef Marine Park Authority; 1996. p. 40-5.
56. Robblee MB, Barber TR, Durako MJ, Fourqurean JW, Muehlstein LK, Porter D, et al. Mass mortality of the tropical seagrass Thalassia testudinum in Florida Bay (USA). Marine Ecology Progress Series. 1991;71:297-9.
57. Bowen BW, Bass AL, Soares L, Toonen RJ. Conservation implications of complex population structure: lessons from the loggerhead turtle (Caretta caretta). Molecular Ecology. 2005;14(8):2389-402.
58. BOM. Tropical cyclones in Queensland 2015 [17th May 2015]. Available from: http://www.bom.gov.au/cyclone/about/eastern.shtml#history
59. Johannes RE, MacFarlane JW. Traditional fishing in the Torres Strait Islands. 1991:268.
60. Fuentes MMPB, Chambers L, Chin A, Dann P, Dobbs K, Marsh H, et al. Adaptive management of marine mega-fauna in a changing climate. Mitig Adapt Strateg Glob Change. 2014:1-16.

Figures

Fig. 1 The five dugong aerial survey regions of Queensland.

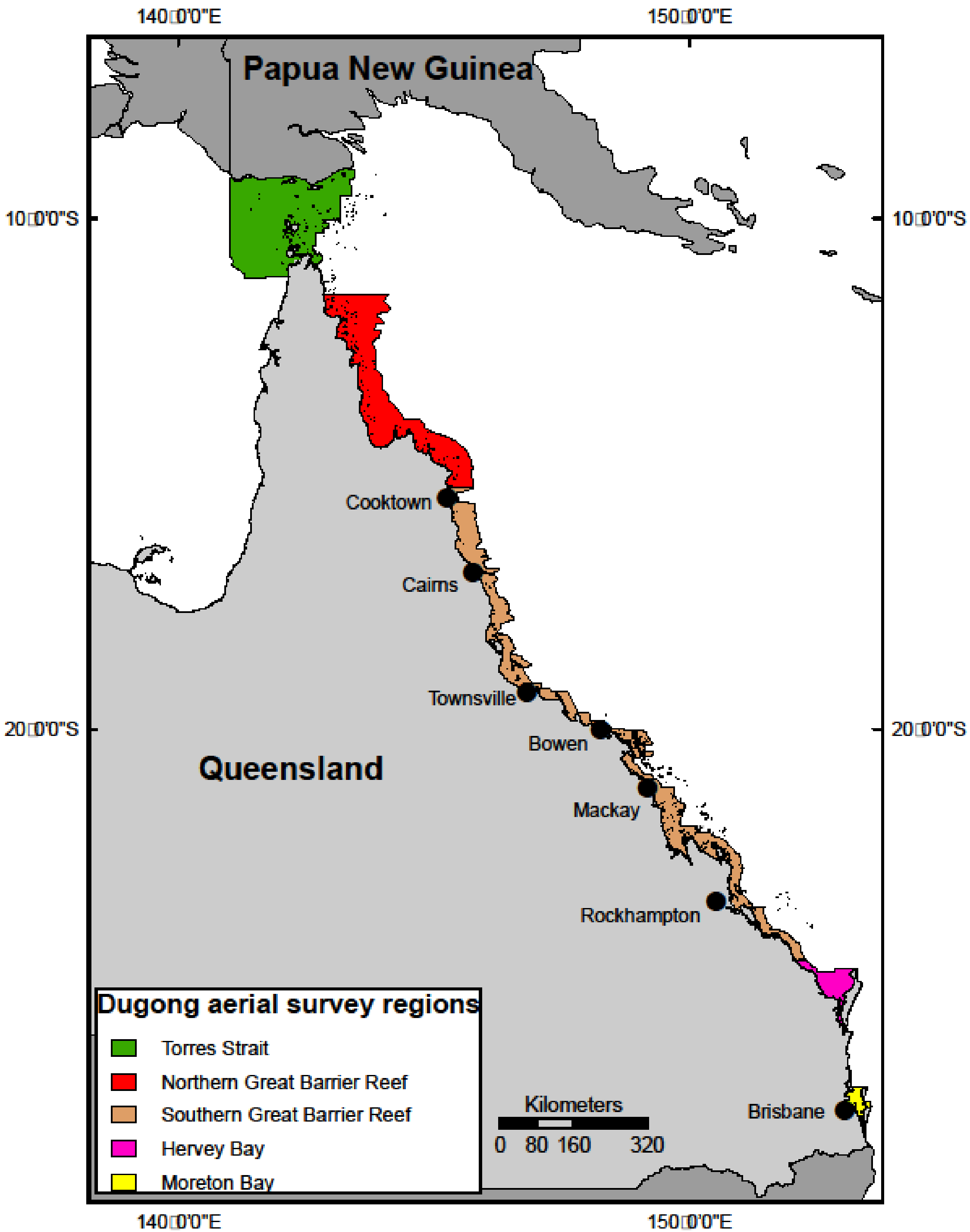


Fig. 2 Trends in proportion of calves including linear smoothers for each subregion across the study period.

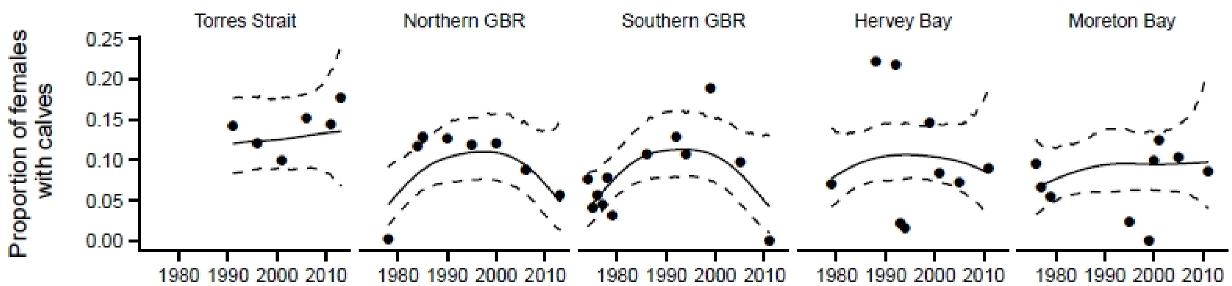


Fig. 3 Gibbs variable selection posterior model probabilities for Beta-Binomial model including population crossed with various lagged and scaled environmental covariates. The higher the posterior probability, the more often the term was included in the model. Variables with posterior model probabilities exceeding 0.5 (50% of models) were considered important predictors of the proportion of dugong calves and thus selected for inclusion in an environmental covariate model.

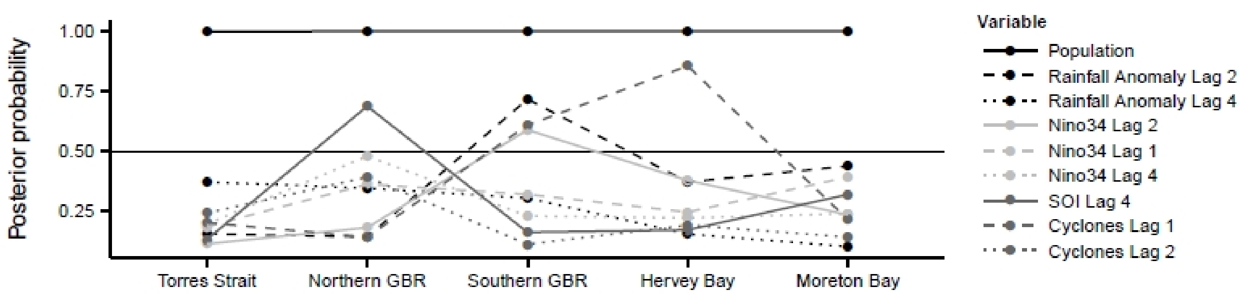
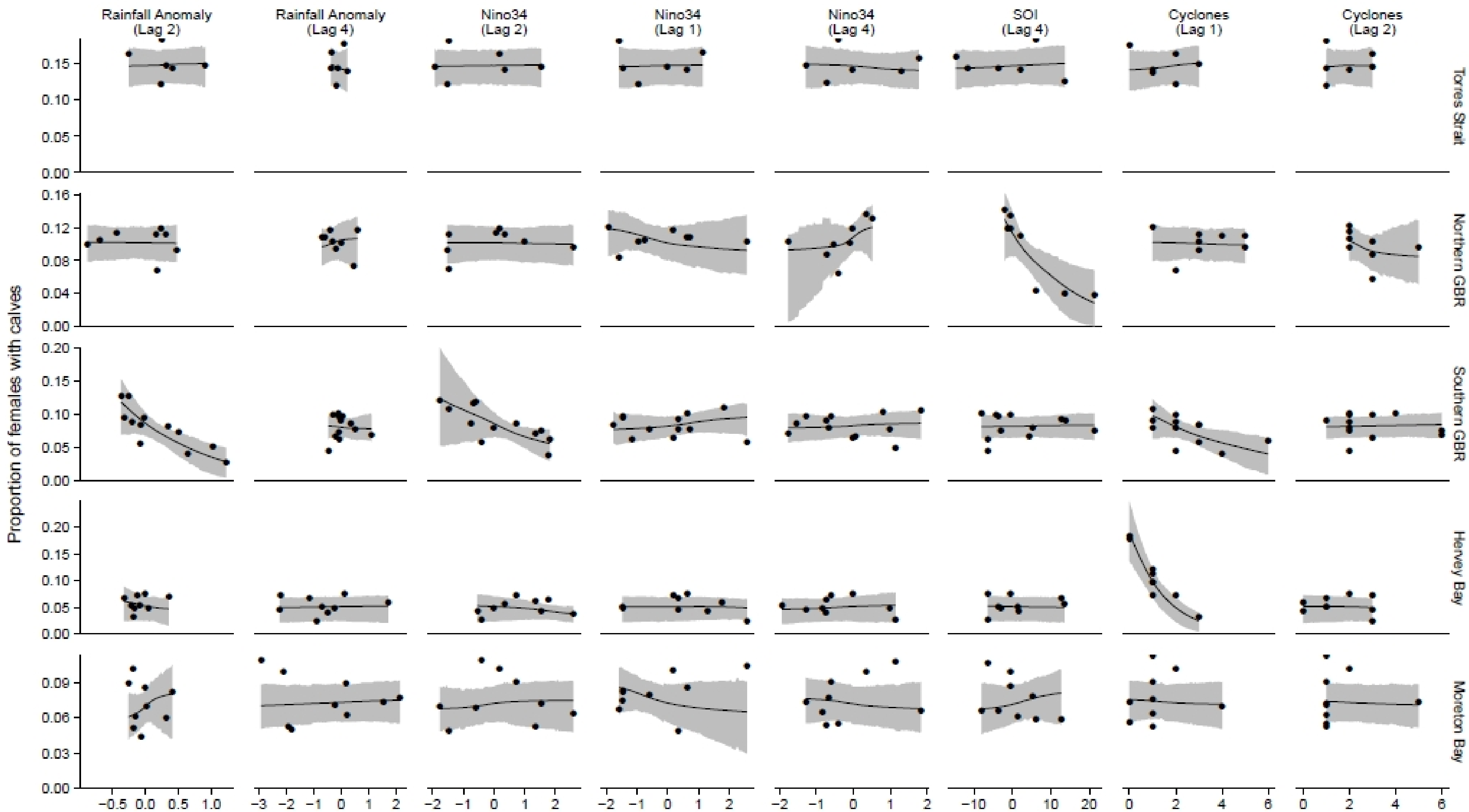
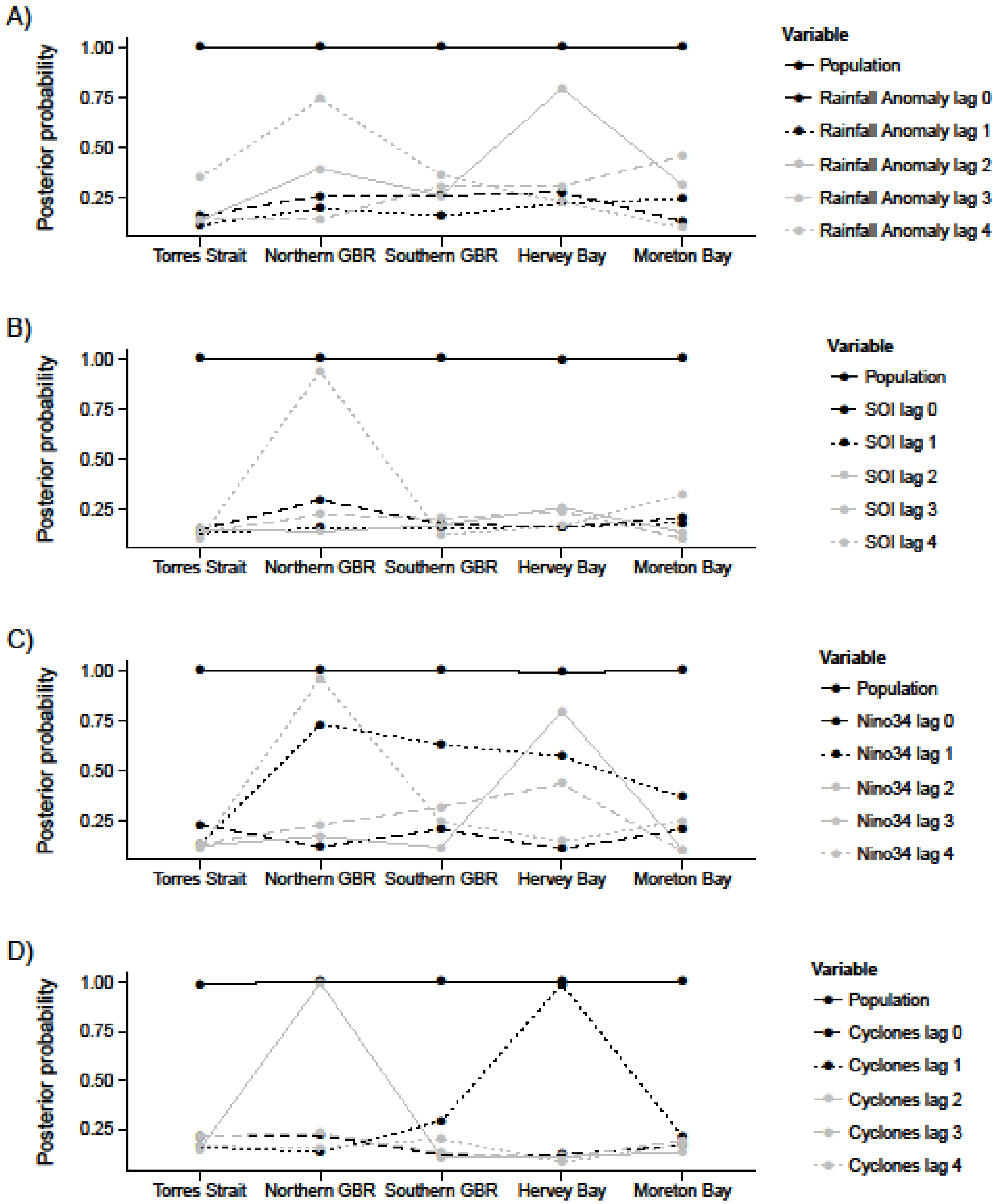


Fig. 4 Partial effects of each of the climatic covariates on the proportion of dugong calves sighted on aerial surveys.



S1 Fig. Gibbs variable selection posterior model probabilities for Beta-Binomial model including population crossed with various (scaled) A) rainfall anomaly lags, B) Southern Oscillation Index lags, C) NINO 3.4 lags and 4) tropical cyclone lags. The higher the posterior probability, the more often the term was included in the model. Variables with posterior model probabilities exceeding 0.5 (50% of models) were considered important predictors of the proportion of dugong calves.



Appendix 6 – Hagihara *et al.* paper in preparation (Abstract only)

Improving dugong population estimates by accounting for heterogeneous availability bias

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Abstract
Precision and accuracy are two important attributes of robust population abundance estimates. However, heterogeneity in environmental conditions and animals traits reduces accuracy and lowers the statistical power to detect trends. To improve dugong population estimates, we improved availability bias estimates (availability detection probability) by: 1) conducting a repeat experiment using dugong replicas (Dugong Secchi Disks) to improve the estimates of detection zones and 2) incorporating measurements of heterogeneous diving behaviour with respect to water depth into estimates of the detection probability. Diving behavioural data were collected from 16 wild dugongs, each fitted with a GPS unit and a time-depth recorder (TDR) in central eastern Australia. Using the archival aerial survey data, we re-estimated the sizes of the dugong population in Moreton Bay and Hervey Bay. In Moreton Bay, where large numbers of dugongs were sighted in clear shallow water and under the Environmental Conditions Class (ECC) 1 (which does not require availability correction), the estimates were similar to the estimate using constant (depth-uncorrected) availability detection probabilities (Pollock et al. 2006). In Hervey Bay, the abundance estimates based on depth-specific availability detection probabilities were lower than using the constant availability correction. However, despite where the distribution of animals changing between 2005 and 2011 with respect to environmental conditions classes and water depths, the 2005 and 2011 abundance estimates were very similar for each of the methodologies.