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Is acoustic tracking appropriate for air-breathing marine animals? Dugongs as a case study

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ABSTRACT

Marine animals face increased pressure through expanded shipping and recreational activities. Effective conservation and management of large species like marine mammals or sea turtles depend on knowledge of movement and habitat use. Previous studies have used data collected from either satellite or acoustic telemetry but rarely both. In this study, data from satellite and acoustic technologies were used to: determine the efficacy of satellite and acoustic telemetry to define dugong movement patterns; compare the benefits and limitations of each approach; examine the costs of each approach in relation to the amount and type of data provided; and relate telemetry data to the boundaries of a Go Slow area designed to protect dugongs and turtles from vessel strike within an urbanised coastal embayment (Moreton Bay, Queensland, Australia). Twenty-one dugongs were captured in seagrass habitats on the Eastern Banks of Moreton Bay in July–September 2012 and July 2013 and fitted with GPS and acoustic transmitters. Both satellite and acoustic telemetry produced reliable presence and movement data for individual dugongs. When the dugongs were within the range of the acoustic array, there was relatively good correspondence between the overall space use measures derived from GPS and acoustic transmitters, demonstrating that acoustic tracking is a potentially valuable and cost-effective tool for monitoring local dugong habitat use in environments equipped with acoustic receiver arrays. Acoustic technology may be particularly useful for species that establish home ranges with stable residency especially near large urban or port environs. However, the relative merits of the two technologies depend on the research question in the context of the species of interest, the location of the study and whether the study site has an established acoustic array.

1. Introduction

The growth of coastal ports and urban areas has increased pressure on marine animals through expanded shipping and recreational activities. For example, the speed of recreational boats has been shown to put dugongs, turtles and other marine species at higher risk of collision or disturbance (Grant and Lewis, 2010; Hazel et al., 2007; Hodgson and Marsh, 2007; Maitland et al., 2006). Data showing the presence and movement patterns of animals in relation to factors such as critical habitat and human use of coastal waters fill a key knowledge gap for managing coastal developments and provide important insights for the effective conservation of exploited or endangered species (Bograd et al., 2010; Cooke, 2008). For managers responsible for protecting these species, defining movement and behavioural variables is challenging due to the dynamic nature of these coastal environments and the difficulty in determining what an individual is doing (e.g., feeding, moving) at a given time. Researchers have used various forms of telemetry to understand these aspects of marine animal behaviour. Telemetry data have been employed to elucidate a wide array of biological factors including: migration, home range, habitat use, mortality, site fidelity, diel and seasonal patterns and habitat preference (see reviews by Hart and Hyrenbach, 2009; Hazen et al., 2012; Heupel and Webber, 2012). Telemetry analyses have also been used to address management and conservation challenges (Bograd et al., 2010).

Two main approaches that are widely used are satellite and acoustic telemetry (e.g., Cooke, 2008; Heupel and Webber, 2012; Marsh and

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Rathbun, 1990; Sheppard et al., 2006). For example, data from acoustic telemetry have been used to calculate the mortality rates of juvenile sharks to improve stock assessment models for fisheries management (Heupel and Simpfendorfer, 2002; Knip et al., 2012a; Pillans et al., 2014), to evaluate the efficacy of marine protected areas (Heupel and Simpfendorfer, 2005; Knip et al., 2012b) and have provided data on the locations and dive movements of humpback (Baumgartner et al., 2008) and right whales (Winn et al., 1995). Similarly, data from satellite tagging have been used to analyse home range and habitat use for management and conservation (Jaine et al., 2014; James et al., 2005; Shillinger et al., 2008; Slone et al., 2013) and for understanding animal movements including migrations in relation to coastal development (Costa et al., 2012; Pendoley et al., 2014; Sheppard et al., 2006).

Passive acoustic telemetry arrays offer considerable benefit for studying behaviours of marine species because the associated small transmitters are light, less expensive and have longer battery life than satellite transmitters. Indeed, acoustic receiver arrays have been used to track over 80 species of marine animals to study migration, home range and habitat use (Heupel and Webber, 2012; Heupel et al., 2006). This approach has been facilitated to some extent by the installation of passive acoustic arrays through national networks such as the Integrated Ocean Observing System (IOOS, the United States, Luczkovich et al., 2012; Malone, 2004; Raynor, 2010), the Australian Animal Tagging and Monitoring System (Heupel and Simpfendorfer, 2014) of the Integrated Marine Observing System (IMOS, Australia), and the Pacific Ocean Shelf Tracking (POST, Canada; Welch et al., 2009) Array. Large arrays are being considered on all the United States and Canadian coasts with plans to be integrated through the Ocean Shelf Tracking and Physics Array (Grothues, 2009). Large arrays that are installed and maintained collectively rather than by individual researchers offer considerable benefits to marine wildlife tracking because many species can be tracked using the same acoustic array (due to the pseudo-random repeat rate of each individual transmitter, designed to avoid signal collision) offering solutions to understanding the behaviour of animals in and around ports and industrial development. The main limitation of acoustic arrays is that movements and activity are not recorded while the animals are outside the array.

However, when continuous spatial and temporal information is required across long distances, most marine mammal and reptile studies have used satellite telemetry (Block et al., 2011; Cooke, 2008; Costa et al., 2012). A major limitation of satellite tracking is that tags are externally attached to the animal (e.g., by attachment to the dorsal fin, Gales et al., 2004; Pennisi, 2005) or attached via a tether with a weak link (Deutsch et al., 1998; Marsh and Rathbun, 1990; Reid et al., 2001) which makes them susceptible to bio-fouling and early loss. In addition, deployment times are limited by battery life; thus, animals are typically tracked only for relatively short periods (often weeks to months; Hart and Hyrenbach, 2009) depending on the size of the battery pack and programming of transmission rates. Typically, satellite tags will be larger than acoustic tags, which constraints the size of animals that can be equipped. Understanding the relative costs and performance metrics of both acoustic and satellite technologies is important because both approaches offer the potential to obtain important insights into behaviour of animals, especially around coastal developments. Despite the broad application of both acoustic and satellite technologies to track animal movements, few studies have fitted animals with both technologies to test and compare the efficacy of each.

While application of both technologies is not appropriate for many small species, larger marine animals provide an opportunity to examine the benefits and limitations of each approach. The dugong, *Dugong dugon*, which is listed as Vulnerable to extinction by the IUCN (Marsh, 2008) and is one of the Great Barrier Reef region's World Heritage Values (GBRMPA, 1981), provides an excellent research opportunity. Individuals are large enough to carry both satellite and acoustic transmitters and they are not likely to be disturbed by the acoustic transmitter frequency of 69 kHz since it is probable that their hearing range is similar to the 400 Hz to 46 kHz range of manatees, *Trichechus* spp. (Marsh et al., 2011; D. Ketten, pers. comm.).

Human activities that affect populations of dugongs and other threatened marine wildlife must be managed more intensively in high human-use areas to reduce the potential for reproductive isolation of populations that remain in the dwindling number of coastal wild places. Although many dugong habitats in eastern Queensland have been protected from incidental fishing by spatial closures (Dobbs et al., 2008; Fernandes et al., 2010), several critical habitats are adjacent to current major or proposed port developments. Managers face significant challenges in protecting dugongs from anthropogenic impacts in these areas. High density human activities occurring within and adjacent to dugong habitats at several of Queensland's major ports such as Brisbane, Gladstone and Townsville greatly increase the risk of exposure to a host of threats that may not exist in less developed areas (Chilvers et al., 2005).

We collected data from acoustic and satellite technologies to describe the presence and movement patterns of dugongs in an urbanised area (Moreton Bay, Queensland) adjacent to the Port of Brisbane, Australia's third busiest port. The study focused on an area of shallow seagrass and an associated Go Slow Zone to define the use of this region by dugongs and the efficacy of the current management arrangements to protect dugongs from boat strikes. Go Slow Zones are reduced speed zones designed to reduce the likelihood of risk of vessel collision (Calleson and Frohlich, 2007; Laist and Shaw, 2006; Marsh et al., 2011). Study site selection was based on persistent dugong presence in this area as representative of conditions in coastal port environs to provide proof of concept for using acoustic telemetry on dugongs.

Data analyses from satellite and acoustic technologies were used to: 1) determine the efficacy of satellite and acoustic telemetry to define dugong movement patterns; 2) compare the benefits and limitations of each approach; 3) examine costs of each approach in relation to the amount and type of data provided and 4) relate telemetry data to the boundaries of a Go Slow area designed to protect dugongs and turtles from recreational vessel strike in an area of considerable recreational and commercial boat traffic. We also evaluate the relative merits of the two technologies for other species of air-breathing marine animals.

2. Materials and methods

The movements of dugongs were examined in Moreton Bay, Queensland adjacent to Brisbane, the third largest city in Australia with a population of over 2 million in 2011 and the nation's third largest cargo port (Government, 2013). The study site, an important dugong habitat area (Chilvers et al., 2005; Lanyon, 2003), includes both shallow and deep water regions in the Eastern Banks–South Passage area adjacent to Moreton and North Stradbroke Islands (Fig. 1). The multiple-use Moreton Bay Marine Park encompasses the entire bay and adjacent waters and includes a range of no-take, limited activity and Go Slow Zones. Water depths within the study site ranged from 2 to 20 m with variable benthic habitat types including sand and seagrass (Roelfsema et al., 2009). The study site was defined by two areas: the acoustic telemetry array and the Moreton Bay Region (Fig. 1).

2.1. Field methods

For deployment of the acoustic array, an area dominated by seagrass in eastern Moreton Bay was selected because it consistently supports large numbers of dugongs (Lanyon, 2003). An array of 28 acoustic receivers (VR2W, Vemco, NS, Canada) was installed over 170 km^2 of this high density dugong habitat (Fig. 1). Acoustic receivers were deployed on paving slabs with metal poles, auger anchors or float and anchor systems depending on depth and current. The array was deployed in March 2012, removed in December 2012 and redeployed at the same locations in May 2013.

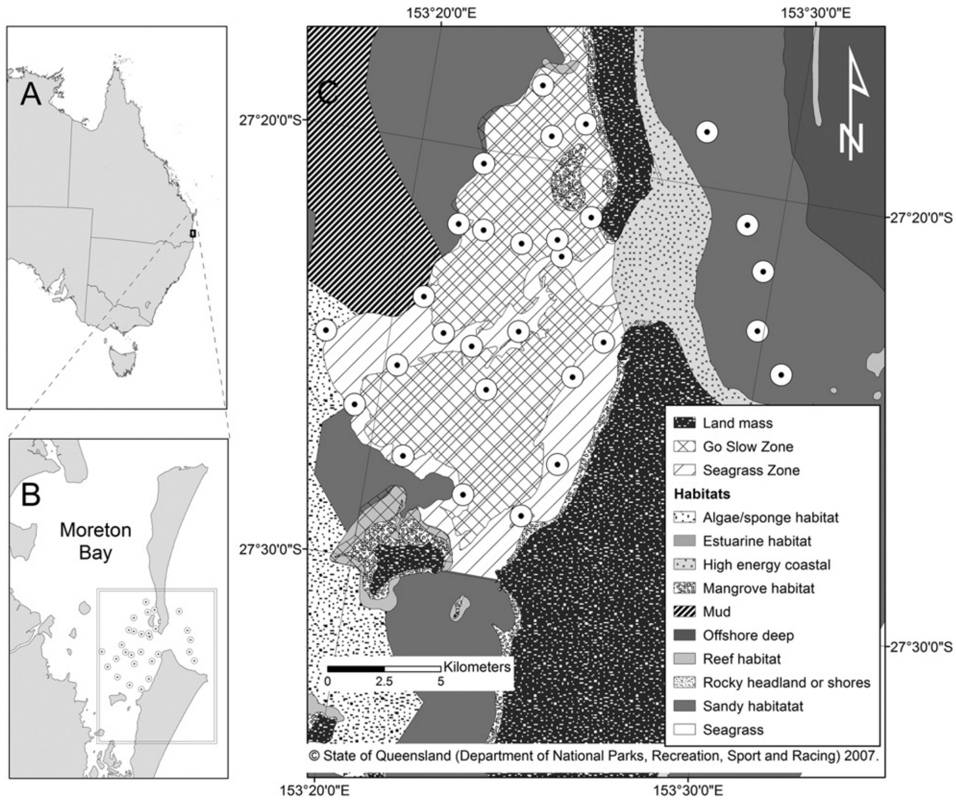

Fig. 1. The study site located on A) the mid-eastern Australian coast. Research was conducted within B) the Moreton Bay Region and C) the acoustic array. The acoustic array encompassed a variety of habitats as indicated in the figure legend. The acoustic receiver locations were mostly deployed in areas mostly dominated by seagrass as indicated by the symbols.

Dugongs were captured in seagrass habitats on the Eastern Banks in July–September 2012 and July 2013 using the rodeo method developed by Marsh and Rathbun (1990) and refined by Lanyon et al. (2002). For each dugong, total body length was measured (cm) in a straight line from snout to fluke notch, sex was noted and a titanium ID tag, satellite transmitter and an acoustic transmitter were attached as standard protocol (Limpus, 1992). An ARGOS GPS transmitter (Gen 4 Marine Unit, Telonics, USA) was attached to 21 dugongs using a 3 m tether and padded tailstock harness developed by Marsh and Rathbun (1990) and modified following Holley (2006) in 2012. In 2013, the harness design was altered again based on the design used for tracking manatees (J. Powell, pers. comm.). Both harness designs used here incorporated a weak link designed to break under stress to enable harness release if the tether snagged and corrodible links designed to release the tailstock harness and tether after several months.

The ARGOS GPS transmitter (Gen 4 Marine Unit, Telonics, USA) was attached to each dugong using a 3 m tether and padded tailstock harness developed by Marsh and Rathbun (1990) and modified following Holley (2006) in 2012. In 2013, the harness design was altered based on the design used for tracking manatees (J. Powell, pers. comm.). Both harness designs incorporated a weak link designed to break under stress to enable harness release if the tether snagged, and a corrodible link to release the harness and tether after several months.

The ARGOS GPS transmitters were programmed to emit a GPS position every hour and location data for each animal were collected daily through the ARGOS website. Location data were defined from the time that the dugongs were released until a transmitter stopped transmitting or detached. Immediate post-capture locations were not removed from the data set as studies of the behaviour of dugongs fitted with time–depth recorders (TDR) in 2012 indicated no behavioural changes after capture and handling (Hagihara et al., 2011). The tag detachment date was determined by the characteristics of the animals' track. While attached, the track pattern was visibly irregular and after detachment the track reflected drift with the current. The clear difference between the pre- and post-detachment tracks enabled accurate estimation of the overall time of GPS transmitter deployment and aided tag recovery. All tracking data were truncated at the estimated detachment date, to ensure that activity spaces excluded drift data.

Each tailstock harness was fitted with an acoustic transmitter (V16TP, Vemco, NS, Canada) to facilitate acoustic tracking. Acoustic transmitters had an estimated battery life of 824 days and emitted a unique code ID, depth (m) and temperature (°C) with data transmitted at 69 kHz at a pseudo-random interval every 45–90 s. The pseudo-random repeat rate was used to avoid signal collision with other deployed transmitters. Acoustic receivers detected the presence of acoustic transmitters that passed within 500 m based on data collected from moored sentinel tags in the study site (M. Heupel, unpublished data). Data were downloaded in November 2012, August 2013, December 2013 and April 2014.

2.2. Data filtering

Data from GPS and acoustic transmitters were standardised by binning into three hour periods to allow direct comparisons of the data from the two technologies and to minimize autocorrelation. GPS data binning and filtering were accomplished using a custom R script based in part on previous speed-filters (Austin et al., 2003; Flamm et al., 2001; Freitas et al., 2008; McConnell et al., 1992). GPS data filters included filtering to: 1) eliminate duplicate times or duplicate consecutive locations, 2) retain only Successful and Resolved QFD data (i.e., the most accurate and most reliable data) and, 3) remove spurious consecutive data points that resulted in calculated speeds greater than 20 km/h for maximum burst swimming speed (Marsh et al., 1981) or calculated speeds greater than 10 km/h for maximum cruising speed (Marsh et al., 1981). Outlier data occurring on land were also deleted.

Acoustic monitoring does not provide GPS location data for individuals since the data consist of receiver based detections. To compare between methods, acoustic data were processed to provide positional locations for individuals using a centre-of-activity approach (Simpfendorfer et al., 2002) that produced mean locations from detections in each three hour time bin. Animal positions were calculated based on a weighted mean of the number of detections at each receiver in the array within each time period.

2.3. Duration of tracking

All GPS data from the Moreton Bay Region (Fig. 1B) were used to analyse the duration of satellite tag deployment; the duration of acoustic tag deployment was estimated from the data recorded by the array. A subset of 21 consecutive days of tracking for 13 individuals (see Supplementary material Appendix A for dates) was used for detailed comparative analysis for indices derived from GPS and acoustic data within both the Moreton Bay Region and the acoustic array (Table 1). The range of 21 consecutive days was the maximum number of days that data were simultaneously available from both technologies for the greatest number of dugongs. Further, using the same time range for all individuals enabled the calculation of composite estimates of activity space of all individuals within the array. GPS data only were used to calculate Array Presence, Seagrass Presence and Go Slow Zone Presence because those analyses are a percentage of the movement in the Moreton Bay Region (not only within the acoustic array itself).

2.4. Comparison of acoustic and GPS data outputs

Eight dugongs were omitted from the analyses because their GPS transmitters detached after a few days or because they remained within the array for only a few days (see Supplementary material Appendix A). Minimum convex polygons (MCP) were calculated to define the extent of movement of individuals. Space use was further refined by calculating 50% and 95% kernel utilisation distributions (KUDs). The 50% KUD represents the core use area of an individual while the 95% KUD represents the extent of movement, similar in scale to MCP estimates. Acoustic telemetry data were restricted to the confines of the acoustic array but the GPS data extended to the Moreton Bay Region. Composite activity space estimates were produced by combining the 13 individual data files into a single file each for GPS and acoustic tracking data sets respectively.

MCPs were calculated using the using the Convex Hull tool in ArcGIS 10.1 (ESRI, 2013). KUDs were calculated using the kde and isopleth tools in the Geospatial Modelling Environment (Beyer, 2012). KUDs are sensitive to sample size and smoothing parameter (Millspaugh et al., 2006; Pillans et al., 2014). After exploratory data analysis, likelihood cross-validation (CVh) was chosen as the most biologically relevant smoothing parameter to compare the acoustic and GPS KUDs given the small sample sizes present (Horne and Garton, 2006; Seaman and Powell, 1996); e.g., sample sizes for 21-day acoustic activity centres were less than 44. This approach is consistent with Gredzens et al.'s (2014) work on dugong home ranges. Land masses were excluded from all KUDs and MCPs using the XTools Pro 9.2 extension for ArcGIS (Data East, 2013).

2.5. Size and overlap of activity spaces (21 day data for 13 dugongs)

Activity space estimates were used to define the amount of space used and identify whether different metrics (MCP, KUD) produced overlapping spatial outputs. Intersections of activity space estimates were calculated between (GPS and acoustic) MCPs, 50% KUDs and 95% KUDs for individuals using the Intersection tool in ArcGIS. Areas of intersection were calculated and the ratio of intersected area to GPS area was calculated as a percentage for each individual. The percentage of intersection provided an indication of the level of agreement between activity space estimates.

2.6. Day–night comparisons

Data from the composite 21 day GPS and acoustic tracking data were divided into day (0600 to 1800 h) and night (1800 to 0600 h) time periods. Activity space estimates were used to define the amount of space used during day and night periods. Intersections of activity space estimates were calculated between (GPS and acoustic) MCPs, 50% KUDs and 95% KUDs for the composite data set using the Intersection tool in ArcGIS. Areas of intersection were calculated and the ratio of intersected area to GPS area was calculated as a percentage of the composite data set. The percentage of intersection provided an indication of whether different areas were used during the day or night.

2.7. Stability of activity space

Patterns of residency and habitat usage within Moreton Bay, the acoustic array, the seagrass area, and Go Slow Zone (Fig. 1C) for each dugong were estimated using indices of time, distance and area (Table 1). To determine whether the full extent of activity space had been identified based on GPS and acoustic telemetry, activity space stability was calculated using cumulative area analysis. Cumulative analysis consisted of weekly MCP areas summed across weeks (e.g., week 1 + week 2, week 1 + week 2 + week 3) to determine whether activity space plateaued over time.

2.8. Cost comparisons

To determine the cost effectiveness of acoustic versus satellite telemetry, the cost of tracking dugongs fitted with GPS and acoustic

Table 1
Analyses applied to the 21 day subset of GPS and acoustic data from 13 dugongs within the Moreton Bay Region (MBR) (i.e., including areas beyond the acoustic array; Anderson and Barclay, 1995; Austin et al., 2003; Bartol and Ketten, 2013; Baumgartner et al., 2008; Beyer, 2012) and comparison of acoustic and GPS data within the array (Block et al., 2011; Bograd et al., 2010; Burgess et al., 2012) where MCP = minimum convex polygon, KUD = kernel utilisation distribution.

Ref	Term	Description	Use
Anderson and Barclay (1995)	Array Presence	Percentage of GPS positions inside the acoustic array relative to the MBR	Calculate proportion of locations within the acoustic array
Austin et al. (2003)	Seagrass Presence	Percentage of GPS positions inside seagrass beds relative to the MBR	Calculate proportion of locations within the seagrass
Bartol and Ketten (2013)	Go Slow Zone Presence	Percentage of GPS positions inside the Go Slow Zone relative to the MBR	Calculate proportion of locations within the Go Slow Zone
Baumgartner et al. (2008)	Array use	GPS MCP within the acoustic array relative to GPS MCP of movement the entire MBR	Measure the overlap in area between MBR
Beyer (2012)	Spatial overlap: MCP	Measure of overlap between acoustic and GPS MCP areas within array	Determine how similar MCP area estimates were between methods
Block et al. (2011)	Spatial overlap: 50%	Measure of overlap between acoustic KUD and GPS 50% KUD areas within array	Determine how similar 50% KUD estimates were between methods
Bograd et al. (2010)	Spatial overlap: 95%	Measure of overlap between acoustic KUD and GPS 95% KUD areas within array	Determine how similar 95% KUD estimates were between methods

Table 2
Activity spaces of the 13 dugongs within the array over the 21 day periods using both GPS and acoustic data.

Tag ID	GPS	Acoustic	Spatial overlap (%)	GPS	Acoustic	Spatial overlap (%)	GPS	Acoustic	Spatial overlap (%)
QA30696	93.4	12.1	12.3	6.8	5.4	24.4	46.5	34.4	50.3
QA30723	94.5	54.5	52.7	10.2	15.7	2.1	68.3	92.4	72.4
QA30677	39.1	61.2	69.3	5.6	26.6	100.0	24.5	169.5	100.0
QA30541	45.0	15.4	33.6	3.3	3.5	42.8	22.1	24.2	60.3
QA30710	104.4	181.1	99.7	10.2	48.3	100.0	81.5	247.1	95.3
QA30676	31.5	14.7	46.6	5.8	1.1	7.3	22.5	7.1	20.9
QA30712	101.0	42.5	41.8	5.9	0.5	0.9	39.1	4.5	8.3
QA30694	41.4	52.8	88.4	2.9	1.3	3.4	16.7	9.2	15.8
QA30709	34.2	21.9	44.9	3.7	10.2	88.9	19.3	56.8	88.6
QA18399	122.1	84.9	68.9	7.4	4.9	19.3	61.9	38.6	33.3
K88240	67.5	50.0	72.2	3.1	7.6	44.4	33.2	47.3	59.8
T71561	113.9	104.8	85.1	85.0	17.0	55.6	55.5	95.5	74.5
QA33315	93.3	37.2	38.6	2.5	8.2	0.0	46.5	54.2	45.0
Composite	167.1	196.0	92.2	6.2	1.2	4.5	64.0	16.3	11.4
Mean	75.5	56.4	58.0	5.8	11.6	376	41.4	67.8	55.7
SD	33.2	46.5	25.0	2.7	13.3	38.1	20.8	70.5	30.2

transmitters was compared for nine scenarios. Scenarios included the two tracking methods (GPS and acoustic) times three levels of logistical difficulty: 1) easy catching and accessible location (e.g., Moreton Bay), 2) difficult catching and accessible location (e.g., Townsville), and 3) difficult catching and remote location (e.g., Boigu, Torres Strait). In addition, scenarios with and without an established acoustic array were considered. Costs were based on dugong catching trips conducted by James Cook University in 2012 and 2013 (e.g., Gredzens et al., 2014). Logistical assumptions are presented as Supplementary material Appendix B. Total cost estimates were based on the cost of different parameters, including equipment, travel, salary, and operating costs. Only direct costs were considered.

3. Results

The tailstock harness that contained the acoustic tag tended to remain on the dugong longer than the tether to which the GPS transmitter was attached. Thus the mean tracking period for acoustic transmitters was 107 days (SD = 95 days, median = 60 days), significantly greater than the mean tracking period of 39 days for GPS (SD = 26 days, median = 35 days, Welch Two Sample t-test, $p < 0.01$). Four dugongs were still being acoustically tracked at the last download in early April 2014, 256–266 days after deployment. The longest GPS track period was 108 days which reflected the battery life of the GPS transmitter.

Habitat use was calculated from GPS data and compared for 13 dugongs. Array Presence values, Seagrass Presence values and Go Slow Zone Presence values all showed high presence of dugongs in these areas (Table 3). Despite this, only five individuals had Go Slow Zone Presence values greater than 80% and one animal spent less than 18% of its time within the Go Slow Zone. Habitat use from composite data also indicated that most of the dugongs' time was spent within these three Go Slow areas. Array Presence for 13 dugongs over the 21 day period had a mean value of 78% (median = 90%; SD = 23%; range =

Table 3
Comparison of the presence of 13 dugongs and composite data in the acoustic array, seagrass and Go Slow Zone over the 21 day periods in which each animal was tracked.

Tag ID	Go Slow			
	GPS points in MCP	Array Presence (%)	Seagrass Presence (%)	Zone Presence (%)
QA30696	157	87.9	77.1	79.0
QA30723	170	88.8	68.8	69.4
QA30677	171	94.7	89.5	91.8
QA30541	65	92.3	83.1	84.6
QA30710	141	83.0	85.8	79.4
QA30676	172	98.3	95.3	97.7
QA30712	162	77.8	73.5	73.5
QA30694	160	84.4	60.6	17.5
QA30709	169	91.7	89.9	89.3
QA18399	121	76.0	63.6	60.3
K88240	162	93.8	84.6	87.7
T71561	141	88.7	80.1	76.6
QA33315	173	97.1	42.2	63.6
Composite	1964	89.1	76.3	74.6

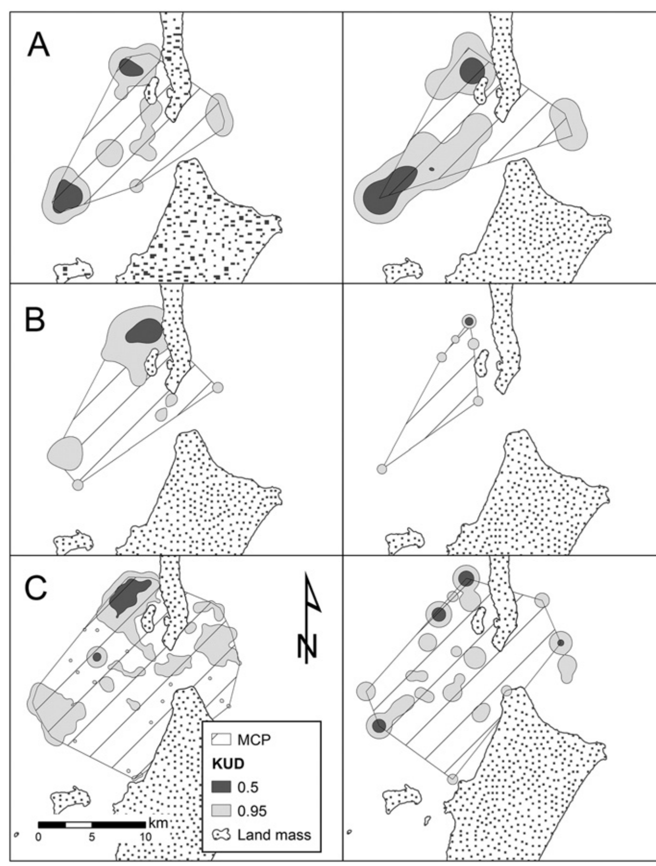

Fig. 2. Maps illustrating the variation in MCP, 50% KUD and 95% KUD estimates for the 21-day data using GPS (left hand column) and acoustic (right hand column) technologies. A) An individual with good agreement between the methods where MCP, 50% KUD and 95% KUD estimates were very similar for GPS and acoustic tracking data. B) An individual with low agreement between methods where 50% KUD estimates had similar locations but MCP and 95% KUD estimates were different in area although locations were consistent. C) Comparison of daytime composite data from the 13 animals.

32–96%) providing further evidence that the activity spaces of tagged dugongs were mostly within the acoustic array.

3.1. Size and overlap of activity spaces (21 day data for 13 dugongs)

The estimates of MCPs, 50% KUDs and 95% KUDs varied between dugongs for the two technologies (Table 2), which is to be expected as the data generated by the two techniques are not directly comparable. The results were very close for some dugongs, but varied for others (Fig. 5), suggesting that individual dugong movements played a role in resulting activity space estimates. However, these metrics also reflect the acoustic array geometry, the number of acoustic receivers recording individual animal signals and the analytical methods used. The intersection of (GPS and acoustic) MCPs as a percentage of the GPS MCP ranged from 12% to almost 100% (Table 2). The corresponding figures for 50% KUDs ranged from 0–100%, and 8–100% for 95% KUDs. The composite GPS and acoustic MCPs overlapped by 92%, composite 50% KUDs by 4.5%, and composite 95% KUDs by 11%. These data indicate that a reliable picture of the activity space use of dugongs in the confines of an acoustic array can be obtained by acoustically tracking several animals. (See Fig. 4.)

3.2. Day–night comparisons (21 day data for 13 dugongs)

The resulting MCP, 50% KUD and 95% KUD estimates calculated for day and night periods were nearly identical indicating that for the 13 animal composite data there was little difference in behaviour between day and night periods. The intersections of the acoustic and GPS day and night MCPs were 87% (day) and 84% (night) as percentages of the corresponding GPS MCPs, indicating a high level of agreement. The overlap of KUD areas was much smaller with only 4.2% (day) and 20.3% (night) overlap of the 50% KUDs and 33.8% (day) and 25.0% (night) overlap of the 95% KUDs. Although these 50% and 95% KUD ratios were small, the mapped KUDs (Fig. 5C) show that the locations of the respective GPS and acoustic 50% and 95% KUDs were spatially close. Thus comparisons using both technologies indicated little difference between day and night use of the array area by the tagged dugongs.

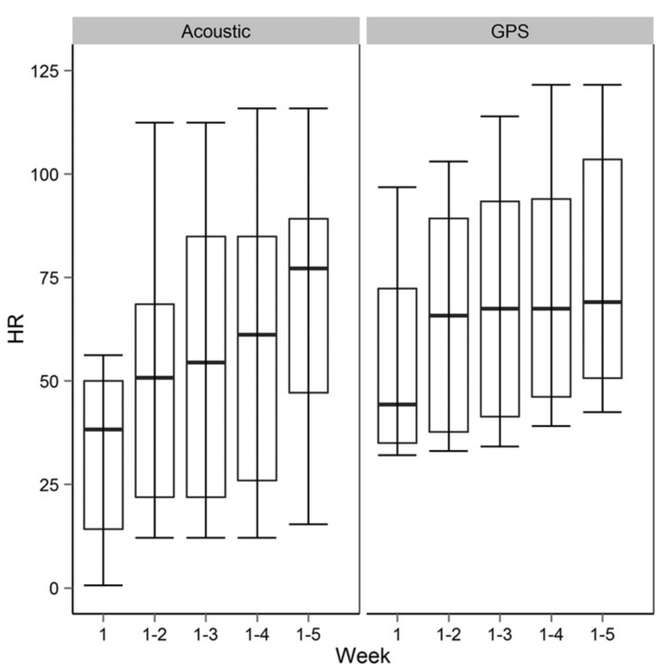

Fig. 3. Cumulative space use of dugongs based on MCP analysis. The horizontal bar shows the median value of days tracked, boxes indicate 75th and 25th percentiles and whiskers show the maximum and minimum values of y (activity space area).

3.3. Stability of activity space

Analysis of cumulative MCP home ranges indicated that space use of dugongs in the Moreton Bay Region continued to increase over five weeks for the 13 dugongs for which the requisite acoustic tracking data were available. However, MCP estimates stabilised after two weeks for the nine dugongs tracked using GPS technology. These data suggest that during this short term study, GPS tracking captured the extent of movement more quickly than acoustic tracking although there was a high degree of overlap and agreement in activity space size using both methods (Fig. 2). However, it is not possible to separate the confounding influences of technology and the analytical methods used and so these conclusions are tentative.

3.4. Cost comparisons

Regardless of the method used, tracking is least costly in easily accessible areas where dugongs are easy to catch, such as in Moreton Bay. In areas where acoustic arrays are established, acoustic tracking is more economical than GPS tracking regardless of the scenario (Fig. 3). However, if an array is not in place, it is likely to be more cost-effective to use GPS tracking unless tracking longevity is a priority or an array can also be used for other species to spread costs across projects or among collaborators. Difficulty of capture also increased costs because catching dugongs in areas of high turbidity will take a greater amount of time and necessitates the use of spotter aircraft compared with catching in clear water where dugongs are more easily spotted. A high proportion of the costs associated with GPS tracking are from equipment costs (>35%), whereas most (>50%) of the expenses with acoustic tracking are associated with operating costs. The proportion of operational costs increases by approximately 20% when acoustic arrays need to be deployed (see Supplementary material Appendix C).

4. Discussion

Our study showed that acoustic and satellite telemetry data provided reliable location results for comparable periods of time with some differences in benefits and limitations.

The duration of acoustic tracking was greater than that of satellite tracking although the range of tracking days was highly variable for both technologies largely due to the attachment mechanism (see

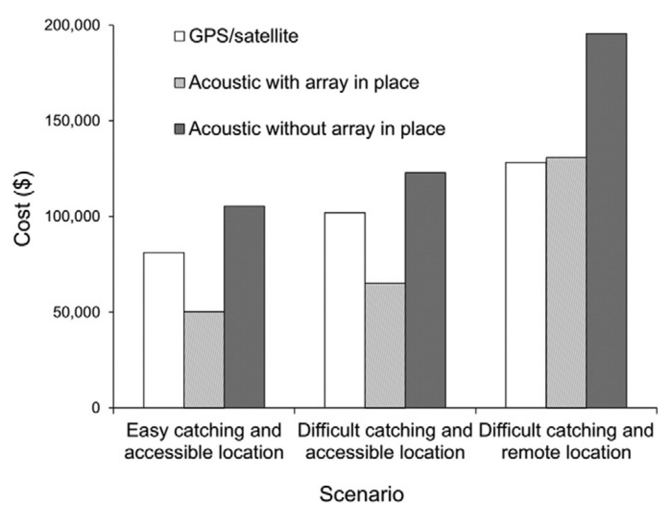

Fig. 4. Costs for each tracking method for each scenario; Scenario 1 — easy catching and accessible location (e.g., Moreton Bay, where the water is clear); Scenario 2 — difficult catching and accessible location (e.g., Townsville, where the water has high levels of suspended sediment); and Scenario 3 — difficult catching and remote location (e.g., Boigu, Torres Strait, where the water can be clear but mangroves and corals make for difficult access).

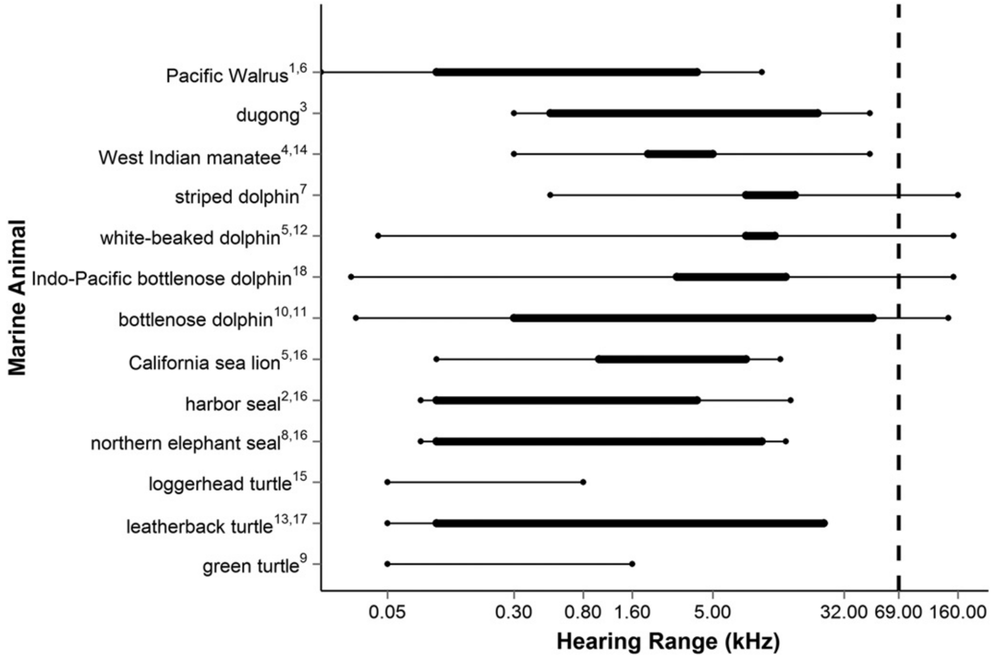

Fig. 5. Comparison of marine animals' hearing ranges with the frequency of the acoustic transmitter, 69 kHz. (shown by a dashed line). Thin lines represent animal hearing ranges and thick lines represent vocalisation ranges. ([1]Stirling et al., 1987, *Odobenus rosmarus rosmarus*, [2]Hanggi and Schusterman, 1994, *Phoca vitulina*, [3]Anderson and Barclay, 1995, [4]Gerstein et al., 1999, *Trichechus manatus*, [5]Wartzok and Ketten, 1999, *Zalophus californianus*, [6]Kastelein et al., 2002, *Odobenus rosmarus divergens*, [7]Kastelein et al., 2003, *Stenella coeruleoalba*, [8]Southall et al., 2003, *Mirounga angustirostris*, [9]Bartol and Ketten, 2013, *Chelonia mydas*, [10]Popov et al., 2007, *Tursiops truncatus*, [11]Sayigh et al., 2007, *Tursiops truncatus*, [12]Nachtigall et al., 2008, *Lagenorhynchus albirostris*, [13]Dow Piniak et al., 2012, *Dermochelys coriacea*, [14]Gaspard et al., 2012, *Trichechus manatus latirostris*, [15]Martin et al., 2012, *Caretta caretta*, [16]Reichmuth et al., 2013, *Zalophus californianus*, [17]Ferrara et al., 2014, *Dermochelys coriacea*, [18]Gridley et al., 2014, *Tursiops aduncus*).

Supplementary material Appendix A). The factors contributing to these differences in longevity between technologies include: 1) operational difficulties with the tether attachment in 2013, which caused several GPS units to detach in a few days; 2) the tether arrangement which is designed to break if the tether becomes entangled; 3) the duty cycle of the GPS transmitters which limited the battery life; 4) the corrodible link in the tailstock belt which in 2012 detached after a maximum of 69 days and 5) acoustically tracked animals leaving the array area.

The requirement to maintain the GPS tag at the surface via a tether mechanism produces a significant limitation to tag life because of the need to incorporate a weak link in the attachment mechanism for animal welfare reasons (Deutsch et al., 1998; Reid et al., 2001). Longevity in tracking can vary by species. For example, West Indian manatees (*Trichechus manatus*) in Florida, USA, have been satellite tracked for longer periods (29 manatees out of 78 were tracked for over 1 year) by the use of re-tagging without re-catching in most cases (Deutsch et al., 2003). In a study of migrating green turtles (*Chelonia mydas*) several turtles were satellite tracked for over 15 months (Hays et al., 2014).

In contrast, acoustic tags are much smaller, producing less drag and enabling a more durable attachment (in this case a tailstock belt) with the capacity to provide data for longer periods. If the acoustic tags had been surgically implanted in the dugongs, the differences in the longevity of the two techniques should have been much greater. The acoustic tags have longevity of 894 days; the battery life of the GPS tags would have lasted no more than a year even with a duty-cycle designed to maximise battery-life.

Cumulative home range analyses indicated that home ranges did not increase by large amounts over the tracking period which also suggests residence within defined spaces for the dugongs that did not leave the area during the tracking period. Spatial residency in various locations was high for many individuals, a result consistent with (Sheppard et al., 2006). Although most of these data only span periods of several weeks, they suggest high use of specific areas over the short to medium term, a result confirmed by our 21-day analyses. Most data collected during the 21 day periods (>75% of satellite locations) were within the acoustic array. Similarly, 70% of individuals spent over 85% of their time within the array when considering the entire GPS tracking period with limited movement into deeper regions outside the barrier islands. This pattern indicates high fidelity to this region and highlights the importance of the seagrass meadows around the Moreton Banks for dugongs as has been established by other studies (e.g., Lanyon, 2003) and is part of the rationale for the Go Slow Zone on the Eastern Banks.

Our studies indicated that in the area of the array, there was very little evidence of diurnal differences in dugongs' activity space. Most information suggests that sirenians do not have well defined periods of circadian activity (see Marsh et al., 2011, for review). This lack of marked diel activity patterns is consistent with the absence of a pineal organ in the brain of sirenians, which can act as a regulator of daily rhythms in temperate zone mammals (Ralph et al., 1985).

The boundaries of the Go Slow Zone overlap much of the mapped seagrass areas. All tracked individuals spent large amounts of time over seagrass areas so it was not surprising that the spatial residence of most individuals examined in the 21 day analyses overlapped extensively with Go Slow Zones (>60% of space used was in Go Slow Zones). However, location data indicated that individuals regularly moved in and out of the Go Slow Zone. This result suggests that the spatial extent of the Go Slow Zone is providing some protection for dugongs from boat strikes but that it is unlikely to be 100% effective. There was a high degree of individual variability in the number of recorded locations within the Go Slow Zone indicating that some dugongs will receive more protection than others from that regulatory initiative. Thus, our data indicate that the current Go Slow Zone does not provide full protection for all dugongs within this region but will mitigate some of the potential interactions with boaters.

Cost is a big factor in decision making for both scientists and funding agencies. Which methodology is more appropriate should be considered in light of the scientific question asked as well as resource availability. Cost–benefit analysis indicated that each method (GPS vs acoustic) can be justifiably costed depending on questions and resources. The use of telemetry can lead to understanding complex animal movements in the context of an animal's use of its environment (Cagnacci et al., 2010; Rutz and Hays, 2009). For example, an investigation of habitat use may include depth data as an indication of feeding activity in dugongs and manatees (Chilvers et al., 2004; Hagihara et al., 2011). Satellite telemetry costs are largely related to equipment or capital type expenses while acoustic telemetry costs are dominated by the installation and maintenance of the network resulting in higher personnel costs. Array costs would of course have been much higher if we had installed a denser array with overlap between the ranges of individual receivers.

A large, national network of acoustic receivers (the Australian Animal Tagging and Monitoring System facility of the Integrated Marine Observing System) provides a platform for the detection of acoustically tagged animals at a broad scale (Heupel and Simpfendorfer, 2014). This network includes receivers in an array of habitats around Australia although there is no guarantee that equipment will be located in areas useful to specific study species. Satellite tracking of dugongs had one distinct advantage over acoustic tracking; it could record locations for individuals beyond the boundaries of the acoustic array. This is an important consideration for dugongs as animals are known to make large and meso-scale movements (Sheppard et al., 2006). For example, our GPS tracking data showed all animals moved beyond the boundaries of the acoustic array and two animals moved over 250 km to Hervey Bay.

This raises the question about which is easier or cheaper to cost and support: equipment or people. The answers to this question will vary based on location, agency and funding body. Disregarding costs that are common across approaches at the same location (e.g., animal capture costs), it is more cost-effective to use acoustic telemetry if an array already exists within the focal area and if the research questions are directly related to a local study site. If broader-scale movement questions are being asked, a larger acoustic network would be required and satellite telemetry would be a more cost effective option. Costs of both approaches also differ depending on the study site. Working in remote locations is better suited to satellite telemetry than acoustic telemetry, a direct result of the differences in costs within approaches.

The suitability of using acoustic and satellite tracking technologies with dugongs was dependent upon animal size and hearing range of the species. When considering acoustic tracking for other coastal marine mammals, the use of acoustic transmitters makes size less critical so that smaller species could be tracked. The hearing range of the species is important: 69 kHz is within the hearing range of many marine mammals, especially dolphins (Ketten, 2000; D. Ketten, pers. comm; Wartzok and Ketten, 1999) and could interfere with their intraspecies communications or searching for prey. Hearing ranges of most pinnipeds and sea turtles have maxima well less than 69 kHz, the frequency of the acoustic transmitter and thus might be considered suitable candidates for acoustic tracking (Ketten, 2000; D. Ketten, pers. comm., 2014; Wartzok and Ketten, 1999). Tubelli et al. (2012) predicted that the hearing range of the minke whale is below 10 kHz making it another possible candidate. Dolphins, however, appear to have hearing ranges clearly including the 69 kHz transmitter frequency. Therefore acoustic tracking using currently available technologies is unlikely to be suitable for all marine mammal species.

5. Conclusion

Data indicated that both satellite and acoustic technologies provided reliable location data for individuals for comparable periods of time demonstrating that acoustic tracking is a potentially valuable and cost-effective tool for monitoring local dugong habitat use in environments equipped with acoustic receiver arrays although failure of the attachment device used in this study led to early loss of satellite transmitters in many cases. The two technologies each have benefits and limitations in the data that they provide. Cost–benefit analysis indicated that each method (GPS vs acoustic) can be appropriate depending on questions and resources. The cost-effectiveness of using acoustic rather than GPS technology for tracking dugongs clearly depends on the research question and the location. When the dugongs are within the range of an acoustic array, this research has shown overall good correspondence between the MCPs and KUDs of the GPS and acoustic transmitters.

Ultimately, the cost effectiveness of the method applied must be driven by the species and the research question. Researchers should then consider what resources are on hand. Is an existing array present or can a collaborative array be established? Is the study site remote? Is staff time limited? Does the animal exhibit stable residency? Careful consideration of available resources in conjunction with the question being addressed should lead to a clear conclusion about which of these two technologies is most cost effective in gaining a research outcome.

We conclude that acoustic tracking is a potentially valuable and cost-effective tool for monitoring dugong habitat use in environments equipped with acoustic receiver arrays. As dugongs are not wilderness animals (Marsh et al., 2011) and ports in developed countries are increasingly fitted with acoustic arrays, we conclude that acoustic transmitters should become the preferred methods of tracking dugong habitat use in the vicinity of ports because they enable more animals to be tracked for longer and with fewer animal welfare problems than GPS transmitters. We expect that similar methods will work as well for some other marine species but advise that each species hearing and sound production ranges will need to be considered.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jembe.2014.11.013.

References

Anderson, P.K., Barclay, R.M.R., 1995. Acoustic signals of solitary dugongs: physical characteristics and behavioral correlates. J. Mammal. 76, 1226–1237. http://dx.doi.org/10.2307/1382616.

Austin, D., McMillan, J.I., Bowen, W.D., 2003. A three-stage algorithm for filtering erroneous Argos satellite locations. Mar. Mamm. Sci. 19, 371–383. http://dx.doi.org/10.1111/j.1748-7692.2003.tb01115.x.

Bartol, S., Ketten, D.R., 2013. Sea turtle and pelagic fish sensory biology: developing techniques to reduce sea turtle bycatch in longline fisheries. Technical Memorandum NMFS-PIFSC-7. Report. National Ocean and Atmospheric Administration (NOAA), U.S. Dept. of Commerce.

Baumgartner, M., Freitag, L., Partan, J., Ball, K., Prada, K., 2008. Tracking large marine predators in three dimensions: the real-time acoustic tracking system. IEEE J. Ocean. Eng. 33, 146–157. http://dx.doi.org/10.1109/JOE.2007.912496.

Beyer, H.L., 2012. Geospatial Modelling Environment (Version 0.7.2.1). (software).

Block, B.A., Jonsen, I.D., Jorgensen, S.J., Winship, A.J., Shaffer, S.A., Bograd, S.J., Hazen, E.L., Foley, D.G., Breed, G.A., Harrison, A.L., Ganong, J.E., Swithenbank, A., Castleton, M., Dewar, H., Mate, B.R., Shillinger, G.L., Schaefer, K.M., Benson, S.R., Weise, M.J., Henry, R.W., Costa, D.P., 2011. Tracking apex marine predator movements in a dynamic ocean. Nature 475, 86–90. http://dx.doi.org/10.1038/nature10082.

Bograd, S.J., Block, B.A., Costa, D.P., Godley, B.J., 2010. Biologging technologies: new tools for conservation. Introduction. Endanger. Species Res. 10, 1–7.

Burgess, E.A., Lanyon, J.M., Brown, J.L., Blyde, D., Keeley, T., 2012. Diagnosing pregnancy in free-ranging dugongs using fecal progesterone metabolite concentrations and body morphometrics: a population application. Gen. Comp. Endocrinol. 177, 82–92. http://dx.doi.org/10.1016/j.ygcen.2012.02.008.

Cagnacci, F., Boitani, L., Powell, R.A., Boyce, M.S., 2010. Animal ecology meets GPS-based radiotelemetry: a perfect storm of opportunities and challenges. Philos. Trans. R. Soc. B 365, 2157–2162.

Calleson, C.S., Frohlich, R.K., 2007. Slower boat speeds reduce risks to manatees. Endanger. Species Res. 3, 295–304.

Chilvers, B.L., Delean, S., Gales, N.J., Holley, D.K., Lawler, I.R., Marsh, H., Preen, A.R., 2004. Diving behaviour of dugongs (*Dugong dugon*). J. Exp. Mar. Biol. Ecol. 304, 203–224. http://dx.doi.org/10.1016/j.jembe.2003.12.010.

Chilvers, B.L., Lawler, I.R., Macknight, F., Marsh, H., Noad, M., Paterson, R., 2005. Moreton Bay, Queensland, Australia: an example of the co-existence of significant marine mammal populations and large-scale coastal development. Biol. Conserv. 122, 559–571. http://dx.doi.org/10.1016/j.biocon.2004.08.013.

Cooke, S.J., 2008. Biotelemetry and biologging in endangered species research and animal conservation: relevance to regional, national and IUCN Red List Threat assessments. Endanger. Species Res. 4, 165–185.

Costa, D.P., Breed, G.A., Robinson, P.W., 2012. New insights into pelagic migrations: implications for ecology and conservation. Annu. Rev. Ecol. Evol. Syst. 43, 73–96. http://dx.doi.org/10.1146/annurev-ecolsys-102710-145045.

Data East, 2013. XTools Pro (version 9.2), ArcView Extension. (software).

Deutsch, C.J., Bonde, R.K., Reid, J.P., 1998. Radio-tracking manatees from land and space: tag design, implementation, and lessons learned from long-term study. Mar. Technol. Soc. J. 32, 18–29.

Deutsch, C.J., Reid, J.P., Bonde, R.K., Easton, D.E., Kochman, H.I., O'Shea, T.J., 2003. Seasonal movements, migratory behavior and site fidelity of West Indian manatees along the Atlantic coast of the United States. Wildl. Monogr. 151.

Dobbs, K., Fernandes, L., Slegers, S., Jago, B., Thompson, L., Hall, J., Day, J., Cameron, D., Tanzer, J., Macdonald, F., Marsh, H., Coles, R., 2008. Incorporating dugong habitats into the marine protected area design for the Great Barrier Reef Marine Park, Queensland, Australia. Ocean Coast. Manag. 51, 368–375. http://dx.doi.org/10.1016/j.ocecoaman.2007.08.001.

Dow Piniak, W.E., Eckert, S.A., Harms, C.A., Stringer, E.M., 2012. Underwater hearing sensitivity of the leatherback sea turtle (*Dermochelys coriacea*): assessing the potential effect of anthropogenic noise. Report. U.S. Department of the Interior, Bureau of Ocean Energy Management, Headquarters, Herndon, VA. OCS Study BOEM 2012–01156.

ESRI, 2013. ArcGIS (Version 10.1). (software).

Fernandes, L., Dobbs, K., Day, J., Slegers, S., 2010. Identifying biologically and physically special or unique sites for inclusion in the protected area design for the Great Barrier Reef marine park. Ocean Coast. Manag. 53, 80–88. http://dx.doi.org/10.1016/j.ocecoaman.2009.12.003.

Ferrara, C.R., Vogt, R.C., Harfush, M.R., Sousa-Lima, R.S., Albavera, E., Tavera, A., 2014. First evidence of leatherback turtle (*Dermochelys coriacea*) embryos and hatchlings emitting sounds. Chelonian Conserv. Biol. 13, 110–114.

Flamm, R.O., Ward, L.I., Weigle, B.L., 2001. Applying a variable-shape spatial filter to map relative abundance of manatees (*Trichechus manatus latirostris*). Landsc. Ecol. 16, 279–288. http://dx.doi.org/10.1023/a:1011182302522.

Freitas, C., Lydersen, C., Fedak, M.A., Kovacs, K.M., 2008. A simple new algorithm to filter marine mammal Argos locations. Mar. Mamm. Sci. 24, 315–325. http://dx.doi.org/10.1111/j.1748-7692.2007.00180.x.

Gales, N., McCauley, R.D., Lanyon, J., Holley, D., 2004. Change in abundance of dugongs in Shark Bay, Ningaloo and Exmouth Gulf, Western Australia: evidence for large-scale migration. Wildl. Res. 31, 283–290. http://dx.doi.org/10.1071/WR02073.

Gaspard III, J.C., Bauer, G.B., Reep, R.L., Dziuk, K., Cardwell, A., Read, L., Mann, D.A., 2012. Audiogram and auditory critical ratios of two Florida manatees (*Trichechus manatus latirostris*). J. Exp. Biol. 215, 1442–1447. http://dx.doi.org/10.1242/jeb.065649.

GBRMPA, 1981. Nomination of the Great Barrier Reef by the Commonwealth of Australia for Inclusion in the World Heritage List. Report. UNESCO (37 pp.).

Gerstein, E.R., Gerstein, L., Forsythe, S.E., Blue, J.E., 1999. The underwater audiogram of the west Indian manatee (*Trichechus manatus*). J. Acoust. Soc. Am. 105, 3575–3583. http://dx.doi.org/10.1121/1.424681.

Government, A., 2013. State of Australian Cities 2013: Brisbane. Report. Department of Infrastructure and Transport.

Grant, P.B.C., Lewis, T.R., 2010. High speed boat traffic: a risk to crocodilian populations. Herpetol. Conserv. Biol. 5, 456–460.

Gredzens, C., Marsh, H., Fuentes, M.M.P.B., Limpus, C., Shimada, T., Hamann, M., 2014. Satellite tracking of sympatric marine megafauna can inform the biological basis for species co-management. PLoS One 9, 1–12.

Gridley, T., Cockcroft, V.G., Hawkins, E.R., Blewitt, M.L., Morisaka, T., Janik, V.M., 2014. Signature whistles in free-ranging populations of Indo-Pacific bottlenose dolphins, *Tursiops aduncus*. Mar. Mamm. Sci. 30, 512–527.

Grothues, T.M., 2009. A review of acoustic telemetry technology and a perspective on its diversification relative to coastal tracking arrays. In: Nielsen, J.L., Arrizabalaga, H., Fragoso, N., Hobday, A., Lutcavage, M., Sibert, J. (Eds.), Tagging and Tracking of Marine Animals With Electronic Devices. Reviews: Methods and Technologies in Fish Biology and Fisheries: Making Fisheries Management Work vol. 9. Springer, pp. 77–90.

Hagihara, R., Jones, R.E., Sheppard, J.K., Hodgson, A.J., Marsh, H., 2011. Minimizing errors in the analysis of dive recordings from shallow-diving animals. J. Exp. Mar. Biol. Ecol. 399, 173–181. http://dx.doi.org/10.1016/j.jembe.2011.01.001.

Hanggi, E.B., Schusterman, R.J., 1994. Underwater acoustic displays and individual variation in male harbour seals, *Phoca vitulina*. Anim. Behav. 48, 1275–1283.

Hart, K.M., Hyrenbach, K.D., 2009. Satellite telemetry of marine megavertebrates: the coming of age of an experimental science. Endanger. Species Res. 10, 9–20. http://dx.doi.org/10.3354/esr00238.

Hays, G.C., Mortimer, J.A., Ierodiaconou, D., Esteban, N., 2014. Use of long-distance migration patterns of an endangered species to inform conservation planning for the world's largest marine protected area. Conserv. Biol. 1–9 http://dx.doi.org/10.1111/cobi.12325.

Hazel, J., Lawler, I.R., Marsh, H., Robson, S., 2007. Vessel speed increases collision risk for the green turtle *Chelonia mydas*. Endanger. Species Res. 3, 105–113.

Hazen, E.L., Maxwell, S.M., Bailey, H., Bograd, S.J., Hamann, M., Gaspar, P., Godley, B.J., Shillinger, G.L., 2012. Ontogeny in marine tagging and tracking science: technologies and data gaps. Mar. Ecol. Prog. Ser. 457, 221–240.

Heupel, M.R., Simpfendorfer, C.A., 2002. Estimation of mortality of juvenile blacktip sharks, *Carcharhinus limbatus*, within a nursery area using telemetry data. Can. J. Fish. Aquat. Sci. 59, 624–632. http://dx.doi.org/10.1139/f02-036.

Heupel, M.R., Simpfendorfer, C.A., 2005. Using acoustic monitoring to evaluate MPAs for shark nursery areas: the importance of long-term data. Mar. Technol. Soc. J. 39, 10–18.

Heupel, M.R., Simpfendorfer, C.A., 2014. Importance of environmental and biological drivers in the presence and space use of a reef-associated shark. Mar. Ecol. Prog. Ser. 496, 47–57.

Heupel, M.R., Webber, D.M., 2012. Trends in Acoustic Tracking: Where Are the Fish Going and How Will We Follow Them?

Heupel, M.R., Semmens, J.M., Hobday, A.J., 2006. Automated acoustic tracking of aquatic animals: scales, design and deployment of listening station arrays. Mar. Freshw. Res. 57, 1–13. http://dx.doi.org/10.1071/MF05091.

Hodgson, A.J., Marsh, H., 2007. Response of dugongs to boat traffic: the risk of disturbance and displacement. J. Exp. Mar. Biol. Ecol. 340, 50–61.

Holley, D.K., 2006. Movement Patterns and Habitat Usage of Shark Bay Dugongs. (Thesis).

Horne, J.S., Garton, E.O., 2006. Likelihood cross-validation versus least squares cross-validation for choosing the smoothing parameter in kernel home range analysis. J. Wildl. Manag. 70, 641–648. http://dx.doi.org/10.2307/3803418.

Jaine, F.R.A., Rohner, C.A., Weeks, S.J., Couturier, L.I.E., Bennett, M.B., Townsend, K.A., Richardson, A.J., 2014. Movements and habitat use of reef manta rays off eastern Australia: offshore excursions, deep diving and eddy affinity revealed by satellite telemetry. Mar. Ecol. Prog. Ser. 510, 73–86.

James, M.C., Andrea Ottensmeyer, C., Myers, R.A., 2005. Identification of high-use habitat and threats to leatherback sea turtles in northern waters: new directions for conservation. Ecol. Lett. 8, 195–201. http://dx.doi.org/10.1111/j.1461-0248.2004.00710.x.

Kastelein, R.A., Mosterd, P., van Santen, B., Hagedoorn, M., de Haan, D., 2002. Underwater audiogram of a pacific walrus (*Odobenus rosmarus divergens*) measured with narrow-band frequency-modulated signals. J. Acoust. Soc. Am. 112, 2173–2182. http://dx.doi.org/10.1121/1.1508783.

Kastelein, R.A., Hagedoorn, M., Au, W.W.L., de Haan, D., 2003. Audiogram of a striped dolphin (*Stenella coeruleoalba*). J. Acoust. Soc. Am. 113, 1130–1137. http://dx.doi.org/10.1121/1.1532310.

Ketten, D.R., 2000. Cetacean ears. In: Au, W.W.L., Popper, A.N., Fay, R.R. (Eds.), Hearing by Whales and Dolphins. SHAR Series for Auditory Research. Springer-Verlag, New York, pp. 43–108 (chapter Cetacean Ears).

Knip, D.M., Heupel, M.R., Simpfendorfer, C.A., 2012a. Evaluating marine protected areas for the conservation of tropical coastal sharks. Biol. Conserv. 148, 200–209. http://dx.doi.org/10.1016/j.biocon.2012.01.008.

Knip, D.M., Heupel, M.R., Simpfendorfer, C.A., 2012b. Mortality rates for two shark species occupying a shared coastal environment. Fish. Res. 125–126, 184–189. http://dx.doi.org/10.1016/j.fishres.2012.02.023.

Laist, D.W., Shaw, C., 2006. Preliminary evidence that boat speed restrictions reduce deaths of Florida manatees. Mar. Mamm. Sci. 22, 472–479.

Lanyon, J.M., 2003. Distribution and abundance of dugongs in Moreton Bay, Queensland, Australia. Wildl. Res. 30, 397–409. http://dx.doi.org/10.1071/WR98082.

Lanyon, J.M., Sneath, H.L., Kirkwood, J.M., Slade, R.W., 2002. Establishing a mark-recapture program for dugongs in Moreton Bay, southeast Queensland. Aust. Mammal. 24, 51–56. http://dx.doi.org/10.1071/AM02051.

Limpus, C.J., 1992. Estimation of tag loss in marine turtle research. Wildl. Res. 19, 457–469.

Luczkovich, J.J., Sprague, Mark W., Krahforst, C.S., Corbett, D.R., Walsh, J.P., 2012. Passive acoustics monitoring as part of integrated ocean observing systems. J. Acoust. Soc. Am. 132, 1915.

Maitland, R.N., Lawler, I.R., Sheppard, J.K., 2006. Assessing the risk of boat strike on dugongs (*Dugong dugon*) at Burrum Heads, Queensland, Australia. Pac. Conserv. Biol. 12, 321–326.

Malone, T.C., 2004. The coastal component of the U.S. integrated ocean observing system. Environ. Monit. Assess. 81, 51–62.

Marsh, H., 2008. *Dugong dugon*. IUCN 2012. IUCN Red List of Threatened Species (version 2012.1).

Marsh, H., Rathbun, G.B., 1990. Development and application of conventional and satellite radio tracking techniques for studying dugong movements and habitat use. Aust. Wildl. Res. 17, 83–100.

Marsh, H., Gardner, B.R., Heinsohn, G.E., 1981. Present-day hunting and distribution of dugongs in the Wellesley Islands (Queensland): implications for conservation. Biol. Conserv. 19, 255–267. http://dx.doi.org/10.1016/0006-3207(81)90002-1.

Marsh, H., O'Shea, T.J., Reynolds III, J.E., 2011. Ecology and conservation of the sirena: dugongs and manatees. Conservation Biology 18. Cambridge University Press, New York.

Martin, K.J., Alessi, S.C., Gaspard, J.C., Tucker, A.D., Bauer, G.B., Mann, D.A., 2012. Underwater hearing in the loggerhead turtle (*Caretta caretta*): a comparison of behavioral and auditory evoked potential audiograms. J. Exp. Biol. 215, 3001–3009. http://dx.doi.org/10.1242/jeb.066324.

McConnell, B.J., Chambers, C., Fedak, M.A., 1992. Foraging ecology of southern elephant seals in relation to the bathymetry and productivity of the Southern Ocean. Antarct. Sci. 4, 393–398. http://dx.doi.org/10.1017/S0954102092000580.

Millspaugh, J.J., Nielson, R.M., McDonald, L., Marzluff, J.M., Gitzen, R.A., Rittenhouse, C.D., Hubbard, M.W., Sheriff, S.L., 2006. Analysis of resource selection using utilization distributions. J. Wildl. Manag. 70, 384–395.

Nachtigall, P.E., Mooney, T.A., Taylor, K.A., Miller, L.A., Rasmussen, M.H., Akamatsu, T., Teilmann, J., Linnenschmidt, M., Vikingsson, G.A., 2008. Shipboard measurements of the hearing of the white-beaked dolphin *Lagenorhynchus albirostris*. J. Exp. Biol. 211, 642–647. http://dx.doi.org/10.1242/jeb.014118.

Pendoley, K.L., Schofield, G., Whittock, P.A., Ierodiaconou, D., Hays, G.C., 2014. Protected species use of a coastal marine migratory corridor connecting marine protected areas. Mar. Biol. 161, 1455–1466. http://dx.doi.org/10.1007/s00227-014-2433-7.

Pennisi, E., 2005. Satellite tracking catches sharks on the move. Science 310, 32–33.

Pillans, R.D., Bearham, D., Boomer, A., Downie, R., Patterson, T.A., Thomson, D.P., Babcock, R.C., 2014. Multi year observations reveal variability in residence of a tropical demersal fish, *Lethrinus nebulosus*: implications for spatial management. PLoS One 9.

Popov, V.V., Supin, Alexander Ya, Pletenko, M.G., Tarakanov, M.B., Klishin, V.O., Bulgakova, T.N., Rosanova, E.I., 2007. Audiogram variability in normal bottlenose dolphins (*Tursiops truncatus*). Aquat. Mamm. 33, 24–33. http://dx.doi.org/10.1578/AM.33.1.2007.24.

Ralph, C.L., Young, S., Gettinger, R., O'Shea, T.J., 1985. Does the manatee have a pineal body? Acta Zool. 166, 55–60.

Raynor, R., 2010. The US Integrated Ocean Observing System in a global context. Mar. Technol. Soc. J. 44, 26–31.

Reichmuth, C., Holt, M.M., Mulsow, J., Sills, J.M., Southall, B.L., 2013. Comparative assessment of amphibious hearing in pinnipeds. J. Comp. Physiol. A. 199, 491–507.

Reid, J.P., Butler, S.M., Easton, D.E., Deutsch, C.J., 2001. Fifteen Years of Success in Tracking Manatees With the Argos System: An Overview of Programs and Techniques.

Roelfsema, C.M., Phinn, S.R., Udy, N., Maxwell, P., 2009. An integrated field and remote sensing approach for mapping seagrass cover, Moreton Bay, Australia. J. Spat. Sci. 54, 45–62.

Rutz, C., Hays, G.C., 2009. New frontiers in biologging science. Biol. Lett. (The Royal Society) 5, 289–292.

Sayigh, L.S., Esch, H.C., Wells, R.S., Janik, V.M., 2007. Facts about signature whistles of bottlenose dolphins, *Tursiops truncatus*. Anim. Behav. 74, 1631–1642.

Seaman, D.E., Powell, R.A., 1996. An evaluation of the accuracy of kernel density estimators for home range analysis. Ecology 77, 2075–2085.

Sheppard, J.K., Preen, A.R., Marsh, H., Lawler, I.R., Whiting, S.D., Jones, R.E., 2006. Movement heterogeneity of dugongs, *Dugong dugon* (Müller), over large spatial scales. J. Exp. Mar. Biol. Ecol. 334, 64–83. http://dx.doi.org/10.1016/j.jembe.2006.01.011.

Shillinger, G.L., Palacios, D.M., Bailey, H., Bograd, S.J., Swithenbank, A.M., Gaspar, P., Wallace, B.P., Spotila, J.R., Paladino, F.V., Piedra, R., Eckert, S.A., Block, B.A., 2008. Persistent leatherback turtle migrations present opportunities for conservation. PLoS Biol. 6, e171. http://dx.doi.org/10.1371/journal.pbio.0060171.

Simpfendorfer, C.A., Heupel, M.R., Hueter, R.E., 2002. Estimation of short-term centers of activity from an array of omnidirectional hydrophones and its use in studying animal movements. Can. J. Fish. Aquat. Sci. 59, 23–32.

Slone, D.H., Reid, J.P., Kenworthy, W.J., 2013. Mapping spatial resources with GPS animal telemetry: foraging manatees locate seagrass beds in the Ten Thousand Islands, Florida, USA. Mar. Ecol. Prog. Ser. 476, 285–299.

Southall, B.L., Schusterman, R.J., Kastak, D., 2003. Acoustic communication ranges for northern elephant seals (*Mirounga angustirostris*). Aquat. Mamm. 29, 202–213.

Stirling, I., Calvert, W., Spencer, C., 1987. Evidence of stereotyped underwater vocalizations of male Atlantic walruses (*Odobenus rosmarus rosmarus*). Can. J. Zool. 65, 2311–2321.

Tubelli, A., Zosuls, A., Ketten, D., Mountain, D.C., 2012. Prediction of a mysticete audiogram via finite element analysis of the middle ear. In: Popper, A., Hawkins, A. (Eds.), The Effects of Noise on Aquatic Life. Advances in Experimental Medicine and Biology vol. 730. Springer, New York, pp. 57–59.

Wartzok, D., Ketten, D.R., 1999. Marine mammal sensory systems. In: Reynolds, J., Rommel, S. (Eds.), Biology of Marine Mammals. Smithsonian Institution Press, pp. 117–175.

Welch, D.W., Melnychuk, M.C., Rechisky, E.R., Porter, A.D., Jacobs, M.C., Ladouceur, A., McKinley, R.S., Jackson, G.D., 2009. Freshwater and marine migration and survival of endangered Cultus Lake sockeye salmon (*Oncorhynchus nerka*) smolts using POST, a large-scale acoustic telemetry array. Can. J. Fish. Aquat. Sci. 66, 736–750.

Winn, H.E., Goodyear, J.D., Kenney, R.D., Petricig, R.O., 1995. Dive patterns of tagged right whales in the Great South Channel. Cont. Shelf Res. 15, 593–611. http://dx.doi.org/10.1016/0278-4343(94)00061-Q.