LARGE-SCALE MOVEMENT PATTERNS OF MALE LOGGERHEAD SEA TURTLES (*CARETTA CARETTA*) IN SHARK BAY, AUSTRALIA

By

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Abstract

The Shark Bay World Heritage Property is home to the largest breeding population of loggerhead turtles in Australia. With little known about the movements of males in this population, I assessed the large-scale movement and habitat use patterns of adult male loggerhead turtles to inform conservation strategies. I tagged nine male loggerhead turtles with SPOT satellite tags and tracked them for seven months. Turtles exhibited fidelity to foraging areas considerably smaller than anticipated, with activity space sizes (85 pvc) that were on average 186.0 km^2 (± 206.0 sd). To complement tracking data, I interviewed eight Aboriginal fishermen and local ecotourism operators and recorded their traditional and local ecological knowledge concerning loggerhead turtle movements and habitat use. Respondents suggested loggerheads stay within small areas and that there are some areas in the bay where loggerheads are more abundant. Traditional and local ecological knowledge therefore corroborated quantitative satellite tracking data.

Keywords: loggerhead turtle; satellite telemetry; traditional ecological knowledge; local ecological knowledge; Shark Bay

Dedication

To the turtles who wore little blue transmitters and shared the locations of their lives.

May this work help create a less threatening world for you to live in.

Acknowledgements

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Introduction

Large marine vertebrates are at increased risk from anthropogenic threats because they tend to be long-lived, late to mature, and wide ranging (Godley *et al.* 2010, Maxwell *et al*. 2011). Accordingly, there is critical need for an improved understanding of their distribution and movement patterns in order to develop effective conservation and recovery strategies (Block *et al*. 2001, James *et al*. 2005, Schofield *et al*. 2007). Until recently, ascertaining these basic properties for large marine vertebrates has been complicated by the difficulty of tracking vagile taxa in the ocean. The advent of satellite telemetry, however, has revolutionized our ability to closely monitor these species and yielded new insights into their ecology. I used satellite telemetry to quantify large-scale movement patterns of loggerhead sea turtles (*Caretta caretta*) in Shark Bay, Australia (Figure 1).

Distributed throughout tropical and temperate oceans worldwide, loggerhead sea turtles are listed as "Endangered" by The World Conservation Union (Eckert *et al.* 2008). To examine loggerhead population viability, previous studies have focused on nesting beaches and female fecundity, survival and abundance (Schroeder *et al*. 2003). The underlying assumption is that these female population parameters are similar for males. Yet there is growing evidence of the need for sex-specific population parameters (Gerber

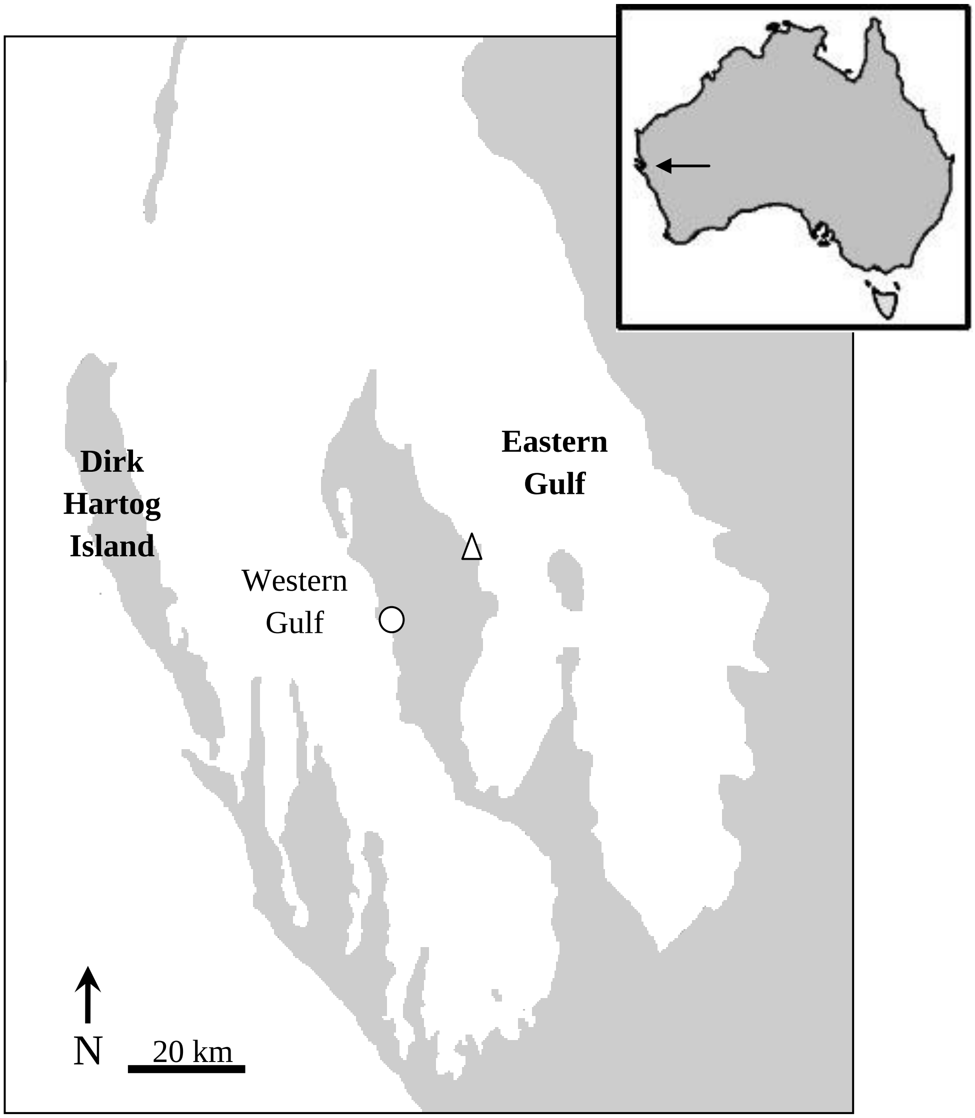

Figure 1. Study site in the eastern gulf of Shark Bay, Western Australia. The circle indicates the location of Denham. The triangle indicates the location of the Monkey Mia Dolphin Resort. Grey = land, white = ocean.

2006). How males use space can influence population dynamics by altering breeding opportunities. Drivers of movements and space use can affect which males are reproductively contributing to the population, which in turn influences population viability (Gerber 2006). Several studies have estimated the spatial scale of movements of female loggerheads (Hawkes *et al*. 2011, Rees *et al*. 2010); however, the movement patterns of adult males are less well known (Godley *et al.* 2008). Since differential use of habitat between sexes has been observed in a wide range of species, movement patterns and habitat use information for female loggerhead turtles cannot be applied to males (Breed *et al*. 2006, Van Dam *et al*. 2008, Schofield *et al*. 2010). Moreover, tracking male loggerhead turtles has the potential to identify sex differences in foraging habitats, reveal breeding areas, and uncover anthropogenic threats to which only male loggerheads are exposed.

Animal movement and space use can be driven by extrinsic factors, such as resource availability, predator presence, competition or abiotic factors (i.e. temperature, salinity, tide). Alternatively, factors driving movement can be intrinsic, such as size, sex or individual knowledge, memory or preference (Rasmussen 2010). Theoretically, loggerhead turtles should use spaces that allow for maximizing energy intake while minimizing costs (i.e. search time, digestion, exposure to predators) (Stephens and Krebs 1986, Walters and Juanes 1993). Subject to a suite of drivers, loggerheads could exhibit various movement and habitat use patterns dependent on their particular situation. Accordingly, there is increasing evidence of behavioral plasticity in loggerhead turtle movements (Rees *et al*. 2010). Much of what is known about sea turtle foraging ecology has been learned from habitats that have been degraded by substantial anthropogenic impact (Heithaus *et al*. 2005). Since anthropogenic impacts can alter drivers of movement, such as resource availability through habitat degradation or abundance of large predators through human take, turtles in less impacted areas could exhibit different movement patterns in response. Thus, undertaking studies in less impacted locations can reveal a degree of behavioral plasticity exhibited in loggerhead turtles that may not exist in more impacted regions.

The Shark Bay World Heritage Area (SBWHA), in Western Australia, provides a unique opportunity to examine the spatial ecology of loggerhead turtles in a relatively pristine seagrass ecosystem (Heithaus *et al*. 2005). Monitoring loggerhead turtle movements in Shark Bay began in 1994, when the Western Australia Department of Environment and Conservation (DEC; formerly the Department of Conservation and Land Management, CALM) started an annual tagging program on the Dirk Hartog Island nesting beach (Baldwin *et al*. 2003). In 1999, the Shark Bay Ecosystem Research Project (SBERP) began monitoring and tagging loggerheads on a foraging ground in the eastern gulf of Shark Bay. These initiatives have revealed that Shark Bay contains the largest nesting population of loggerhead sea turtles in Australia and that many females nesting on Dirk Hartog Island migrate to the foraging grounds in the eastern gulf (Heithaus *et al*. 2002, Baldwin *et al*. 2003). Yet, long-term and large-scale space use by loggerhead turtles in the bay, and especially the movements of males in this population, remain unknown.

Using satellite telemetry, loggerhead sea turtles have been shown to exhibit long-distance transoceanic migrations (Nicols *et al*. 2000). In Shark Bay, a pilot study in 2004 revealed that after seven months two females stayed within 10 km of their initial capture location while the only tagged male moved approximately 140 km north, out of the SBWHA (Wirsing *et al.* 2004). This pilot study confirmed that satellite telemetry is an effective method for exploring loggerhead movements in Shark Bay and suggested that males might travel significantly greater distances than females, thereby exposing themselves to a greater diversity of possible threats.

I used satellite telemetry and kernel density estimation, to quantify large-scale movement and habitat use patterns of adult male loggerhead turtles with the aim of informing conservation strategies. I also examined how satellite-derived Argos location class accuracy altered our estimates of loggerhead activity spaces. Finally, I compared male loggerheads activity spaces during and outside of the breeding season.

Methods

Study Area

Shark Bay, Western Australia, is a World Heritage Area featuring expansive seagrass meadows (Walker *et al.* 1988) that have experienced minimal human impacts and support intact populations of large-bodied grazers and predators (Heithaus *et al*. 2005, Vaudo and Heithaus 2009). Located at a latitudinal transition between tropical and temperate marine ecosystems, Shark Bay is at the southern end of Western Australia's loggerhead turtle breeding range (Baldwin *et al.* 2003). The northern beaches of Dirk Hartog Island, found along the bay's western margin, are home to the largest nesting population of loggerhead sea turtles in Australia and the third largest in the world (Baldwin *et al.* 2003). Both the eastern and western gulfs of Shark Bay are foraging grounds for large numbers of adult and subadult loggerhead turtles that may frequent nesting beaches of Dirk Hartog Island or those along the northwest coast of Western Australia (Heithaus *et al*. 2005, Thomson 2011).

This research was conducted in the eastern gulf (*ca.* 25º 45’ S, 113º 44’ E), offshore of the Monkey Mia Dolphin Resort (Figure 1). This region encompasses extensive nearshore sandflats that support loggerhead turtles and other large benthic predators (Vaudo and Heithaus 2009, Thomson 2011), numerous offshore seagrass banks (<4.0m depth), and largely unvegetated deeper waters (6.5-15.0m depth) (Heithaus *et al.* 2005).

Turtle Capture and Tagging

In February and March 2009, nine male loggerhead turtles were captured by hand while searching haphazardly in shallow waters (<5.0m depth) from a 4.5m boat. Once captured, each turtle was brought alongside the boat, placed in a harness and weighed (±1 kg) using a hanging Salter scale (see Thomson *et al*. 2009). Turtles were brought onboard, measured (curved carapace length, CCL) and equipped with a titanium flipper tag. Each turtle was fitted with a Wildlife Computers SPOT satellite transmitter (Wildlife Computers, Redmond Washington State USA; Figure 2). Satellite tags were attached to the highest part of the carapace, using West Systems 105 epoxy with 205 hardener and borosilicate micro-balloons (see Eckert *et al*. 2008). Each tag was covered in dark blue Interlux Micron 66 antifouling paint (International Paint, Union New Jersey USA) which was allowed to dry prior to each turtle being released.

Satellite Telemetry, Accuracy and Filtering

SPOT tags used the Argos system (www.argos-system.org) to derive positional information by geolocating animals using animal-borne transmitters and satellite-borne receivers (CLS 2011). Position estimates were then managed using the Satellite Tracking and Analysis Tool (STAT; Coyne and Godley 2005).

Figure 2. Male loggerhead with SPOT satellite tag and antifouling paint.

Each Argos position estimate contains a location classification (LC) representing an estimated accuracy, which enables researchers to filter points based on accuracy requirements. LCs 3, 2, and 1 have Argos estimated errors of less than 250m, 500m, and 1500m, respectively. LCs 0, A, and B have no associated error estimations. Empirical studies by Hays *et al.* (2001) and Royer and Lutcavage (2008) found location class A comparable in accuracy to class 1 (errors from Hays *et al.*: LC1 1.33 ± 1.35 km, LCA 0.99 ± 1.36 km; errors from Royer and Lutcavage: LC1 2.01 km, LCA 2.78 km). More recently, Witt *et al*. (2010) found errors such that LC3 < LC2 < LC1 < LCA < LCB < LC0; with error for LC1 = 0.8 ± 0.7 km, and error for LCA = 1.4 ± 2.5 km.

Acknowledging the trade-off between filtering location classes with greater error and retaining enough position estimates to get a realistic estimate of a turtle's space use, I filtered positions by removing points classified as LC 0 and B and retained points classified as LC 3, 2, 1 and A. Including LC A positions nearly doubled (and in some cases tripled) the number of position estimations gathered during the seven month tracking period. Because the methods I used to estimate activity space places a high probability of use where the density of points is greater, the cost of including points that could be less accurate was offset by the value of having more points to provide a more complete representation of space used.

Further filtering removed visually erroneous land based points, and points requiring a swimming speed >5 km h^{-1} (Luschi *et al*. 1998, Mangel *et al*. 2011). Filtered positions were plotted using ArcGIS 9.3 (ESRI, Redlands California USA).

Activity Space Analysis

I estimated loggerhead movement patterns with kernel density estimation in ArcGIS 9.3 using Hawth's tools Fixed Kernel Density Estimator (www.spatialecology.com/htools) with a bivariate normal kernel. Kernel density estimation is the established method for describing intensities of space use for free ranging animals (Worton 1989). This method generates three dimensional probability density functions with percent volume contours (pvc) that delineate the space where there is a specified probability that an animal will be found over a particular time period (Kernohan *et al.* 2001). Thus, an 85 pvc activity space displays an area in which there is an 85% probability of finding the animal, given a particular time period.

Bandwidth selection is critical in kernel density estimation because as a smoothing parameter, it controls the width of each point's probability density kernel. Various bandwidth selectors have been developed that use spatial data to minimize the mean integrated square error between the estimated density and the true unknown density. Two of the most robust bandwidth selectors are least squares cross-validation (LSCV) and direct plug-in (Lichti and Swihart 2011). I used the 'ks' package in R to produce 85 pvc activity spaces for each of the nine turtles using both the LSCV and direct plug-in methods. While LSCV and direct plug-in performed similarly for most of the turtles (mean difference for seven of the turtles: 11 km^2 ± 6.5 sd), the LSCV bandwidth for a turtle with two foraging sites that were far apart was not ecologically realistic. Based on this and that other studies have found direct plug-in methods to be more precise (Wand and Jones 1995, Duong 2007, Lichti and Swihart 2011), I chose to use the direct plug-in bandwidth selector.

Kernel density estimations were generated for each of the nine male loggerhead turtles using data transmitted between release (22 Feb – 27 Mar 2009) and 1 Oct 2009. I then calculated 50 pvc activity spaces to identify highly used, or core, spaces within each turtle's home range, 85 pvc activity spaces to encompass a larger amount of each turtle's movements, and 95 pvc activity spaces to incorporate area closer to edges of each turtle's range. While 95 pvc areas are frequently used in animal space use studies (Seaman *et al*. 1999), I also chose to calculate 85 pvc activity spaces based on findings by Seaman *et al*. (1999) that estimates in the outer contours are less reliable than the inner contours and because of the trade-off between incorporating LC A points and using a higher pvc activity space. By retaining LC A points in generating activity spaces, points that are outliers due to error will be in a space of low probability and be excluded by a smaller pvc area. By including more position estimates (by retaining LC A points), true movements will more likely be captured with multiple position estimates, resulting in a greater probability at those spaces and thus a greater probability of being retained by smaller pvc areas. These factors resulted in the 85 pvc area being deemed biologically appropriate for examining activity space in this study. Thus, 85 pvc activity spaces were used in subsequent analysis.

Location Class Sensitivity

To examine the sensitivity of activity spaces due to location class filtering, kernel density estimates were generated and 85 pvc activity spaces calculated using only LCs 3, 2, and 1. Since the data sets with LCs 3, 2, 1 and A have more points than the data sets with LCs 3, 2 and 1, 85 pvc activity spaces were also generated for each turtle by randomly selecting points from the data sets with LCs 3, 2, 1 and A, to match the sample size of the data sets with LCs 3, 2 and 1.

Seasonality of Spatial Activity

To test if loggerhead space use varies as a function of season, I calculated 85 pvc activity spaces for three-month periods during the breeding season (1 Nov 2009 – 1 Feb 2010) and outside the breeding season (1 May – 1 Aug 2009) (Baldwin *et al*. 2003) for the four turtles that continued transmitting through 1 Feb 2010. The effect of season on activity space size was tested with a paired t-test on normalized data.

Results

Activity Spaces

The nine male loggerhead turtles on which I deployed satellite transmitters ranged in size from 90 – 103 cm CCL (mean 98.6 ± 3.7 sd) and from 106 – 135 kg (mean 117.7 ± 8.9 sd) (Table 1). The mean number of days tracked was 172 (± 41 sd) and the mean number of data points for each turtle was 227 (± 79 sd) (Table 1). Displacements between release locations and final position points ranged from 2.2 – 100.4 km, with a mean of 27.4 km (± 32.3 sd) (Table 1). Core activity spaces based on a 50% probability of occurrence ranged from 5.2 to 171.5 km^2 with a mean of 43.5 km^2 (± 57.5 sd) (Table 1; Figure 3). Activity spaces based on an 85% probability of occurrence ranged from 27.9 to 586.8 km^2, with a mean of 186.0 km^2 (± 206.0 sd) (Table 1; Figure 3), and activity spaces based on a 95% probability of occurrence ranged from 60.3 to 1771.9 km^2 with a mean of 438.9 km^2 (± 562.4 sd) (Table 1; Figure 3).

Individual turtles could be classified into two major groups based on movements. Turtles in the first group (2, 3, 4, 7) used a single area (each <52.8 km^2 based on 85pvc activity spaces) exclusively for the duration of the tracking period (22 Feb – 1 Oct 2009). Turtles in the second group (1, 5, 6, 8, 9) used one area for a period of time, but then transited to another area where they took up residence, staying sometime between a week to several months (Figure 3). For example, turtle 5 inhabited an area in the eastern gulf for several months, and then over the course of three days in June moved roughly 85 km to the coastal waters off of Bernier and Dorre Islands, where it stayed until the end of September (Figure 3). Some of the turtles in the second group (1, 6, 8, 9) returned to the

Table 1. Summary of physical and tracking information for nine male loggerhead turtles fitted with SPOT satellite transmitters from Wildlife Computers. Turtles were tracked between 22 Feb and 1 Oct 2009. Data points retained are of location classes 3, 2, 1 and A. Displacement based on distance between release location and final transmission location. Percent volume contours (pvc) calculated from kernel density estimations generated for each turtle.

						Activity Spaces		
Turtle	Length (ccl in cm)	Weight (kg)	Days Tracked	Number of Data Points	Displacement (km)	50pvc (km^2)	85pvc (km^2)	95pvc (km^2)
1	98	120	215	203	2.5	25.5	182.8	309.1
2	100	108	220	298	2.2	7.8	52.3	107.4
3	102	120	219	232	26.7	5.5	27.9	60.3
4	101	--	219	249	2.7	5.2	36.5	81.5
5	98	115	219	311	100.4	171.5	586.8	1771.9
6	96	106	202	208	3.3	10.3	62.0	131.9
7	99	120	105	83	49.8	7.3	52.8	90.3
8	103	135	217	336	25.5	35.1	139.3	297.9
9	90	--	146	128	33.9	123.0	533.5	1099.6

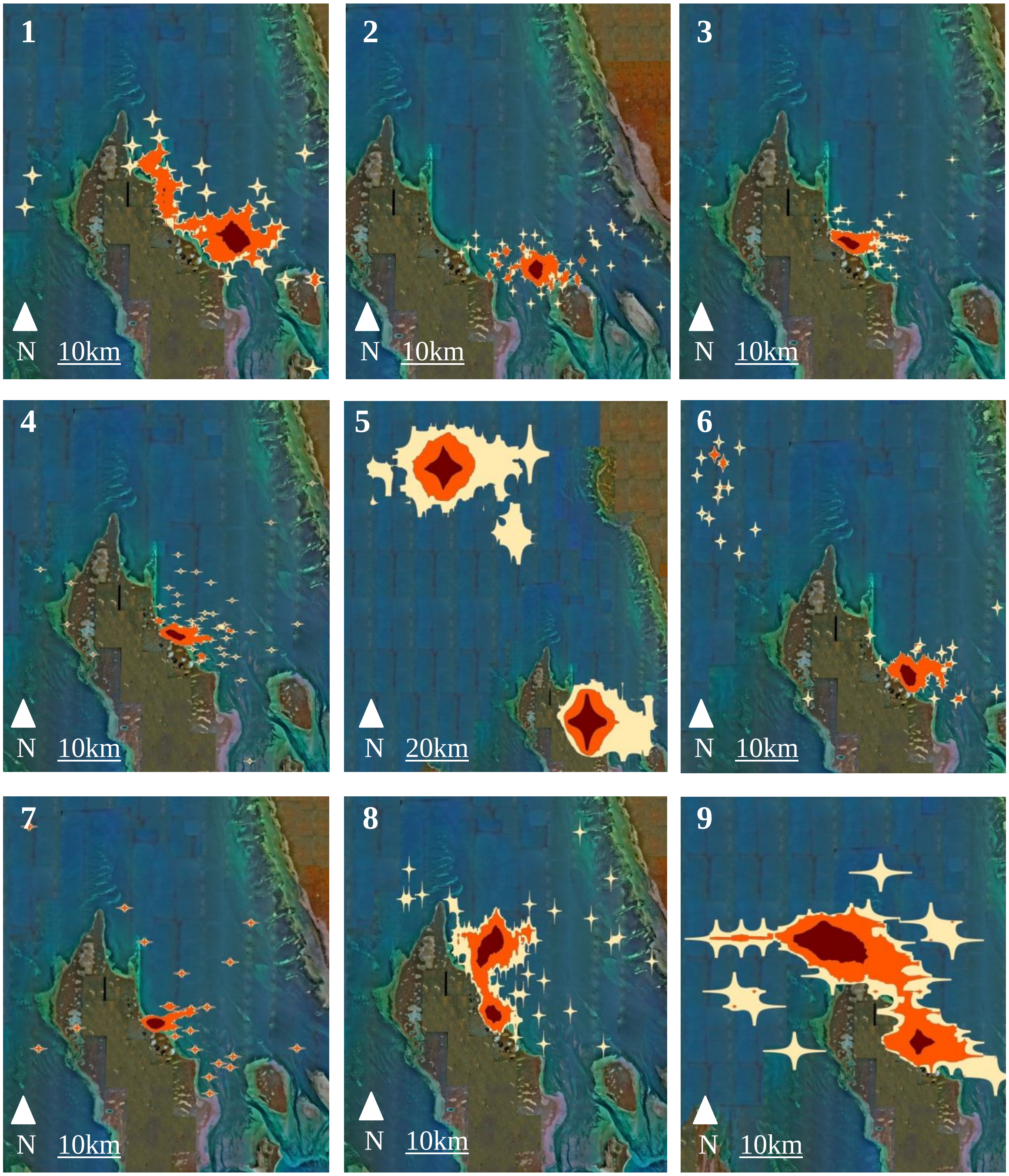

Figure 3. Probability density functions generated from kernel density estimation for three percent volume contours (pvc) for nine turtles: 50 pvc areas (yellow), 85 pvc areas (orange), and 95 pvc areas (red). Note the variation in spatial scale for wide ranging turtle 5.

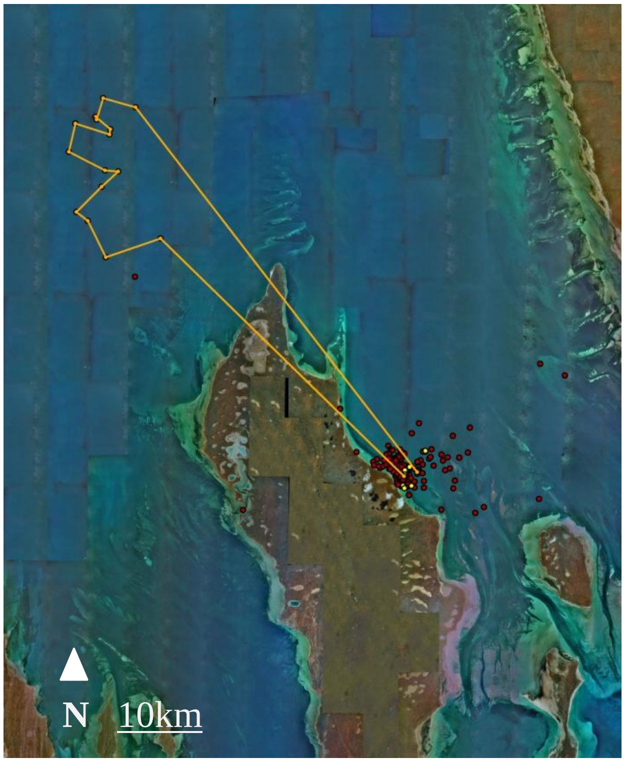

Figure 4. Location estimates for turtle 6. Lines chronologically connect points during 21Jul – 4 Sept 2009 to highlight when the turtle travelled from one foraging area to a second foraging area and back again.

area they used initially (Figure 4), with turtle 8 transiting between the two areas three times and turtle 9 moving between its two areas eleven times.

Location Class Analysis

When I used LCs 3, 2 and 1 (mean 84.4 km^2 ± 140.7 sd), the 85 pvc activity spaces generated were 20.7 – 87.5% smaller than the 85 pvc activity spaces generated using points with LCs 3, 2, 1 and A (mean 186.0 km^2 ± 206.0 sd) (Table 2; Figure 5). Similarly, 85 pvc activity spaces using LCs 3, 2 and 1 (mean 84.4 km^2 ± 140.7 sd) were 52.2 – 84.6% smaller than 85 pvc activity spaces generated by randomly selecting points from the data set with LCs 3, 2, 1 and A (mean 277.8 km^2 ± 366.0 sd) (Table 2; Figure 6).

Table 2. Summary of 85 pvc activity spaces for each turtle, calculated using: (a) All points with LCs 3, 2 and 1. (b) All points with LCs 3, 2, 1 and A. (c) Randomly selected points from the data set with LCs 3, 2, 1 and A, to match the sample size of the data set of LCs 3, 2, and 1.

	all LC321		all LC321A		randomly selected LC321A	
Turtle	Number of Data Points	85pvc Activity Space (km^2)	Number of Data Points	85pvc Activity Space (km^2)	Number of Data Points	85pvc Activity Space (km^2)
1	60	49.5	203	182.8	60	274.5
2	127	12.6	298	52.3	127	59.1
3	96	6.6	232	27.9	96	20.6
4	110	6.7	249	36.5	110	32.6
5	107	465.5	311	586.8	107	972.9
6	57	20.3	208	62.0	57	38.3
7	21	6.6	83	52.8	21	14.0
8	180	50.7	336	139.3	180	170.4
9	27	141.4	128	533.5	27	918.1

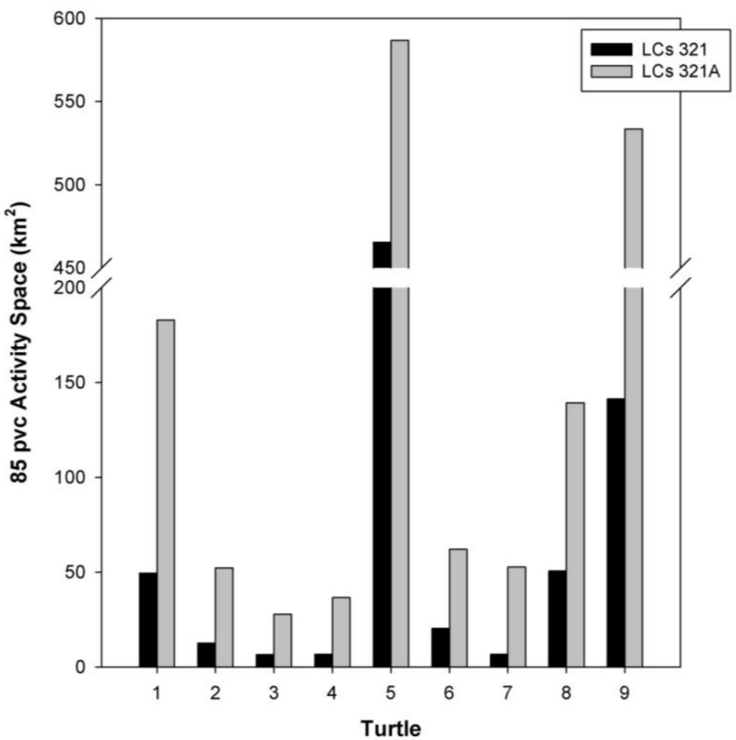

Figure 6. 85 pvc activity spaces for each of the nine turtles generated using LCs 321 and LCs 321A.

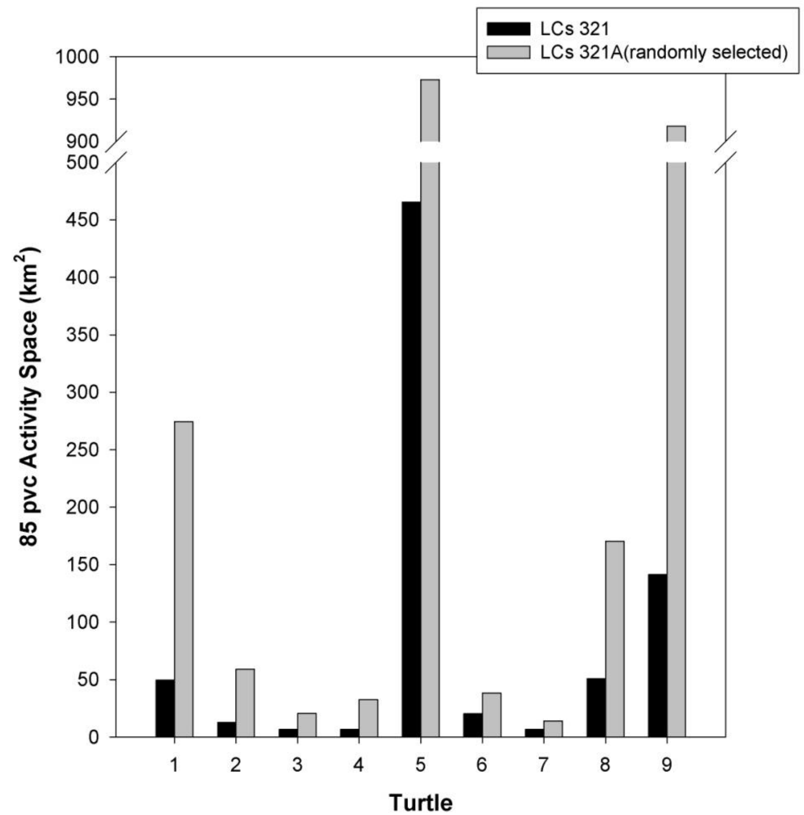

Figure 5. 85 pvc activity spaces for each of the nine turtles generated using LCs 321 and randomly selected points from LCs 321A to match the number of points with LCs 321.

Seasonality of Spatial Activity

Based on four turtles for which I have sufficient time series of spatially explicit data, three-month 85 pvc activity spaces were generated both during the breeding season (1 Nov 2009 – 1 Feb 2010) and outside of the breeding season (1 May – 1 Aug 2009). Breeding season activity spaces ranged from 67.8 to 423.3 km^2, with a mean of 178.2 km^2 (± 143.5 sd) (Figure 7). Activity spaces outside of the breeding season ranged from 45.6 to 1043.9 km^2, with a mean of 478.1 km^2 (± 361.4 sd) (Figure 7). Three turtles (1, 5, 9) exhibited smaller activity spaces during breeding season (Figure 7). One turtle (2)

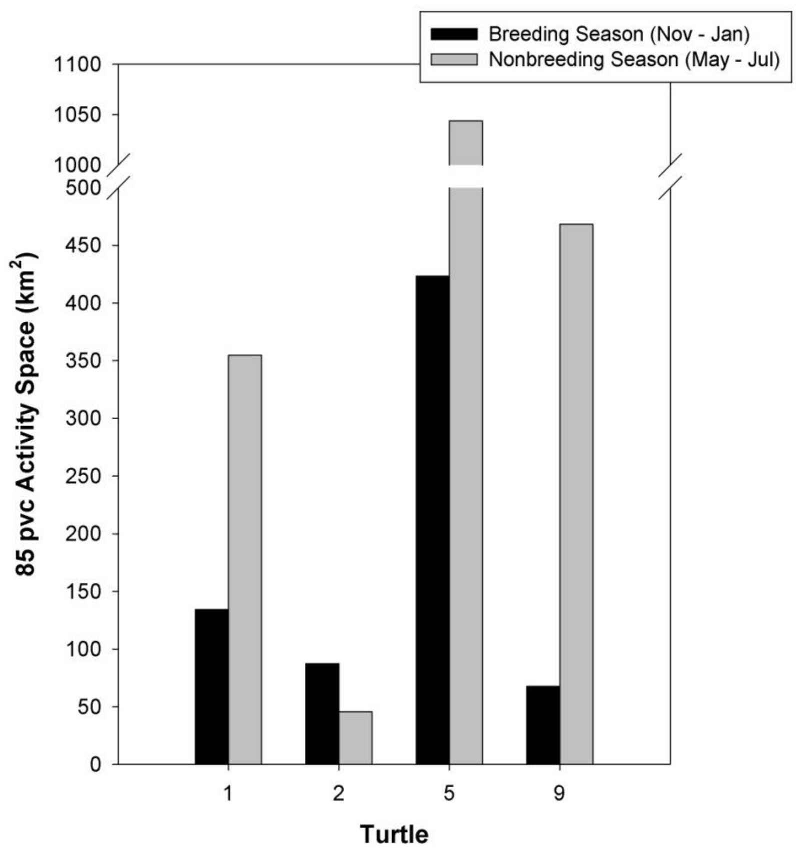

Figure 7. Summary of during and outside of breeding season activity space analysis.

manifested a larger activity space during breeding season (Figure 7). Based on a sample size of four, I found no significant difference in loggerhead activity space as a function of breeding season (n=4, t =2.14, p =0.12).

Discussion

Activity space sizes of nine male loggerhead sea turtles in Shark Bay Australia were restricted to 186.0 km^2 (± 206.0 sd) on average with a maximum of 586.8 km^2. After seven months of tracking, eight of the nine turtles were within 50 km of their original capture location, and four of those within 4 km of their original capture location. These activity spaces were smaller than anticipated given previous research in which loggerhead turtles have exhibited transoceanic migrations (Nicols *et al*. 2000), activity spaces >1000 km^2 (Hawkes *et al*. 2011), and the previous pilot study which revealed that one male loggerhead tracked for seven months moved approximately 140 km north up the coast of Australia and out of the SBWHA (Wirsing *et al.* 2004). Based on our satellite tracking data from nine turtles, two spatial use patterns emerged: (1) males that use one foraging area, and (2) males that use two foraging areas. Finally, I found no clear trend regarding differences in the extent of space used by male loggerheads during and outside of breeding seasons, but it was clear that none of the turtles exhibited any movement toward the Dirk Hartog Island nesting beach on the western edge of Shark Bay.

I found male loggerhead turtles in Shark Bay to exhibit fidelity to small foraging areas compared to the wide variety of foraging area sizes observed worldwide. Female loggerheads in the northwestern Atlantic have been found to occupy foraging areas anywhere from hundreds to thousands of km^2 (Hawkes *et al*. 2011); females off the coast of Brazil occupy foraging areas between 500 and 1500 km^2 (Marcovaldi *et al*. 2010); and Mediterranean females use foraging areas between 3.5 and 1198 km^2 (Zbinden *et al*. 2008). Recent studies on adult male loggerheads in the Mediterranean suggest they follow similar migratory patterns as adult females, but differ in the sites in which they forage (Schofield *et al*. 2009), with foraging areas ranging from 10 km^2 in neritic habitats to 1000 km^2 in oceanic habitats (Schofield *et al*. 2010). I found male loggerhead turtles in Shark Bay use foraging area sizes comparable to the smaller neritic foraging areas used by Mediterranean males. If neritic areas are more resourceful, turtles could be staying in smaller foraging areas to forgo expending energy on unnecessary movement (Stephens and Krebs 1986). Regional and local variability in movement and activity space sizes suggest there is a suite of drivers (extrinsic and intrinsic) acting at multiple scales.

While all turtles in this study exhibited relatively small foraging areas, movement patterns on the foraging grounds differed, with individuals either (1) staying in one foraging area, or (2) using two different foraging areas. Among the latter group, I observed differences in both the distance between the two areas and the frequency with which turtles moved between them; the greater the distance between the two areas, the less often turtles switched foraging sites. For example, turtle 5 travelled 85 km to a second site just once in seven months, while turtle 9 moved eleven times between two foraging areas that were only 15 km apart. So why do some turtles chose to move between sites while others remain in one area?

Alternative hypotheses can be invoked to explain differences in the extent of loggerhead spatial activity. Schofield *et al*. (2010) suggest that the choice to move to another area could be related to resource productivity. Maintaining high site fidelity is low-risk when resources are abundant but when resources become scarce, movement to another site becomes a better option despite the risk inherent in transiting between sites (Stephens and Krebs 1986). A male tracked in the Mediterranean moved to four distinct foraging sites in one three month period outside breeding season (Schofield *et al*. 2010). In Shark Bay, some turtles moved between two sites but none were observed using a third site during our seven month observation window. Since Shark Bay contains one of the largest seagrass meadows in the world and areas of high species richness (Walker *et al.* 1988), an abundance of prey could be reducing the necessity for turtles to use more than two sites, and could be allowing the turtles of group 1 to remain at one site. Competition could drive movement as well. While no antagonistic interactions were observed in video foraging studies (Thomson 2011), it could be that some turtles leave an area without confrontation when other turtles begin to occupy similar foraging arenas. Individual differences in decisions about whether to move, where to move, and movement frequency, could be due to intrinsic drivers such as knowledge of surrounding habitats or physical condition (Schofield *et al*. 2010). At the foraging site scale, further research into site qualities, loggerhead densities, and the physical conditions of loggerheads, would reveal influences behind individual differences in movement behavior.

While foraging areas were all relatively small, the size of the small sites varied. Of the turtles that used one foraging site, 85 pvc activity spaces ranged from 27.9 to 52.8 km^2. Multiple factors could be interacting together to drive these observed differences. One factor, resource availability, could alter site size with lower prey densities driving turtles to expand their foraging site area. Conversely, if Shark Bay's large seagrass meadows provide a high density of prey, then turtles would not benefit by expending more energy moving than necessary, and exhibit small activity space sizes at their foraging sites (Stephens and Krebs 1986). Another possible driver of foraging site size could be shark presence. Shark Bay is used by large numbers of tiger sharks (*Galeocerdo cuvier)*, the main predator for loggerhead turtles (Heithaus 2001, Heithaus *et al*. 2002). Thus, the activity spaces I observed could in part reflect anti-predator behavior. In the patchwork of seagrass banks that characterizes the eastern gulf, turtles are most vulnerable to sharks in the middle of banks, and least vulnerable at the edges where they can quickly find refuge in deeper waters (where they can more easily maneuver to avoid an attack) (Heithaus *et al.* 2008). Thus, shark presence could drive turtles to use larger foraging areas in order to encompass more seagrass bank edges and deeper refugia. Also, individual intrinsic drivers such as age, size, or body condition, may elicit more or less risky behavior that could result in individual differences in site sizes at the same location.

Predator effects could drive seasonal differences in turtle foraging area size as well. In Shark Bay tiger shark abundance fluctuates on an annual basis, with the lowest numbers typically in July and highest numbers in February (Heithaus 2001). If sharks are influencing turtle foraging area as previously described, then I would expect to observe larger foraging areas in the austral summer, or breeding season. Yet, while I did observe seasonal differences in space use, three of the four turtles for which this comparison was possible actually used larger spaces in the austral winter. With a limited sample size of four turtles, however, further research is required to quantify seasonal differences in foraging area sizes.

A notable finding from our seasonal analysis is that, during the breeding season, none of the males made any movement towards a nesting beach, including the rookery on the northern tip of Dirk Hartog Island. Although I expected to see movement patterns change during the breeding season, it could be that males in Shark Bay are not exhibiting changes because they do not have to. In the Mediterranean and off the coast of eastern Australia, males are known to migrate between breeding sites and foraging areas (Schroeder *et al*. 2003). On the foraging grounds of the eastern gulf of Shark Bay, the largest nesting beach in Australia is located just 95 km on the other side of the bay. Thus, male loggerheads in the eastern gulf could be finding breeding opportunities without having to move away from their foraging areas. Mating has been observed in the eastern gulf (M. Benson, personal communication), however further research is required to uncover the spatial extent of mating in Shark Bay.

I captured nine male loggerhead turtles outside of the breeding season in a known foraging ground. Therefore, inferences made from our findings may reflect bias associated with the timing and location of satellite tag deployment. Population abundance is known to double in Shark Bay in the warmer breeding season months (Thomson 2011). If there are loggerheads that migrate for breeding, it is possible I may not have been exposed to them during our capture time (22 Feb – 27 Mar 2009). Thus, the males in our study could all be part of a population that exhibits movement and habitat use patterns different from the individuals that cause the population to double in the warmer months.

Furthermore, I captured turtles in waters with a depth less than 5m. Future tracking by capturing turtles in different seasons as well as at different depths will reveal potential alternative movement and habitat use patterns of male loggerheads in Shark Bay.

Shark Bay has been identified as having important foraging and nesting habitats in The Marine Turtle Recovery Plan for Western Australia (Department of Environment and Conservation 2009). The Marine Turtle Recovery Plan identifies the need to understand movement characteristics in order to identify critical habitat, and states that “A primary goal of conservation reserves is to provide adequate protection for critical habitat of threatened species” (Department of Environment and Conservation 2009, p.38). The lack of larger migratory movements up the coast of Western Australia by the nine turtles in this seven month tracking study suggests that some turtles in the eastern gulf of Shark Bay are likely part of a resident population. The high frequency of recaptures in ongoing research by the Shark Bay Ecosystem Research Project further supports this evidence (Heithaus *et al*. 2005). Findings from this study also suggest there are localized foraging hotspots within Shark Bay. Since Shark Bay is within a protected area (SBWHA), existing conservation frameworks can be implemented to protect this resident population at the biologically relevant scale at which turtles are moving in Shark Bay, including regulations such as zoning for slower boat speeds to reduce vessel strikes and fishing guidelines to reduce bycatch. Further work into identifying the fine-scale drivers of male loggerheads space use will help to unravel characteristics of critical habitat for this endangered species and further inform conservation strategies.

When applying space use information to management, it is important to acknowledge the accuracy of satellite location classes and the uncertainty they generate when estimating the spatial extent of habitat use. When filtering Argos location estimations, a trade-off exists between using fewer points with greater accuracy and having enough points to provide a realistic estimate of space use. In this study, using only location classes 3, 2 and 1 resulted in 85 pvc activity spaces that were, in eight out of nine cases, less than half the size of the activity spaces using location classes 3, 2, 1 and A (Table 2; Figure 5; Figure 6). Location class A points are less accurate but more frequent and represent biologically relevant information. In kernel density estimation, a higher density of points results in a higher probability at that location. Thus, the cost of incorporating points that may be more erroneous is offset by the benefit of having more points which provide a more complete representation of the animal's space use. Strategically choosing percent volume contours is also an interacting factor since lower pvcs can potentially exclude low probability space only based on erroneous points. Exploring multiple filtering and pvc possibilities, knowledge of the study system, and knowing the objective for the application of the results, aids in determining how to filter and what pvcs to calculate. For this study, when quantifying activity spaces used by an endangered species for informing conservation initiatives, it was important not to underestimate space use due to a lack of location estimations.

Identifying male loggerhead turtle movement patterns contributes to the global research priority for marine turtles of identifying loggerhead biogeography in foraging habitats (Hamann *et al.* 2010). The turtles in this study exhibited high fidelity to relatively small foraging areas. Differences in loggerhead foraging strategies have been observed in the

Mediterranean and off the eastern coast of the USA (Schofield *et al*. 2010, Hawkes *et al*. 2011). Possibly due to the loggerhead generalist diet facilitating occupation of a wide range of habitats and use of multiple foraging strategies (Schofield *et al*. 2010), there is increasing evidence of behavioral plasticity around movements of loggerhead turtles (Rees *et al*. 2010). This variation in movement strategies around the world highlights the need for studies at multiple scales and locales. Wallace *et al*. (2010) has proposed Regional Management Units (RMUs) as an effective way to organize marine turtles at a scale above nesting populations, but below the species level, to regions that may be on different evolutionary trajectories. Within this framework, Western Australia's loggerhead population is distinct from the eastern Australian population (Wallace *et al*. 2010). With less known about Western Australia's loggerhead population (Limpus 2008), loggerhead spatial ecology must be explored further in Western Australia. Shark Bay has been deemed a hotspot in the Marine Turtle Recovery Plan for Western Australia (Department of Environment and Conservation 2009), making it an important site for which to continue research into the degree of behavioral plasticity around loggerhead turtles spatial ecology.

Our results offer direction for future research. They suggest, for example, that studies should track individuals captured at various times throughout the year in order to capture the range of individual variability in movement and habitat use patterns displayed by male turtles in Shark Bay. Then, groups that exhibit similar patterns (such as the one site and two site groups identified in this study) should be pieced together to inform management strategies of the multiple biological scales at which conservation activities must be applied (Hilborn *et al*. 2005). To inform conservation management of the characteristics of critical habitat, combining tracking information with measures of resource availability, predation pressure, abotic dynamics, and physical conditions will reveal drivers of movement and habitat use. Finally, similar studies with female conspecifics on these same foraging grounds will reveal sex-specific differences in space use requirements and anthropogenic threats, as well as begin to uncover breeding dynamics.

Chapter 2 – Documenting Traditional and Local Ecological Knowledge of Loggerhead Sea Turtle (Caretta caretta) Movement and Habitat Use in Shark Bay, Australia

Introduction

Conservation strategies require an understanding of species' distribution and movement patterns (Block *et al*. 2001, James *et al*. 2005, Schofield *et al*. 2007). Uncovering movement patterns, however, poses a challenge for elusive marine species. Integrating multiple lines of evidence, each with their unique levels of uncertainty can inform challenging research objectives. There has been a growing application of incorporating traditional and local ecological knowledge (TEK & LEK) into quantitative scientific research to better inform ecological questions (Gadgil *et al*. 1993, Berkes *et al*. 2000, Huntington *et al*. 2004, Drew 2005, Salomon *et al*. 2007). I combined TEK, LEK and satellite telemetry discussed in Chapter 1, to assess loggerhead sea turtle movement and habitat use in Shark Bay, Australia.

Theoretically, loggerhead turtles should use spaces that allow for maximizing energy intake while minimizing costs (i.e. search time, digestion, exposure to predators) (Stephens and Krebs 1986, Walters and Juanes 1993). External drivers of movement can be resource driven (i.e. prey availability), consumer driven (i.e. exposure to predators), conspecifically driven (i.e. competition), or driven by abiotic factors. Alternatively, individual decisions regarding movement and habitat use can driven by intrinsic factors, such as size, sex, and individual knowledge, memory or preference. When collecting traditional and local ecological knowledge, one can document observations about loggerhead turtles as well as hypotheses regarding why loggerheads exhibit the movement and habitat use patterns observed.

Shark Bay is a home to just under 1000 permanent residents (Department of Environment and Conservation 2009). Two of the main industries are fishing and tourism (Department of Environment and Conservation 2009). In Shark Bay, fishermen fish with their family members and fishing techniques are passed down through generations. These fishermen learn about their local waters from their elders and are continually observing and gathering information about their local ecosystem. Similarly, local ecotourism operators, who may or may not have grown up in Shark Bay, have spent extensive time on its waters, continually collecting knowledge about the marine environment. Some of these operators specifically pay attention to movement and habitat use patterns of marine turtles because their tourists are interested in seeing turtles.

I documented traditional and local ecological knowledge of loggerhead sea turtles habitat use in Shark Bay to inform understanding of loggerhead movement patterns in Shark Bay and the factors that drive variation in their use of space. I then compared these qualitative data with my quantitative satellite telemetry data.

Methods

Study Area

Shark Bay, Western Australia, is a World Heritage Area featuring expansive seagrass meadows (Walker *et al.* 1988) that have experienced minimal human impacts and support intact populations of large-bodied grazers and predators (Heithaus *et al*. 2005, Vaudo and Heithaus 2009). Located at a latitudinal transition between tropical and temperate marine ecosystems, Shark Bay is at the southern end of Western Australia's loggerhead turtle breeding range (Baldwin *et al.* 2003), and home to between 1000 and 2500 loggerhead sea turtles, depending on the season (Thomson 2011).

The Shire of Shark Bay is a home to just under 1000 people (permanent residents) (Department of Environment and Conservation 2009). The main population centre is Denham, on the eastern shore of the western gulf (Figure 1). Operating out of Denham, fishing and tourism are two of the main industries (Department of Environment and Conservation 2009). Another main tourism site, The Monkey Mia Dolphin Resort is located on the western shore of the eastern gulf. The geographical scope for this study was the entire marine area of Shark Bay, including both the eastern and western gulfs (Figure 1).

Collecting Traditional and Local Knowledge

Semi-directed interviews were conducted with eight locals to document their knowledge concerning loggerhead turtle movements and space use. Using a semi-directed format for each interview, a list of topics (Appendix A) was used as a guide and to prompt further discussion. However, respondents were able to pursue their own train of thought in the mode of a conversation rather than a question-and-answer session (Huntington 2000). Respondents were asked to discuss their observations of loggerhead turtles in Shark Bay (i.e. where and when they observe turtles), if there are areas they notice more loggerheads, and changes in the number of loggerheads seasonally and over many years.

Respondents were also asked to discuss their hypotheses concerning their observations, such as reasons why loggerheads exhibit observed movement and habitat use patterns, as well as what the key threats are to the loggerhead population.

Participants were identified through recommendations from local residents and chain-referral. Participants were selected because they are or have been fishermen in Shark Bay for many years, or they spend considerable time on the water in Shark Bay. Traditional and local knowledge was gathered from six Aboriginal fishermen who have lived in Shark Bay since they were children, one Aboriginal ecotourism operator who has lived in Shark Bay since childhood, and one non-Aboriginal ecotourism operator who has lived in Shark bay for 15 years. Responses were grouped and analyzed according to key ecological themes that emerged, relevant to this research.

Results

The traditional and local ecological knowledge collected from eight participants provided both direct observational data on loggerhead activity space size and movement, habitat use, population abundances and seasonal differences in behavior as well as hypotheses postulating the factors influencing habitat use and the major contemporary threats to loggerheads (Appendix B).

Activity Space

Qualitative data revealed that loggerhead turtle movement in Shark Bay is limited and that loggerheads are staying in small areas. Furthermore, participants reported that loggerheads are observed throughout the entire bay, yet there are some areas in which turtles are more prevalent (each circle ~ 120 km^2; Figure 8). These areas were consistent across respondents. These responses corroborate findings from satellite tracking, since tracked loggerheads stayed in relatively small activity spaces over the seven month tracking period (mean of 186.0 km^2 ± 206.0 sd for 85 pvc activity spaces), and five turtles moved between two sites, spending minimal time in between those sites, suggesting localized hotspots.

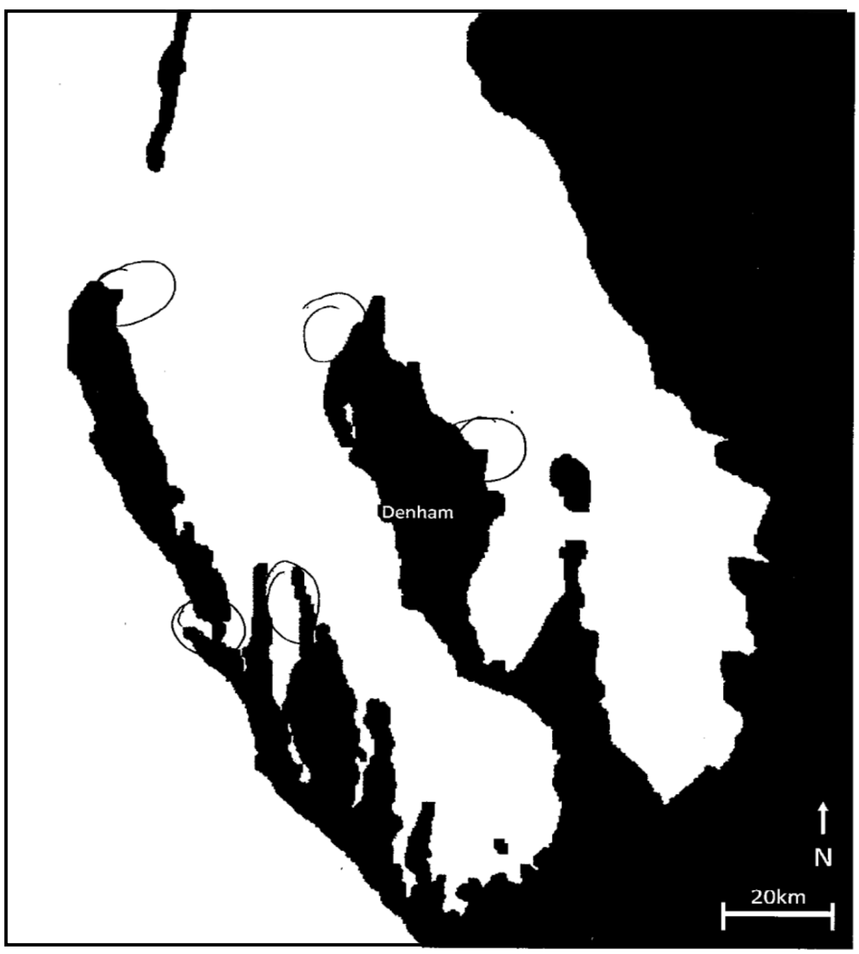

Figure 8. Respondents indicated loggerhead turtle aggregation areas. Black = land, white = ocean.

Factors Influencing Habitat Use

Responses explaining loggerhead habitat use included bottom-up (resource driven) and top-down (consumer driven) drivers. The most commonly discussed reason for loggerhead presence was abundance of food. Avoidance of their main predator, tiger sharks, was also mentioned. Some of the respondents discussed how loggerheads tend to be in deeper water or in areas with quick access to deeper water. Yet one articulated how turtles could be spending more time at the surface in deeper areas, increasing visibility and biasing their perception from actual abundance. Also discussed was the complexity of the ecosystem and the difficulty in detangling explanatory variables when trying to identify the areas loggerhead turtles use.

Seasonality

Loggerhead turtles are observed less in the winter months. This seasonal variability in loggerhead presence was consistent across participant responses. Two fishermen suggested it was at least in part due to changes in water temperature. Findings from satellite tracking did not suggest a seasonal variation in loggerhead presence. Of the four turtles that were tracked during and outside of the breeding season, I found no significant difference in loggerhead activity space ($n=4$, $t=2.14$, $p=0.12$) and the turtles stayed in the same general location.

Population Abundance and Trends

Responses regarding loggerhead population trends through time differed among participants, ranging from population decline, no change, and increase. Also discussed was the difficulty of estimating population level because there are so many fluctuations in numbers of turtles observed. The possibility that the Department of Environment and Conservation efforts on the Dirk Hartog nesting beach are having a positive effect on the population was also discussed.

Contemporary Threats

Participants suggested that the primary threats to loggerhead turtles in Shark Bay included lack of understanding by humans about how their activities impact the ecosystem, increasing tourism and boating, climate change, and predation by their main natural predator, tiger sharks. Responses included both direct and indirect effects. For example, lack of understanding was an indirect threat since it contributes to why humans pursue activities detrimental to loggerhead turtles. Some respondents cited the direct effect of turtles being hit by boats as their biggest threat. Other respondents did not deem direct boat impacts a threat, but stated changes in climate as the biggest threat. With Shark Bay having a pristine environment and a sizeable population of tiger sharks, respondents noted the threat tiger sharks pose on turtles.

Discussion

Traditional and local ecological knowledge suggested that loggerhead turtles stay within small areas. Responses also indicated that while loggerheads are observed throughout the bay, there are some areas in which loggerheads are more abundant. Several hypotheses were given for why loggerheads are more abundant in some areas, including bottom-up and top-down drivers. Seasonally, respondents discussed observing loggerhead turtles less in winter months than summer months. Responses concerning the population trend were not consistent across participants and various impacts were provided as the biggest threat loggerhead sea turtles face.

Traditional and local ecological knowledge corroborates satellite telemetry findings from Chapter 1. The nine male loggerheads tracked 22 Feb – 1 Oct 2009, exhibited displacements that ranged from 2.2 – 100.4 km, with a mean of 27.4 km (± 32.3 sd), and 85 pvc activity spaces that ranged from 27.9 to 586.8 km^2, with a mean of 186.0 km^2 (± 206.0 sd). Based on previous research, I expected to observe movements outside of Shark Bay with activity spaces in the order of thousands. However, the foraging sites used were much smaller than anticipated. Traditional and local ecological knowledge documented in this study also suggests activity spaces used by loggerhead turtles are relatively small, with turtles staying in localized areas within the bay. Furthermore, traditional and local ecological knowledge comes from bay-wide experiences and observations, suggesting that findings from the nine turtles satellite tracked are not unique cases.

Respondents discussed observing less loggerhead turtles in winter than summer. This differs from satellite tracking findings, in which loggerheads did not show any significant seasonal variation in space use. However, it does corroborate findings from Thomson (2011), who combined data on diving variability with boat-based surveys to estimate population abundances in the eastern gulf of Shark Bay. In interviews to document traditional and local knowledge, some respondents acknowledged that loggerhead detection varies as a function of water depth such that turtles in clear or shallow waters are easier to observe. No information on how detection varies seasonally was collected, however, respondents postulated that the difference in seasonal abundance was due to temperature. Accounting for detection probability, Thomson (2011) found loggerhead abundance doubled during winter months from 1150 (± 106 se) in the cold months to 2141 (± 131 se) during the warm months. This could also explain satellite tracking results, in that the four turtles tracked could be part of a population that stays in Shark Bay year-round. Another potential driver for seasonal variability in loggerhead population abundance could be breeding and nesting. Since Shark Bay contains the largest nesting beach in Australia, there may be turtles migrating into the bay during the breeding season, which is in the warm months.

When integrating traditional and local ecological knowledge into studies of ecological phenomena, it is crucial to be aware of how that information was gathered or observed and how it was shared (Lewis *et al*. 2009). For example, fishermen observe loggerhead turtles in Shark Bay as a side effect of being on the water to fish. They may notice larger aggregations or unique events (i.e. mating), but do not necessarily note individuals. On the other hand, ecotourism operators may be intentionally monitoring loggerhead turtles on the water. For both fishermen and ecotourism operators, observations are based on the spatial and temporal extent of their observations. In this study, that varied among respondents. For example, the non-Aboriginal ecotourism operator interviewed was only on the water in the eastern gulf, while the fishermen fished throughout both gulfs. Thus, information gathered from each must be interpreted for when and where they spend time on the water. In this study, information was shared via semi-directed interviews. Documented traditional and local ecological knowledge was based on the questions that were asked and the memory of each respondent (Lewis *et al*. 2009). Accounting for these factors, traditional and local ecological knowledge provided valuable insights into loggerhead turtles movements and habitat use in Shark Bay.

A robust assessment of male loggerhead turtle space use in Shark Bay was achieved by combining traditional and local ecological knowledge and satellite telemetry, since each contain unique levels of uncertainty. Satellite telemetry studies provide novel insights into long-term movements of elusive species. However, they involve expensive equipment, often necessitating small sample sizes. It is difficult to make management decisions based on small sample sizes. Yet conservation management decisions must be undertaken using available information. Incorporating multiple methodologies in tackling a research question can provide complimentary information and allow for more informed management decisions (Gadgil *et al*. 1993, Berkes *et al*. 2000, Huntington *et al*. 2004, Drew 2005, Salomon *et al*. 2007). Furthermore, involving local people's knowledge in conservation strategies fosters connections within the community, and forms a basis for collaborative conservation management (Fernandez-Gimenez *et al*. 2006, Christie *et al*. 2009, Salomon *et al*. 2011).

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Appendices

Appendix A

Semi-Directed Interview Questionnaire

Previously determined questions:

Do you see or interact with sea turtles?

- If so, when does this happen?
- What are you doing when this happens?
    - Are you doing something related to your job?
- How often do you see or interact with sea turtles?
- Where do you see or interact with sea turtles?

Do sea turtles prefer certain places?

- If so, where?

Are there places where sea turtles tend to feed?

- If so, where?

What are sea turtles eating?

Are there areas that sea turtles tend to use for traveling/migrating?

Where do sea turtles mate?

- What do the males do during the mating season?
- What do the females do during the mating season?

Are there more, less, or the same number of sea turtles as there has been in the past?

- If not the same, what do you think is the reason for this?

Do sea turtles use the same areas that they did in the past?

- If not the same, what do you think is the reason for this?

Do you think sea turtles are important for the Shark Bay ecosystem?

- Why or why not?

What do people in the area think of sea turtles?

Appendix B

Traditional and local ecological knowledge on loggerhead sea turtles in Shark Bay, based on semi-directed interviews with 8 respondents, grouped by ecological theme.

Ecological Theme	Traditional and Local Ecological Knowledge Quotes from Respondents
Activity Space Size and Movement	"...they stay in one place, they don't move too far from an area. You see the same one there every day for 20 years." "I reckon that there are some here that have never left 2 kilometres of coastline that I've seen them in for the last 40 years. "...I think they're staying in their areas."
Habitat Use in Shark Bay	"But you see green turtles and loggerheads all the way. Never been anywhere where you don't see some of each." "You do see some everywhere we go. I say everywhere. If you went along the beach, or you went in a boat somewhere, if you covered 3 or 4 miles, you shoulda seen 1 or 2 loggerheads. And that's just about anywhere, really."
Factors Influencing Habitat Use	Prey Abundance: "Abundances of food I guess." Predation Risk: "Maybe what they eat… you know, they like the area or something like that, just depends. They may get out of the area because the sharks, because there's tiger sharks. Bathymetry: "Where we get little congregations, like the north end of Witchy is a popular spot. Because it comes off a fairly deep water into the shallows." "The loggers, just about anywhere, but more deeper though. We really do find them in deeper water. Maybe I think deeper because when they're in deep water, when they get to the top, they sit there and they take their breaths, they're not as quick to disappear. And in the shallows, I don't get to see them breath too many times, over there. I mean, they come up, but they don't seem to rest on the top for some reason." Uncertainty: "But if you knew, as you know, that there's a greenie there, or a loggerhead there, and you say, ah, it's in 2 metres of water, it's on seagrass, if I find another area like that I'm bound to fine one, I'm sure to find one, but you won't. You may, you may not, but don't count on it."

Seasonal Variability in Habitat Use and Detection	"In the winter season we don't see too many." "A bit quieter in winter, usually." "When they get a bit cold, they're a bit quieter."
Population Abundance Through Time	"I think they're thinning out a bit…but you still see a lot." "I think there's just as many around now as I seen when I was a kid." "Yeah, I'd say so. I'd say it's pretty much the same. Nah, it'd be pretty much the same. There always seem to be enough out there. And, like I say, sometime you get heaps and then other times, not much. And I haven't worked out the pattern for that. But yeah, I don't notice any loss or anything getting bigger or anything like that." "There's more loggerhead turtles around than I've ever seen. Whether what they do out there at Turtle Bay has helped 'em I don't know, but there's a lot of 'em. Pretty hard to tell because it can fluctuate up and down, from day to day, from week to week, as in what you see. But overall, I reckon, I be seein' more loggerhead turtles." "There's not the number of loggerheads compared to green turtles of course."
Contemporary Threats To Loggerheads	"Lack of understanding on the account of humans, about our ecosystem here, certainly our turtle habitats and things like that. Increasing boating activity here and certainly recreational fishermen and things like that, driving across turtle grounds and habitats and things like that. Increased activity within turtle zones, will force turtles to look for other places to go and feed and forage in the quiet. And destruction of natural habitat, through boating and things like that." "Well, as this area gets bigger, you gonna get a lot more tourists. I guess power boats are going to be the biggest threat to turtles, dugongs as well. That's the biggest threat." "The sharks I think, which is part of the ecosystem. I'm pretty sure boats hit them too, speed boats, although they might hear the sound coming and avoid it, but I'm sure boats, they get hit by a prop every now and again, that sort of thing. Be about the only thing. There's no other real pollution around. So it's pretty pristine. So pretty much natural causes for turtles." "The climatic changes. The turtle population is one of the few things that hasn't altered or been affected by humans." "Environment could be the only thing to take them down I reckon.