

FINE SCALE DIEL MOVEMENTS AND SHORT TERM ACTIVITY RANGES OF A  
MARINE MEGAHERBIVORE AT A HIGH BYCATCH LAGOON

By

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To my parents, Fred and Denise Senko, for always believing in me, nurturing my passion and teaching me the power of a dream

There exists a presence in the ocean, seldom glimpsed in waking hours, best envisioned in your dreams. While you drift in sleep, turtles ride the curve of the deep, seeking their inspiration from the sky. From tranquil tropic bays or nightmare maelstroms hissing foam, they come unseen to share our air. By night and by light, sea turtles glide always, their parallel universe strangely alien, yet intertwining with ours. Riding the churning ocean's turning tides and resisting no urge, they move, motivated neither by longing nor love nor reason, but tuned by a wisdom more ancient – so perhaps more trustworthy – than thought. Through jewel-hued sultry blue lagoons, through waters wild and green and cold, stroke these angels of the deep—ancient, ageless, great grandparents of the world.

—Carl Safina, *Voyage of the Turtle*

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# TABLE OF CONTENTS

	<u>page</u>
ACKNOWLEDGEMENTS .....	5
LIST OF TABLES .....	8
LIST OF FIGURES .....	9
ABSTRACT.....	10
CHAPTER	
1 FINE SCALE DIEL MOVEMENTS and SHORT TERM ACTIVITY RANGES OF A MARINE MEGAHERBIVORE AT A TIDALLY DRIVEN LAGOON.....	12
Introduction .....	12
Methods .....	16
Study Area.....	16
Turtle Capture and Morphometric Measurements .....	17
Tracking.....	18
Analysis .....	20
Habitat Survey and Analysis of Data.....	20
Do Diel Movements, Net Displacement or Short-Term Activity Ranges Vary With Turtle Size and Diurnal or Nocturnal Periods of Activity? .....	22
Are Turtles More Active at Crepuscular, Nocturnal or Diurnal Periods of Activity and at Spring or Normal Tides? .....	23
Does Water Depth and Seagrass Affect Turtle Distribution and Does This Effect Vary With Diurnal or Nocturnal Periods of Activity?.....	23
Statistical Analysis .....	24
Results .....	25
Study Animals and Tracking Effort .....	25
Do Diel Movements, Net Displacement or Short-Term Activity Ranges Vary With Turtle Size and Diurnal or Nocturnal Periods of Activity? .....	25
Are Turtles More Active at Crepuscular, Nocturnal or Diurnal Periods of Activity and at Spring or Normal Tides? .....	26
Does Water Depth and Seagrass Affect Turtle Distribution and Does This Effect Vary With Diurnal or Nocturnal Periods of Activity?.....	26
Discussion.....	27
Diel Movements, Net Displacement and Short-Term Activity Ranges.....	28
Turtle Activity and Movement Patterns .....	29
Ecological and Conservation Implications .....	32

2	TETHERED VHF-GPS TELEMETRY: AN IMPROVED, LOW COST TOOL FOR THE FINE SCALE TRACKING OF A LONG-LIVED MARINE MEGAVERTEBRATE .....	44
	Introduction .....	44
	Methods .....	46
	Tracking Device .....	46
	Field Trials .....	47
	Laboratory Trials .....	48
	Results and Discussion .....	49
	Effects of Tracking .....	49
	Challenges, Limitations, and Prospects for Future Studies.....	50
	Conclusions and Implications for Conservation .....	52
 APPENDIX		
A	STUDY AREA .....	58
B	DEPTH CLASSES .....	59
C	SEAGRASS COVERAGE .....	60
D	ALL TURTLES .....	61
E	CM 1 .....	62
F	CM 2 .....	63
G	CM 3 .....	64
H	CM 4 .....	65
I	CM 5 .....	66
J	CM 6 .....	67
	LIST OF REFERENCES .....	68
	BIOGRAPHICAL SKETCH.....	75

## LIST OF TABLES

<u>Table</u>		<u>page</u>
1-1	Summary of morphological and tracking data of six <i>Chelonia mydas</i> tracked in Laguna San Ignacio, BCS, Mexico .....	35
1-2	Summary of linear mixed-effects model estimates fitted to <i>Chelonia mydas</i> diel vagility, net displacement and short-term (24-h) activity ranges of six green turtles tracked in Laguna San Ignacio, BCS, Mexico .....	35
1-3	Summary of diel vagility and 24-h activity ranges of six <i>Chelonia mydas</i> tracked in Laguna San Ignacio, BCS, Mexico.....	36
1-4	Summary of mean diel vagility and 24-h activity ranges of six <i>Chelonia mydas</i> tracked in Laguna San Ignacio, BCS, Mexico.....	37
1-5	Summary of <i>Chelonia mydas</i> MCP home/activity ranges and vagility (km traveled per day) reported here and from other green turtle foraging areas.....	43
2-1	Costs associated with the two iterations of our tracking device. ....	56
2-2	Summary of tracking effort and device performance for 13 turtles tracked during the course of the study .....	57

## LIST OF FIGURES

<u>Figure</u>	<u>page</u>
1-1 Relationship between turtle size (SCL) and short-term activity ranges (ha) of six green turtles tracked in Laguna San Ignacio, BCS, Mexico.....	38
1-2 Relationship between turtle size (SCL) and mean net displacement (km) of six green turtles tracked in Laguna San Ignacio, BCS, Mexico.....	38
1-3 Relationship between turtle size (SCL) and mean total distance (km) of six green turtles tracked in Laguna San Ignacio, BCS, Mexico. ....	39
1-4 Proportion of mean total distance and mean net displacement (km) of six green turtles tracked in Laguna San Ignacio, BCS, Mexico. ....	39
1-5 Actual mean total distance and mean net displacement (km) of six green turtles tracked in Laguna San Ignacio, BCS, Mexico.....	40
1-6 Proportion of distance moved in three distinct eight h time periods for each of the six green turtles tracked in Laguna San Ignacio, BCS, Mexico. ....	40
1-7 Proportion of time spent in water depth classes for each of the six green turtles tracked in Laguna San Ignacio, BCS, Mexico.....	41
1-8 Proportion of time spent in water depth classes by diurnal (0500 to 1859) and nocturnal (1900 to 0459) periods of activity for six green turtles tracked in Laguna San Ignacio, BCS, Mexico.....	41
1-9 Proportion of time spent over areas of seagrass for each of the six green turtles tracked in Laguna San Ignacio, BCS, Mexico.....	42
1-10 Proportion of time spent over areas of seagrass by diurnal (0500 to 1859) and nocturnal (1900 to 0459) periods of activity for six green turtles tracked in Laguna San Ignacio, BCS, Mexico. ....	42
2-1 Annotated diagram of 2007 floating buoy (22 x 5 cm; 200 g total; 1% of average turtles body mass) that houses GPS device and VHF transmitter.....	54
2-2 Schematic drawing of 2008 floating buoy (26 x 9 cm; 250 g total; 1.5% of average turtles body mass) that houses GPS device and VHF transmitter.....	55
2-3 Force (N) imposed by telemetry unit at increasing current speeds measured in a flow tank. Average speed for all turtles tracked in June 2008 = 0.54 km/h. ....	56

Abstract of Thesis Presented to the Graduate School  
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Marine megavertebrates are particularly vulnerable to overexploitation due to their life history characteristics and the incidental removal of these animals could lead to cascading ecological changes. Like most vertebrates, sea turtles play key ecological roles in their environment. Green turtles are especially important because their grazing behavior significantly reduces nutrient cycling times in seagrass pastures.

Understanding the fine scale spatial requirements of green turtles at neritic foraging areas is important because green turtles spend the majority of their lives in these areas where they are often subject to incidental bycatch. Therefore, I examined the fine scale diel movements and activity ranges of East Pacific green turtles at a coastal foraging area with high levels of sea turtle gillnet bycatch. I hypothesized that larger turtles would travel greater distances and occupy larger short-term home ranges in order to satisfy potentially greater energy demands. I also predicted that turtles would be most active during the day and spend more time over areas of seagrass and in shallow water during this period of activity.

Six turtles, ranging from 44.6 to 83.5 cm in straight carapace length and from 10.9 to 75.6 kg in mass were tracked with GPS-VHF telemetry for 41 h to 184 h periods. Straight carapace length and lifestage did not influence diel vagility, net displacement or short-term activity ranges. Turtles occupied all depth classes (0 to 5 m, 5 to 10 m, 10+ m) and spent the majority of their time in the 0 to 5 m depth class (59%), followed by the 5 to 10 m depth class (34%) and the 10+ m depth class (7%), while spending 69% of their tracking duration over areas of seagrass. Significant nocturnal (0500 – 1859 h)-diurnal (1900 – 0459 h) differences were noted in diel vagility (greater by day). However, there were no significant differences between diurnal and nocturnal speeds and net displacement. When tracks were partitioned into three separate eight hour periods, turtles were most active during the nocturnal period, followed by the crepuscular and diurnal period, although no significant differences among the three time periods were found. Disparities in movement patterns within individual turtles highlight the need for continued fine scale tracking over a larger temporal scale. These results suggest that green turtles demonstrate complex and variable spatial use, traverse multiple habitats and move relatively large distances, all over short temporal durations. Therefore, conservation strategies should ideally encompass the entire lagoon rather than focus on a few high use areas within the foraging area.

CHAPTER 1  
FINE SCALE DIEL MOVEMENTS AND SHORT TERM ACTIVITY RANGES OF A  
MARINE MEGAHERBIVORE AT A TIDALLY DRIVEN LAGOON

**Introduction**

Many large marine vertebrates (i.e. marine mammals, sharks, seabirds and sea turtles) are especially vulnerable to overexploitation due to their life history characteristics, including late age at maturity, low (and uncertain) recruitment rates over a long lifespan, low adult mortality rates, low reproductive rates and large home ranges (Baum et al. 2003; Fujiwara and Caswell 2001; Lewison et al. 2004a,b). Protecting such megafauna is important because these animals often play a critical role in ecosystem function and food-web structure and their incidental take could lead to cascading ecological changes (Fujiwara and Caswell 2001; Lewison et al. 2004b). Like most large vertebrates, sea turtles play key ecological roles in their marine environment (Bjorndal 2003; Bjorndal and Bolten 2003; Bjorndal and Jackson 2003). Green turtles are especially important because their grazing behavior significantly reduces nutrient cycling times in seagrass pastures (Moran and Bjorndal 2005, 2007).

Despite technological advancements to reduce or even eliminate unwanted take in commercial and small-scale fisheries, incidental fisheries bycatch remains a major source of exploitation for many marine megafauna and has contributed to the decline of many populations. These include, but are not limited to North Atlantic harbor porpoises (*Phocoena phocoena*), vaquita porpoises (*Phocoena sinus*) in the Gulf of California, Mediterranean striped dolphins (*Stenella coeruleoalba*), wandering albatross (*Diomedea exulans*) and white chinned petrels (*Procellaria aequinoctialis*) of the Southern Ocean and Pacific loggerhead (*Caretta caretta*) and leatherback (*Deromchelys coriacea*) turtles (Lewison et al. 2004b).

Large vertebrate populations that are subject to incidental bycatch can decline, often without detection, in as little as a decade (Casey and Myers 1998), even if only a few individuals from sensitive age classes are removed (Fujiwara and Caswell 2001). Sea turtles resident at neritic foraging areas are especially vulnerable to incidental fisheries bycatch because most turtles inhabiting these areas are juveniles or sub-adults. These turtles represent a critical lifestage where the removal of only a small amount of individuals could substantially limit or impede population recovery (Crowder et al. 1994; Crouse 1999). In addition, most sea turtle species spend the vast majority of their lives in these areas (Musick and Limpus 1997), as immature turtles may spend up to 20 years or more (Seminoff et al. 2002; Nichols 2003; Seminoff 2004; Koch et al. 2007) in these developmental “hot spots”, while adults may use these areas in between nesting seasons (Seminoff et al. 2002).

The East Pacific green turtle (*Chelonia mydas*) is a marine megaherbivore that lives in tropical and subtropical regions throughout the world (Seminoff et al. 2003) and is considered endangered throughout most of its range (Seminoff 2004). In northwestern Mexico this distinct subpopulation of the green turtle is commonly referred to as the black turtle largely due to morphological and color variations (Nichols 2003). Green turtles from the Baja California Peninsula originate at Mexican rookeries located hundreds to thousands of kilometers south in the state of Michoacán and the Revillagigedo Archipelago, Tres Marias Islands, and perhaps even to a lesser extent from the Galápagos and Hawaiian islands (Márquez 1990, Nichols 2003, Koch et al. 2007). After hatching, it is assumed that green turtles immediately enter an oceanic stage for a relatively short time (~ 3–5 y for Atlantic green turtles; Reich et al. 2007)

before recruiting to neritic foraging areas and undergoing a rapid ontogenetic diet shift (Balazs et al. 1987, Carr 1987, Bjorndal 1997, Bolten 2003).

East Pacific green turtles have declined dramatically throughout the Mexican Pacific due, in large part, to incidental fisheries bycatch (Seminoff et al. 2003; Koch et al. 2006). Populations have struggled to recover despite almost 20 years of complete legal protection and over 30 years of widespread protection on central nesting beaches (Koch et al. 2007). The annual nesting population at Michoacán, Mexico was estimated at ~ 25,000 females in the early 1970s (Clifton et al. 1982) but populations have since dropped to less than 500 females (Alvarado-Diaz et al. 2001). Even though commercial fisheries are nonexistent today, green turtles are frequently incidentally captured in bottom set gillnets commonly used for stingrays and halibut (Garcia-Martinez and Nichols 2000; Nichols 2003; Koch et al. 2006; Mancini and Koch 2009). In Northwestern Mexico, sea turtle harvest and bycatch mortality is estimated to be as high as 35,000 turtles year<sup>-1</sup> (Nichols et al., 2002, 2003; Nichols, 2003), with at least 7,5000 green turtles killed year<sup>-1</sup>, representing the region with the highest known sea turtle mortality rates in the world (Hays et al. 2003; Nichols and Safina 2004; Peckham et al. 2008).

Understanding the fine scale spatial requirements of green turtles during this vulnerable and important life stage is critical to their conservation, as broad scale conservation strategies (i.e. the complete moratorium on the use of sea turtles and widespread nesting beach protection) have failed to provide adequate conservation gains throughout the Baja California peninsula (Nichols 2003; Koch et al. 2006). For example, understanding when and where turtles are most active may help reduce incidental bycatch in gillnets via temporal or spatial closures of fishing or increased

monitoring. Most green turtles captured in these nets drown before fishermen return to their nets, usually several hours or even days after being set (Nichols 2003; Koch et al. 2006; Mancini and Koch 2009; Senko pers. obs.).

Regional, national and international threat assessments require a basic understanding of animal behavior, distribution and habitat use, which can usually be obtained through biotelemetry studies (Cooke 2008). Despite technological advances in animal-attached devices that have contributed to our knowledge of migrating adult sea turtles, knowledge of turtles inhabiting coastal foraging areas continues to lag behind (Godley et al. 2003). Unlike adult sea turtles that are migrating, turtles at neritic foraging grounds are especially difficult to track via satellite telemetry since their diving behavior leads to very few, if any, high quality locations (i.e. Plotkin 1998). I was able to overcome these challenges by using a buoy that housed a GPS and VHF unit at the surface without having to follow turtles. In an effort to understand the fine scale spatial requirements of East Pacific green turtles at a coastal foraging area, I tracked turtles using GPS-VHF telemetry at Laguna San Ignacio (LSI), Baja California Sur (BCS), Mexico. Specifically, the objectives of my study were to determine: (1) total distance traveled, net displacement, short-term activity ranges and minimum travel speeds and if these values varied with turtle size or size and lifestage; (2) whether turtles were more active at crepuscular, nocturnal or diurnal time periods and during spring or normal tides; (3) if water depth influenced turtle distribution and if there were any differences during diurnal or nocturnal periods and (4) if the presence of seagrass influenced turtle distribution and if there were any differences during diurnal or nocturnal periods.

I hypothesized that turtles would travel greater distances during the diurnal period because of the temporal disparity in the diel cycle (14 hours of daylight), but that turtles would still be more active during this period based on previous studies that have suggested green turtles forage during the day and rest at night. I predicted that larger turtles would travel greater distances (total and net displacement) and occupy larger short-term home ranges in order to satisfy potentially greater energy demands. I also predicted that, based on previous studies, turtles would spend the majority of their time in shallow water, presumably foraging, and that turtles would spend more time in deeper water at night, presumably resting. Finally, I hypothesized that turtles would spend most of their time over areas of seagrass regardless of the time of day because almost half of the lagoon contains areas of seagrass, their principal food source.

## **Methods**

### **Study Area**

Located in Baja California Sur, Mexico, LSI is part of the El Vizcaino Biosphere Reserve. The lagoon exists as a critical foraging and developmental habitat for east Pacific green turtles (*Chelonia mydas*). Tidal currents are strong with tidal amplitudes commonly exceeding 2 m at spring tides. Average depth is < 10 m and large shallow and intertidal areas are common. The substrate consists primarily of sand and mud in the shallow areas and rocky outcrops in the deeper areas towards the mouth of the lagoon. Sea grass and red algae are abundant but patchily distributed throughout the lagoon and extensive mangrove swamps are present near the shoreline. (Nichols 2003). Although green turtles are the most abundant sea turtle species in the area, hawksbill turtles (*Eretmochelys imbricata*) are sometimes, albeit rarely, encountered.

The community of Laguna San Ignacio is comprised of ~ 200 individuals and the local economy is based primarily upon artisanal fisheries and gray whale ecotourism.

### **Turtle Capture and Morphometric Measurements**

Turtles were captured using nylon and cotton entanglement nets (100 m long, 50 cm stretched mesh) specifically designed to catch sea turtles. Captured turtles were able to surface and breathe as the nets have little weight on the lead line. The nets soaked for approximately 2-4 hours while being monitored at regular intervals (0.5 h) for entangled turtles. Nets were always set at slack tide and the majority of capture effort was conducted during the night because turtles were less likely to see the nets and turn around during the night. Capture sites included: (1) La Pocita, a shallow water region (~ 2 m) with extensive seagrass beds adjacent to Isla Pelicano, a large island system located in the north-central region of the lagoon; (2) Surghediro, a rocky area with moderate depth (~ 5 – 7 m); (3) Bajo Blanco, a shallow (~2 m) region with a sandy bottom that borders a deep channel with moderate eelgrass beds and (4) El Mapache, a protected cove with moderately shallow depth (~ 3 – 4m) located within the south-central region of the lagoon with extensive seagrass and algal pastures (see study area in Appendix A). I do not believe there was an inherent sampling bias with the nets we used because they have successfully captured the smallest immature turtles (SCL = 35 cm) at other monitoring sites along the Baja California peninsula (Lopez-Castro unpub. data).

Upon capture, turtles were taken to the nearest landing and no turtles were kept > 2 hours. I measured mass to the nearest kilogram using a spring balance scale. Metal forester's calipers were used to measure straight carapace length and width (SCL, SCW). Length was measured from the tip of the nuchal scute to the longest posterior

portion of the rear marginal scutes. I used a tape measure to find curved carapace length and width (CCL, CCW). Smaller calipers were used to measure head width, total tail length, and partial tail length (tip of tail to cloaca). We noted carapace and plastron coloration, distinguishing marks and number of central, lateral and marginal scutes. All measurements were recorded on standardized sea turtle data sheets modified from Nichols (2003). After measurements were completed, turtles were tagged using metal Inconel tags (National Band and Tag Company, Newport, Kentucky), applied proximal and adjacent to the first large scale on each rear flipper following Balazs (1999). I defined sexual maturity as 77.3 cm, the mean size of nesting female black turtles at the closest major nesting beach (Michoacán, Mexico) following Seminoff et al. (2003). All individuals encountered  $\geq 77.3$  cm were considered mature, and those turtles  $< 77.3$  cm that exhibited a disproportionately large or small tail in comparison to their SCL were considered mature where appropriate.

## **Tracking**

I tracked green turtles using VHF radio (148.103 – 148.146 MHz) and GPS telemetry in June 2008. The telemetry unit consisted of hand-carved, self-righting, floating buoys made out of balsa wood (26 x 9 cm; 250 g total package;  $\leq 1.5\%$  of average turtles body mass). Before placing the GPS device in the buoy, I vacuum-sealed the unit in Ziploc brand vacuum freezer bags to protect it from saltwater intrusion. The buoy had a fixed rudder that provided directional stability and an enlarged bow to prevent pitching down at speed (see Figures 2-1). The buoy was attached to the turtles with a monofilament floating line (10 m length, 30-pound test), a weak link and a carapace attachment point. The weak link was comprised of 3 eight-pound monofilament test lines of differing lengths (3, 4 and 5 cm) connected to a snap-swivel.

This was used to facilitate the turtle's escape should the buoy or tether became entangled. The attachment point was a small, magnesium-dissolving hook that was glued to the middle of the first central scute using 5 min quick set epoxy (see Figure 2-2). A length of 10 m was selected because water depth is typically  $\leq 10$  m throughout most of the lagoon and 10 m was a good compromise between possibly affecting the turtle's diving ability and the likelihood that greater length would increase the risk of snags. All turtles were released at the capture location once all measurements were completed and the tracking device was affixed. The attachment of all transmitter devices was performed in full compliance with the regulations of SEMARNAT, the Mexican Department of Marine Fisheries and Natural Resources, under the permit number: SGPA/DGV/S/06840/07.

To record fine scale spatial resolution and conserve battery capacity, the GPS data loggers were configured to receive and record locations ( $\pm 3$  m) every 15 seconds. I used these intervals because locations were not always successfully recorded (at intervals  $> \text{once}/30$  s) due to waves or lack of satellites. Since my objective was to record fine scale movement data, it was necessary to set a short acquisition interval at the expense of diminished battery life. Turtles were tracked with a Yagi antenna (Advanced Telemetry Systems; Isanti, MN) using a VHF (148.103 – 148.146 MHz) transmitter to locate the buoys (turtles were never followed) in order to recover and download the GPS data. I triangulated positions from shore every two hours to make sure turtles did not travel out of range during unsupervised periods and checked on turtles (from a distance  $> 30$  m)  $\geq$  once every 24 h to ensure their safety. Tracking was terminated when the tether became detached from the turtle under natural conditions.

## **Analysis**

Data were downloaded on site from the GPS data loggers upon termination of each tracking period. The data loggers contained latitude and longitude of each location, time and date. Hawth Tools extension in ArcGIS was used to convert point locations to lines (tracks) for all tracks. Distance moved and area occupied for each track was calculated using the X Tools extension in ArcGIS. Data were screened to remove location errors and these included GPS fixes with abrupt changes in direction that clearly deviated substantially from the animal's track.

To account for initial responses to capture and handling, data from the first six hours post-release were not used in the analysis. The sufficiency of this exclusion period was confirmed by video analysis of each track that indicated some turtles resumed normal behavior in 1-2 h based on swimming speed and behavior, while others showed little to no apparent response. To determine when the tag became detached from the turtle, I recorded the last time I observed the tether attached to the turtle from daily supervision of the tracked turtle. I then created videos of each track in ArcGIS and conservatively estimated the first possible point in which the tether became detached. All subsequent points were removed from further analysis.

## **Habitat Survey and Analysis of Data**

Water depth in the lagoon was measured using a portable depth sounder (Humminbird 500 Series, Eufaula, AL) mounted on the transom of a 6 m fiberglass boat. The location of the boat was determined using a handheld GPS (Garmin GPS7, Olathe, KS). Depth measurements were corrected for tidal height using the nearest known station (Puerto San Carlos, BCS, Mexico) via the online tidal height prediction program published by the University of South Carolina (<http://tbone.biol.sc.edu/tide>) and merged

in a GIS. Upon correcting for tidal height, I geo-referenced a high-resolution satellite image of the lagoon and overlaid it with the depth data (points) and created distinct depth polygons. Depth data confirmed the presence of channels that were visible on the high-resolution image and data were partitioned into three classes based on the relative shallowness of the lagoon. These included: shallow (0 – 5 m), moderate (5 – 10 m) and deep (10+ m) depth classes. Depth classes were chosen because they afforded less importance to individual depth points and allowed for some degree of error that tidal heights may have exerted on depth.

Seagrass coverage was determined using an underwater video camera (AquaVue Scout II, Brainerd, MN) suspended from the boat and connected to a handheld VCR (Canon series). One-minute recordings were made as the boat drifted in the wind and current at numerous locations throughout the lagoon, spaced out on a regular 1.6 km grid, with sampling stations approximately every 0.5 km. I partitioned seagrass coverage into 6 coverage categories, where 0=none, 1=occasional blade, 2=<20%, 3=20-50%, 4=50-75% and 5=>75%. Snorkel surveys were also conducted in areas where turtles were sited or captured in order to determine bottom substrate. Seagrass coverage was overlaid on a map of the lagoon using ArcGIS and all zero and one values were pooled and partitioned as 'no seagrass', while values three through five were pooled and partitioned as 'seagrass'. I subsequently made seagrass polygons by using the inverse distance weighted interpolation in ArcGIS. I believe this method was appropriate because of my relatively small number of reliable data points; thus the resulting polygons were more influenced by nearby points and less influenced by distant points.

## **Do Diel Movements, Net Displacement or Short-Term Activity Ranges Vary With Turtle Size and Diurnal or Nocturnal Periods of Activity?**

I hypothesized that turtles would travel greater distances during the diurnal period because of the temporal disparity in the diel cycle (14 hours of daylight), but that turtles would still be more active during this period based on previous studies that have suggested green turtles forage by day and rest at night (Bjorndal 1980; Mendonca 1983; Seminoff et al. 2001; Makowski et al. 2006; Taquet et al. 2006; Hazel et al. 2009; Hazel 2009). I predicted that larger turtles would travel greater distances (total distance, net displacement and short-term activity ranges) in order to satisfy potentially greater energy demands. I determined diel vagility by calculating the total distanced traveled of each turtle for one diel cycle (24 h). Track partitions followed Seminoff et al. (2002a) and Seminoff and Jones (2006) and were partitioned into diurnal (0500 – 1859 h) and nocturnal (1900 – 0459 h) periods to determine variability in movement patterns throughout the diel cycle. *Total distance* was determined by connecting successive GPS fixes with straight lines. These calculations assumed that turtles followed a straight line between successive GPS fixes. Although the GPS loggers recorded a large number of fixes, these calculations should be considered minimum estimates (Tremblay et al. 2006). *Net displacement* was calculated by measuring the distance from the start and finish of each track. *Minimum travel speeds* were determined by dividing the *total distance* moved over time (day = 14 h, night = 10). Short-term (24 h) activity ranges were calculated using the 100% Minimum Convex Polygon method (Burt 1943) via the Hawth Tool's extension in ArcMap 9.3 GIS software. Mean values (diel vagility and activity ranges) for each turtle were calculated (table 1-4).

### **Are Turtles More Active at Crepuscular, Nocturnal or Diurnal Periods of Activity and at Spring or Normal Tides?**

I hypothesized that turtles would be more active during the diurnal period based on previous studies that have suggested green turtles forage by day and rest at night (Bjorndal 1980; Mendonca 1983; Seminoff et al. 2001; Makowski et al. 2006; Taquet et al. 2006; Hazel et al. 2009; Hazel 2009). To determine whether turtles were more active at crepuscular, nocturnal or diurnal time periods, tracks were partitioned into three separate eight h periods (day = 10:00 – 18:00; Night = 22:00 – 6:00; Crepuscular = 6:00 – 10:00 and 18:00 – 22:00 or 1.5 h before and after sunrise and sunset). I also predicted that turtles would travel greater distances during spring tides. To determine this, tides were designated as spring or neap if they fell within 1 day of spring or neap tides. All other tides were designated as normal.

### **Does Water Depth and Seagrass Affect Turtle Distribution and Does This Effect Vary With Diurnal or Nocturnal Periods of Activity?**

I hypothesized that turtles would spend the majority of their time in shallow water, because the majority of the lagoon consists of shallow water. I also hypothesized that turtles would spend more time in deeper water during the night because previous studies have suggested that green turtles rest in deeper water during this period of activity. To determine if water depth affected turtle distribution, I calculated the proportion of time that turtles spent in each depth class and compared these values for diurnal and nocturnal periods of activity. I corrected for the temporal disparity in the diel cycle by dividing the time traversed over depth class by 14 h for diurnal and 10 h for nocturnal periods of activity.

I hypothesized that turtles would spend the majority of their time over areas of seagrass because this is their principal food source. I also hypothesized that turtles

would spend more time over seagrass during the day because previous studies have shown that turtles forage more during the day and rest at night. To determine if the presence of seagrass affected turtle distribution, I calculated the proportion of time that turtles spent over seagrass and compared these values for diurnal and nocturnal periods of activity. I corrected for the temporal disparity in the diel cycle by dividing the time traversed over seagrass and depth class by 14 h for diurnal and 10 h for nocturnal periods of activity.

### **Statistical Analysis**

Data were tested for normality using the Shapiro-normality test and log transformed where necessary. I averaged values for each individual turtle with more than one diel cycle to avoid pseudo replication. A paired t-test was used to compare diurnal and nocturnal diel vagility and speed, diel vagility at spring and normal tides and the SCL of turtles captured and tracked during the study period. The relationship between diel vagility, net displacement and activity range predictors (log SCL and life-stage) were analyzed using a linear mixed-effects model because tracking durations (number of diel cycles) were unequal amongst turtles. In this model, turtle ID was considered a random effect to acknowledge correlated measures within individual turtles. Sex was unknown for all but two turtles (both probable female) and I therefore grouped lifestage into juvenile or adult. Additionally, I used linear regression analysis to examine the relationship between turtle size (log SCL) and mean diel vagility, net displacement and activity range. A one-way analysis of variance was used to test for differences in activity between crepuscular, diurnal and nocturnal time periods. All

analyses were performed in R 2.9.2 and values are given as means  $\pm$  standard deviations.

## Results

### Study Animals and Tracking Effort

Study animals measured from 44.6 cm to 83.5 cm SCL and 10.9 to 75.6 kg in mass (Table 1). One turtle was classified as female based on SCL ( $> 77.3$  cm) and another turtle was classified as female based on its TTL in relation to its SCL (Table 1-1). Substrate at capture sites included sand, sand and seagrass, dense seagrass and coral/pebble. There was no significant difference between the SCL (log) of turtles captured and the SCL (log) of those turtles tracked throughout the study period ( $T = -0.8498$ ;  $DF = 6.968$ ;  $P = 0.4237$ ).

Tracking was initiated during the diurnal period (0500 – 1859 h) for CM 1 – 5 and during the nocturnal (1900 – 0459 h) period for CM 6 and tracking time ranged from 41.5 to 184.0 h. In aggregate, turtles used the entire lagoon and no individuals ventured outside the lagoon. Among the six turtles tracked, five provided data for a period  $\geq$  one complete diel cycle (24 h). Four of the six turtles remained within 2 km of their capture-release location, although the other two turtles traveled  $> 10$  km away from their capture-release location. The movement patterns of turtles varied from day-to-day, night-to-night, day-to-night and within diel cycles.

### **Do Diel Movements, Net Displacement or Short-Term Activity Ranges Vary With Turtle Size and Diurnal or Nocturnal Periods of Activity?**

Diel vagility (total distance traveled per 24 h) ranged from 2.0 km to 29.6 km (mean =  $12.92 \pm 4.67$  km) with minimum travel speeds of 0.1–1.2 km h<sup>-1</sup>. Net displacement (24-h) ranged from 0.18 km to 19.10 km (mean =  $4.67 \pm 4.17$  km), while

short-term (24-h) activity ranges were from 1 ha to 1575 ha (mean =  $404 \pm 386$  ha).

Turtles moved significantly farther during the diurnal period versus the nocturnal period for total distance ( $T = -2.3822$ ;  $DF = 9.518$ ;  $P = 0.03965$ ) but exhibited no significant differences in nocturnal-diurnal net displacement ( $T = -0.2359$ ,  $DF = 5$ ,  $P = 0.8229$ ). In addition, no significant differences were noted with minimum travel speeds during the diurnal and nocturnal periods ( $T = -0.816$ ;  $DF = 9.896$ ;  $P = 0.4337$ ).

The linear mixed-effects model indicated that diel vagility, net displacement and short-term activity ranges were independent of turtle size (log SCL) and lifestage (Table 1-2). Linear regression analysis indicated that diel vagility (F-statistic = 0.1439 on 1 and 4 DF;  $P = 0.7237$ ;  $r^2 = 0.034$ ) net displacement (F-statistic = 1.383 on 1 and 4 DF;  $P = 0.3047$ ;  $r^2 = 0.257$ ) and short-term activity ranges (F-statistic = 2.049 on 1 and 4 DF;  $P = 0.2256$ ;  $r^2 = 0.3387$ ) were all independent of turtle size (log SCL) when analyzed individually.

#### **Are Turtles More Active at Crepuscular, Nocturnal or Diurnal Periods of Activity and at Spring or Normal Tides?**

The greatest proportion of total turtle movement occurred during the nocturnal period (37.8%), followed by the crepuscular period (31.6%) and the diurnal period (30.6%). However, there were no significant differences in total distance moved during the three time periods ( $DF = 2$ ;  $F = 0.58$ ;  $P = 0.5695$ ). There was also no significant difference between distance moved during spring or normal tides ( $T = 0.6421$ ;  $DF = 1$ ;  $P = 0.6366$ ).

#### **Does Water Depth and Seagrass Affect Turtle Distribution and Does This Effect Vary With Diurnal or Nocturnal Periods of Activity?**

Turtles occupied all depth classes and spent the majority (59%) of their tracking duration in the 5 to 10 m depth class, followed by the 5 – 10 m depth class (34%) and

the 10+ m depth class (7%). Turtles spent more time in the 0 – 5 m depth class during the diurnal period and spent more time in the 5 – 10 m depth class during the nocturnal period. Turtles spent 69% of their tracking duration over areas of seagrass and slightly more time (71%) over these areas in the diurnal period compared to the nocturnal period (66%).

## **Discussion**

I examined the fine scale diel movements and activity ranges of an endangered marine megaherbivore, the East Pacific green turtle, within a highly dynamic marine environment. Although my sample size is relatively small, marine megavertebrate tracking studies are costly as well as labor and time consuming and I believe this study represents a reasonable compromise between sample size and available resources. Additionally, I believe the effects of my tracking device on my study animals were minimal (see Chapter 2). Turtle size did not influence diel vagility, net displacement or short-term activity ranges and turtles traveled significantly greater distances during the diurnal period. However, there were no significant differences between diurnal and nocturnal speeds and net displacement and turtles were most active during the nocturnal period, followed by the crepuscular and diurnal period. Disparities in movement patterns within individual turtles highlight the need for continued fine scale tracking over a larger temporal scale. These results suggest that green turtles demonstrate complex and variable spatial use, traverse multiple habitats and move relatively large distances, all over short temporal durations. Therefore, conservation strategies should ideally encompass the entire lagoon rather than focus on a few high use areas within the foraging area.

## **Diel Movements, Net Displacement and Short-Term Activity Ranges**

Diel vagility in sea turtles is the distance traveled over one 24 h period and diel activity range is the area traversed over one 24-hour cycle (Mendonca 1983; White and Garrott 1990; Seminoff and Jones 2006). The mean diel vagility and speed recorded in this study were within the range of those recorded for green turtles in Baja California and other areas (Table 3). Similar variations in green turtle diel movements were observed in Florida (Mendonca 1983), Hawaii (Brill et al. 1995), BCS, Mexico (Seminoff and Jones 2006) and Australia (Hazel 2009). However, it is unclear why these studies did not calculate net displacement of tracks.

Turtles moved significantly more during the diurnal period versus the nocturnal period but there were no significant differences in speed between diurnal and nocturnal periods. It is unclear why several other studies have failed to address temporal disparities in the diel cycle. The diurnal period was 40% longer in our study and the significant difference in diel vagility was therefore a function of the temporal disparity, as there were 14 hours of daylight when turtles were tracked. These results highlight the importance of considering multiple scales when analyzing high-resolution data such as diel movements. Turtles in this study had short-term activity ranges that varied considerably, but overall were relatively large (mean =  $404 \pm 386$  ha) when compared to other studies ( $238 \pm 178$  ha, Makowski et al. 2006;  $458 \pm 202$  ha, Seminoff and Jones 2006;  $662 \pm 294$  ha, Hazel 2009).

Tidal currents likely played at least a partial role in mediating the movement patterns described here, although I was unable to test this hypothesis due my inability to quantitatively measure tidal flows. Tidally oriented movements have been observed in oceanic leatherback turtles (Luschi et al. 2003), loggerhead turtles in MD, USA (Byles

1988), green turtles in Australia (Limpus et al. 1994; Hazel 2009), Kemp's ridley turtles in FL, USA (Schmid et al. 2002) and green turtles in BCS, Mexico (Brooks et al. 2009). During the course of our study, turtles were frequently seen swimming with the tidal currents and never observed swimming against tidal currents. The passive uses of tides may allow green turtles to conserve energy and exploit the patchy distribution of eelgrass characteristic of the lagoon. High swim speeds are energetically costly (Feldkamp 1987). Therefore, strong selective pressure exists for animals to optimize locomotion over large- and small-scale movement (Wilson et al. 2002) and this is particularly true for air breathers (Shepard et al. 2008).

The disparities in diel vagility, net displacement and activity ranges within diel cycles of individual turtles are likely a result of the short tracking duration. Irregular and complex movements might be teased out over a larger temporal scale if the factors that mediate these behavioral decisions are operating over a period of weeks or months, as opposed to days (Hazel 2009). Therefore, I recommend future studies with a larger temporal scale. In addition, seasonal differences in movement patterns also probably vary with changing water temperatures. For example, Schofield et al. (2009) found that female loggerhead turtles positioned themselves in warm water patches at the start of the breeding season when water temperatures were coolest and green turtles at other foraging area in BCS, Mexico have been known to overwinter during cold periods (Felger et al. 1976).

### **Turtle Activity and Movement Patterns**

Like other similar studies of green turtle movements in BCS, Mexico (Seminoff et al. 2002a, Seminoff and Jones 2006; Brooks et al. 2009), I found no evidence that turtle size or turtle size and lifestage significantly affected diel vagility, net displacement or

short-term activity ranges. Turtles were most active during the nocturnal period, followed by the crepuscular and diurnal period, although there were no significant differences between the three time periods. Whereas turtles traveled significantly greater total distances during the diurnal period, turtles were most active at night when tracks were partitioned into three separate eight h time periods. So far as I know, this is the first study to examine differences between crepuscular, diurnal and nocturnal periods of activity.

Turtles spent 69% of their tracking duration over areas of seagrass. Although turtles spent slightly more time (71%) over these areas in the diurnal period versus the nocturnal period (66%), no significant day-night differences were found. These data suggest that green turtles at our study site use seagrass beds during both day and night periods. However, it remains unclear whether or not turtles are foraging with similar frequencies during day and night periods. In Florida, Mendonca (1983) demonstrated that green turtles fed on seagrass beds in mid-morning and mid-afternoon and moved to deeper water and rested during the evening.

Turtles occupied all depth classes (0 to 5 m, 5 to 10 m, 10+ m) and spent the majority of their time in the 0 to 5 m depth class (59%), followed by the 5 to 10 m depth class (34%) and the 10+ m depth class (7%), although no day-night differences were found. Despite this, I believe the spatial scale at which turtles are selecting these areas may not be fine enough to tease out high resolution differences such as day or night use. In other words, turtles are likely selecting this lagoon based on its shallowness and the corresponding widespread availability of seagrass. This seems reasonable given

that our study site has the second highest green turtle CPUE for all foraging areas along the Baja California peninsula (Lopez-Castro and Koch unpub. data).

It is unclear whether turtles visited deeper areas specifically for feeding or whether green turtles opportunistically feed at these deeper water sites during movements. Feeding on non-algal foods may be nutritionally advantageous to offset the costs associated with moving to and diving in these areas (Seminoff et al. 2002). Green turtles at several other foraging areas have demonstrated a mixed diet (Bjorndal 1997), including East Pacific green turtles in BCS, Mexico (Seminoff et al. 2002b) and Hawaii (Arthur and Balazs 2008). Without the use of time-depth recorders (TDRs), however, it is impossible to know exactly where the turtles were in the water column. The use of TDRs in future studies would provide better data on vertical distribution and depth selection of turtles. Use of shallow water (Brill et al. 1995; Seminoff et al. 2002a; Southwood et al. 2003) during the night has been documented before, although other studies (Bjorndal 1980; Makowski et al. 2006; Taquet et al. 2006; Hazel et al. 2009) have demonstrated that green turtles were more active in shallow water by day and rested in deeper water at night, with individual variation (Seminoff et al. 2001) also being reported. In addition to foraging behaviors, responses to predation pressures (Heithaus et al. 2007) may play important roles in mediating these movement patterns (Heithaus et al. 2008). For example, Heithaus et al. (2007) found that green turtles in good body condition foraged in less optimal areas with lower risks of predation from tiger sharks, whereas animals in poor condition foraged in the best areas which corresponded with higher predation risks, thus demonstrating that these animals appear to trade off high predation risks with foraging success. Seminoff et al. (2002a) also

suggested that green turtles may select shallow water in areas with high fishing pressures as a mechanism to avoid fishing nets. However, this seems unlikely at our study site given fishermen routinely fish in shallow water (Senko pers. obs.) and hundreds of green turtles continue to drown in gillnets set in shallow water (Mancini and Koch 2009).

### **Ecological and Conservation Implications**

Green turtle spatial requirements encompassed the entire lagoon as turtles traveled relatively large distances and traversed multiple habitats over short temporal durations. Overlapping locations of four turtles indicated aggregated foraging areas in the northern and central regions of the lagoon. Four of the six turtles remained within 2 km of their capture-release location. The affinity to specific regions within the lagoon suggests at least some degree of site fidelity. However, spatial use in green turtles resident at coastal foraging areas is highly variable. Immature green turtles tracked on their foraging areas in Brazil may utilize areas that span up to 90 km of coastline (Godley et al. 2003). While our data lacks the appropriate temporal scale to infer long-term home ranges, the turtles tracked in our study remained in the lagoon and may exhibit small home ranges due to the abundance of food and protection from natural predators. Senko et al. (in press) reported that only two out of 154 green turtles recaptured at least once over 7 years in foraging areas along the Baja California peninsula were captured in a different foraging area. However, not all green turtles appear to stay in foraging areas as permanent residents. Many individuals may commence extensive developmental migrations (Bjorndal and Bolten 1997, Musick and Limpus 1997). For example, immature green turtles tagged on foraging grounds in the southern Bahamas remain in these coastal habitats for varying lengths of time before

emigrating to other foraging areas throughout the Greater Caribbean (Bjorndal et al. 2003) and juvenile Brazilian green turtles tracked on their foraging areas via satellite telemetry (Godley et al. 2003) exhibited three main patterns of behavior: extended residency with high site fidelity, moderate range movements (<100 km) and pronounced long range movements (>100 km) (Senko et al. in press).

Before sea turtle populations were depleted, they exerted considerable effects on their marine environments as consumers, prey and competitors, as well as hosts for parasites and pathogens, substrates for epibionts, seascape and marine substrate engineers and nutrient transporters (Bjorndal 2003; Bjorndal and Bolten 2003; Bjorndal and Jackson 2003). The precipitous decline of green turtles in LSI and other foraging areas along the Baja California peninsula is likely to have profound ecological impacts. These impacts extend past foraging areas to nesting beaches, as turtles transport nutrients from highly productive marine foraging grounds to nutrient-poor beach ecosystems (Bouchard and Bjorndal 2000). Additionally, grazing by green turtles has been shown to significantly reduce nutrient cycling times in seagrass pastures, drastically altering the physical structure of seagrass ecosystems (Moran and Bjorndal 2005), which serve as critical nursery areas for several ecologically and commercially important fish and invertebrate species. In LSI, seagrass beds are considerably higher (sometimes > 1 m) now than 20-30 years ago when green turtles were far more abundant in the lagoon (Mayoral, pers. comm.).

Despite decades of incidental fisheries bycatch, this study indicates that green turtles continue to use this neritic foraging area. These results have critical conservation implications as green turtles feed and occur in areas that coincide with human activities

such as non-commercial fisheries. For example, foraging areas used by the turtles tracked in this study overlapped extensively with gillnet fishing targeted at Pacific guitarfish. Most green turtles captured in these nets drown before fishermen return to their nets, usually several hours or even days after being set (Nichols 2003; Koch et al. 2006; Mancini and Koch 2009; Senko pers. obs.). However, even assuming turtles are released alive, the non-lethal impacts of capture and subsequent release are unknown and deserve further attention. Finally, green turtle spatial requirements encompassed the entire lagoon and turtles traveled relatively large distances over short temporal durations. Conservation efforts may therefore need to include the entire coastal foraging area rather than target a few “hot spots” within the lagoon.

Table 1-1. Summary of morphological and tracking data of six *Chelonia mydas* tracked in Laguna San Ignacio, BCS, Mexico. SCL = straight carapace length; CCL = curved carapace length; TTL = total tail length; U = undetermined; F = female based on SCL and TTL; \*Probable female

Turtle ID	SCL (cm)	CCL (cm)	Mass (kg)	TTL (cm)	Sex	Tracking Interval		Total Hours
						Begin	End	
CM 1	59.2	62.0	26.9	10	U	6/20/08	6/24/08	98.5
CM 2	69.9	74.5	43.5	13.4	F *	6/20/08	6/21/08	41.5
CM 3	62.4	67.5	31.2	7.3	U	6/19/08	6/22/08	75.5
CM 4	83.5	88.5	75.6	16.5	F *	6/25/08	6/27/08	56.1
CM 5	44.6	46.0	10.9	9.1	U	6/18/08	6/21/08	86.0
CM 6	56.2	59.0	24.1	10.3	U	6/11/08	6/19/08	184.0

Table 1-2. Summary of linear mixed-effects model estimates fitted to *Chelonia mydas* diel vagility, net displacement and short-term (24-h) activity ranges of six green turtles tracked in Laguna San Ignacio, BCS, Mexico. The t-test significance is based on P = 0.05.

Parameter	Value	SE	t-value	p-value
<u>Diel Vagility</u>				
(Constant)	18.572745	94.92414	0.19565882	0.8482
Lifestage	-1.556232	9.36995	-0.16608754	0.8787
SCL (log)	-1.06068	21.79702	-0.04866172	0.9642
<u>Net Displacement</u>				
(Constant)	29.605431	60.3068	0.4909136	0.6323
Lifestage	1.662549	5.92349	0.2806705	0.7972
SCL (log)	-6.341271	13.85271	-0.4577641	0.6782
<u>Activity Range</u>				
(Constant)	5746.36	6260.746	0.9178395	0.3768
Lifestage	-92.221	609.14	-0.1513955	0.8893
SCL (log)	-1281.425	1439.064	-0.890457	0.4388

Table 1-3. Summary of diel vagility and 24-h activity ranges of six *Chelonia mydas* tracked in Laguna San Ignacio, BCS, Mexico.

Turtle ID	Diel Cycle	Distance Moved (km)						Minimum Travel Speed (km/h)			MCP (ha)
		Day	Net Day	Night	Net Night	Total	Net Total	Day	Night	Overall†	
CM 1	1*	15.55	7.1	14.07	12	29.62	19.10	1.11	1.41	1.23	1575.00
	2	12.44	5.26	4.29	1.3	16.73	6.56	0.89	0.43	0.70	682.00
	3	6.81	3.89	8.24	6	15.05	9.89	0.49	0.82	0.63	452.00
CM 2	1*	7.97	1.51	4.82	1.46	12.79	2.97	0.57	0.48	0.53	125.00
CM 3	1*	4.96	0.15	3.50	2.48	8.46	2.63	0.35	0.35	0.35	51.00
	2*	4.87	0.07	4.46	2.8	9.33	2.87	0.35	0.45	0.39	193.00
	1**	4.43	1	3.02	0.81	7.45	1.81	0.32	0.30	0.31	45.00
CM 4	2	16.65	0.73	5.55	0.1	22.20	0.83	1.19	0.56	0.93	398.00
CM 5	1*	7.09	7	3.90	1.5	10.99	8.50	0.51	0.39	0.46	715.00
	2*	10.40	6.12	4.28	3.1	14.68	9.22	0.74	0.43	0.61	1174.00
	3*	8.94	3.72	2.40	1.2	11.34	4.92	0.64	0.24	0.47	811.00
	1*	8.20	1.25	5.90	0.17	14.10	1.42	0.59	0.59	0.59	140.41
	2*	2.59	0.3	0.69	0.16	3.28	0.46	0.19	0.07	0.14	23.29
	3*	0.82	0.16	1.21	0.02	2.03	0.18	0.06	0.12	0.08	0.98
	4	7.60	2.45	2.46	0.66	10.07	3.11	0.54	0.25	0.42	368.79
CM 6	5	7.80	0.29	1.85	0.08	9.65	0.37	0.56	0.19	0.40	179.63
	6	5.33	1.76	3.90	1.6	9.23	3.36	0.38	0.39	0.38	206.87
	7	6.66	1.39	2.25	0.85	8.91	2.24	0.48	0.22	0.37	156.00
	Mean	7.73	2.45	4.27	2.02	11.99	4.47	0.55	0.43	0.50	405.39
SD	4.06	2.45	3.05	2.89	6.43	4.75	0.29	0.30	0.27	434.59	

Each diel cycle represents one 24-h period and tracks are partitioned into day (0500–1859 h) and night (1900–0459 h) periods of activity. Diel (24-h) activity polygons were calculated with the Minimum Convex Polygon (MCP) method (Burt 1943). Mean values are reported as per turtle and per day to prevent skewing data to turtles with longer tracking durations. Tides were designated as spring or neap if they fell within 1 d of spring or neap tides. \*Spring tide; \*\*Neap tide; †Adjusted for actual proportion of the 14-h day and 10-h night; where Overall Speed = Day (14/24) + Night (10/24)

Table 1-4. Summary of mean diel vagility and 24-h activity ranges of six *Chelonia mydas* tracked in Laguna San Ignacio, BCS, Mexico.

Turtle ID	Diel Vagility (km)						Minimum Travel Speed (km/h)			Mean MCP (ha)
	Mean Day	Mean Net Day	Mean Night	Mean Net Night	Mean Total	Mean Net Total	Mean Day	Mean Night	Mean Total	
CM 1	11.60	5.42	8.87	6.43	20.47	11.85	0.83	0.89	0.85	903.00
CM 2	7.97	1.51	4.82	1.46	12.79	2.97	0.57	0.48	0.53	125.00
CM 3	4.92	0.11	3.98	2.64	8.90	2.75	0.35	0.40	0.37	122.00
CM 4	10.54	0.87	4.29	0.46	14.83	1.32	0.75	0.43	0.62	221.50
CM 5	8.81	5.61	3.53	1.93	12.34	7.55	0.63	0.35	0.51	900.00
CM 6	5.57	1.09	2.61	0.51	8.18	1.59	0.40	0.26	0.34	153.71
Mean	8.23	2.43	4.68	2.24	12.92	4.67	0.59	0.47	0.54	404.20
SD	2.65	2.43	2.18	2.22	4.46	4.17	0.19	0.22	0.19	386.87

Each diel cycle represents one 24-h period and tracks are partitioned into day (0500–1859 h) and night (1900–0459 h) periods of activity. Diel (24-h) activity polygons were calculated with the Minimum Convex Polygon (MCP) method (Burt 1943). Mean values are reported to prevent skewing data to turtles with longer tracking durations.

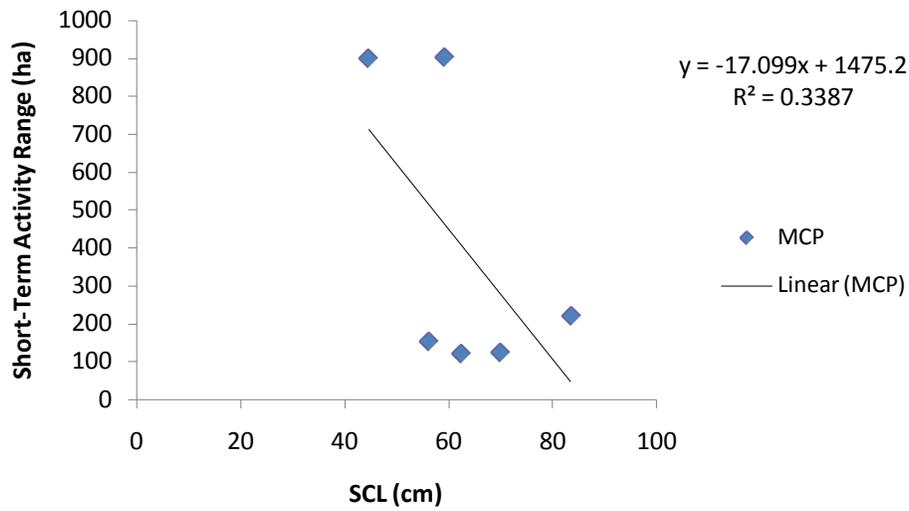


Figure 1-1. Relationship between turtle size (SCL) and short-term activity ranges (ha) of six green turtles tracked in Laguna San Ignacio, BCS, Mexico.

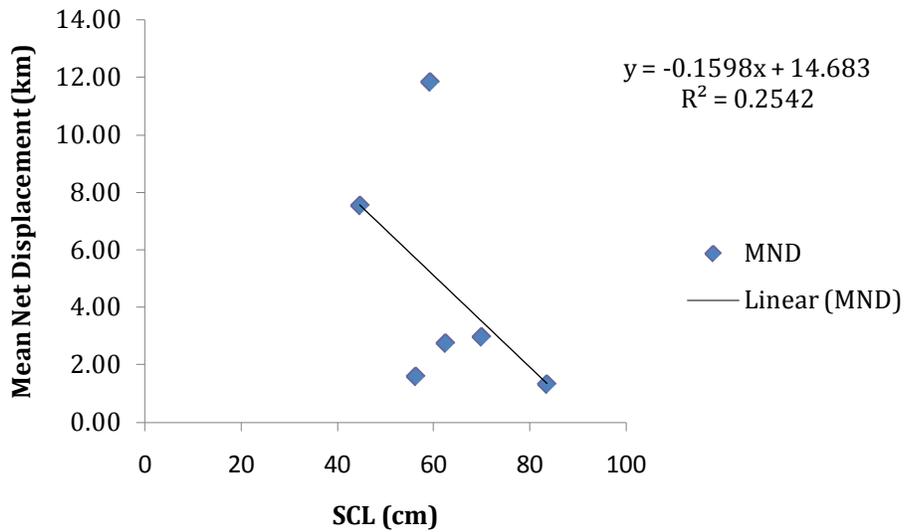


Figure 1-2. Relationship between turtle size (SCL) and mean net displacement (km) of six green turtles tracked in Laguna San Ignacio, BCS, Mexico.

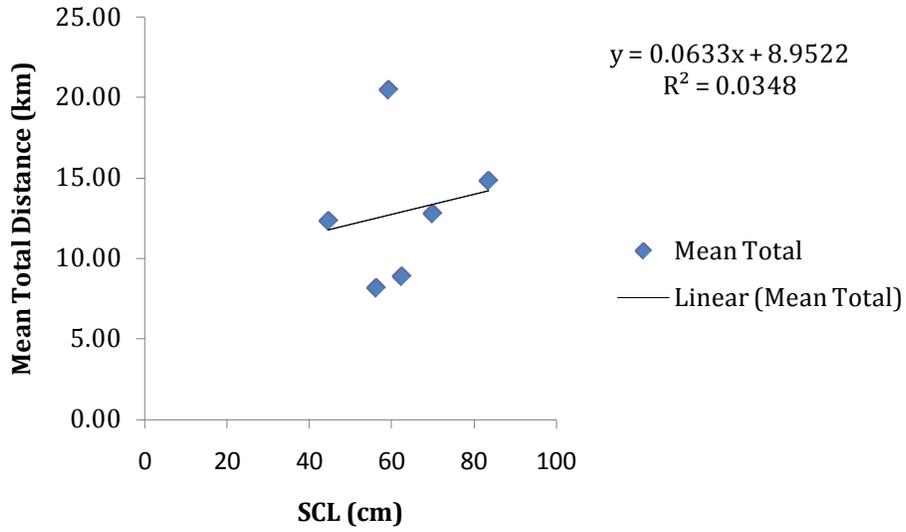


Figure 1-3. Relationship between turtle size (SCL) and mean total distance (km) of six green turtles tracked in Laguna San Ignacio, BCS, Mexico.

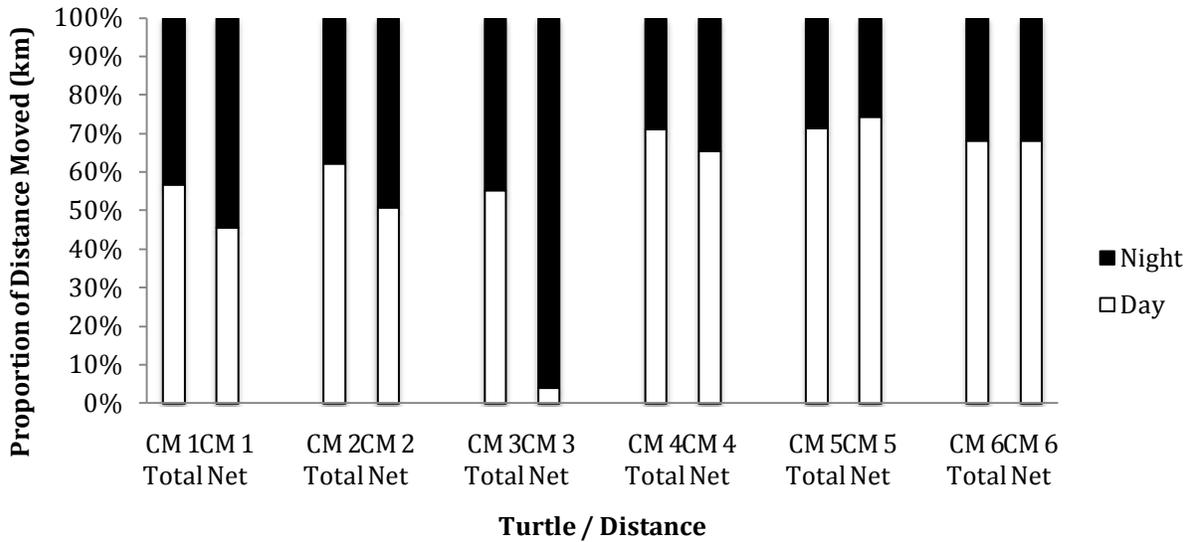


Figure 1-4. Proportion of mean total distance and mean net displacement (km) of six green turtles tracked in Laguna San Ignacio, BCS, Mexico.

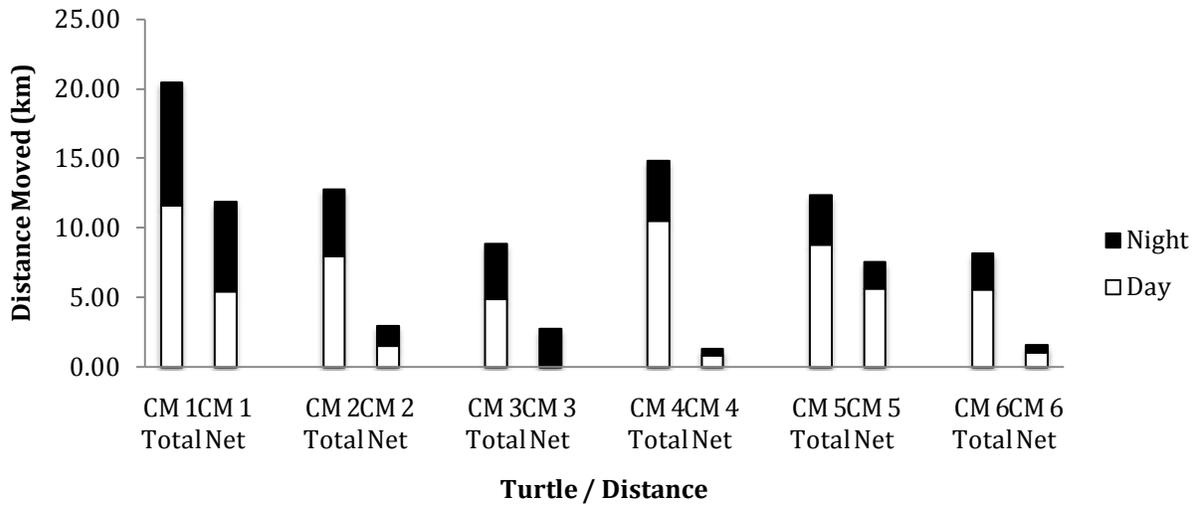


Figure 1-5. Actual mean total distance and mean net displacement (km) of six green turtles tracked in Laguna San Ignacio, BCS, Mexico.

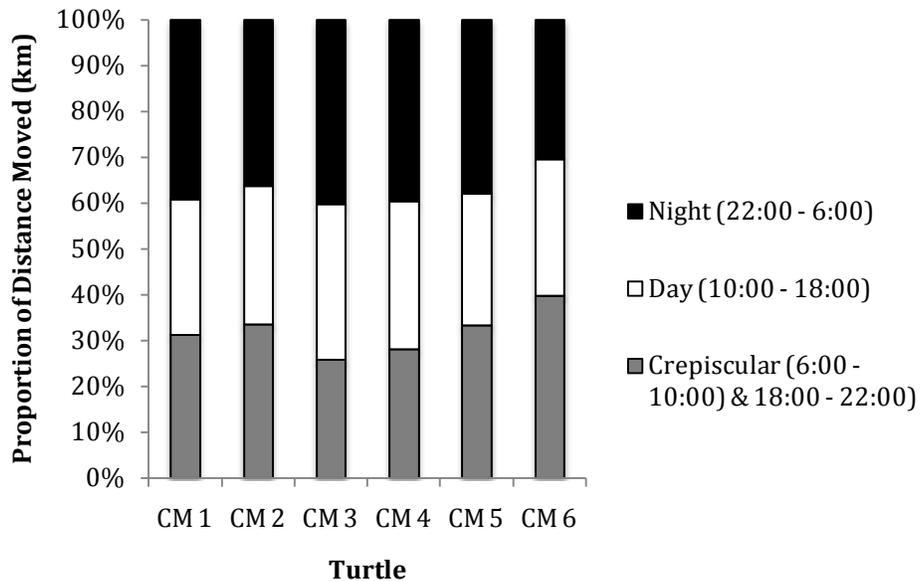


Figure 1-6. Proportion of distance moved in three distinct eight h time periods for each of the six green turtles tracked in Laguna San Ignacio, BCS, Mexico.

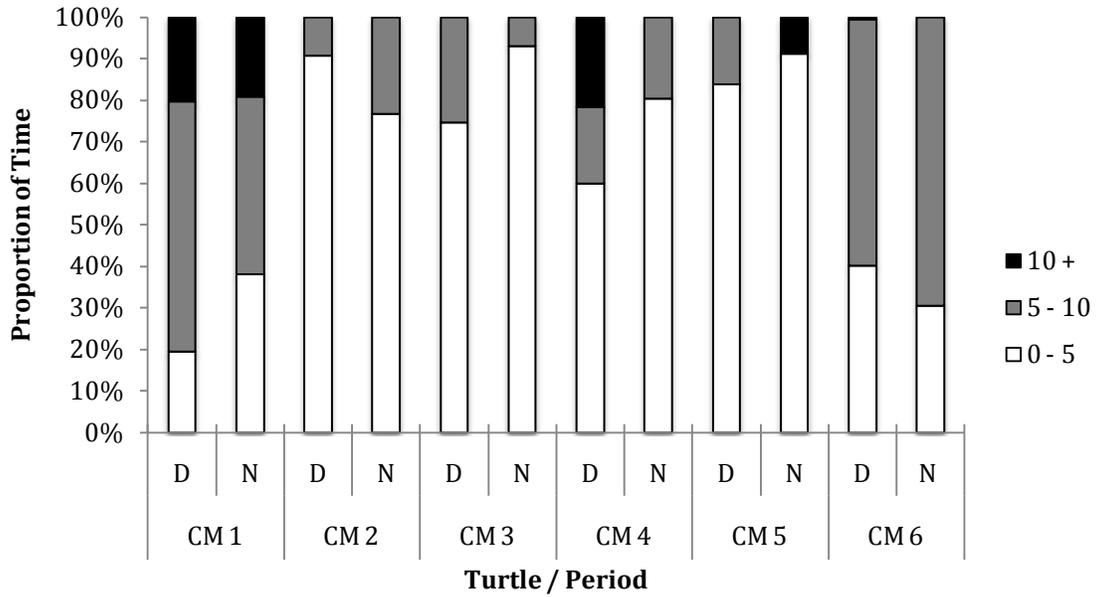


Figure 1-7. Proportion of time spent in water depth classes for each of the six green turtles tracked in Laguna San Ignacio, BCS, Mexico. Data are partitioned by diurnal (0500 to 1859) and nocturnal (1900 to 0459) periods of activity.

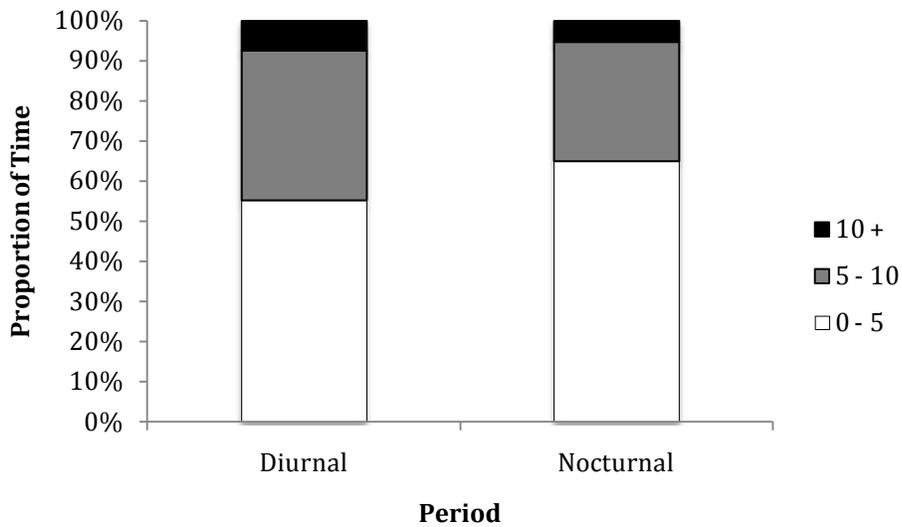


Figure 1-8. Proportion of time spent in water depth classes by diurnal (0500 to 1859) and nocturnal (1900 to 0459) periods of activity for six green turtles tracked in Laguna San Ignacio, BCS, Mexico.

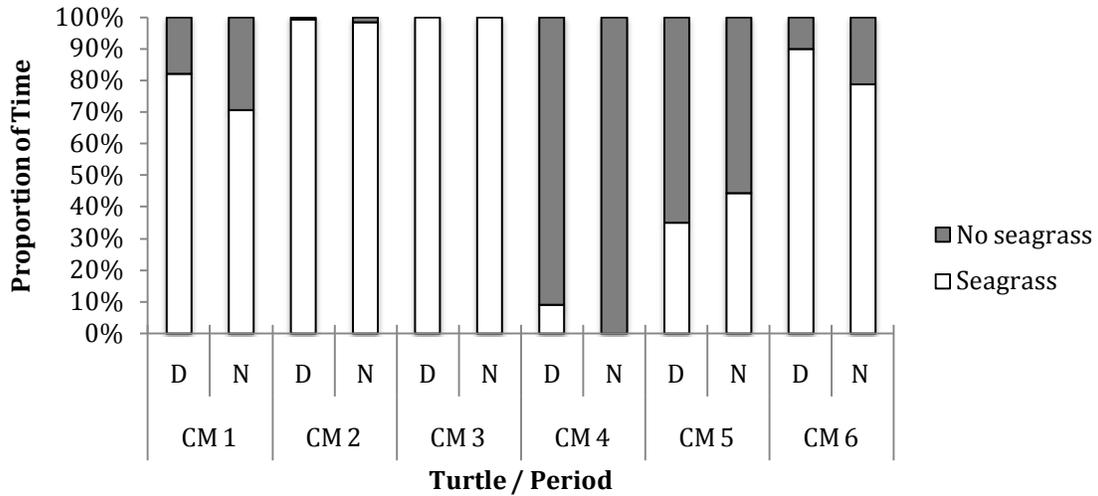


Figure 1-9. Proportion of time spent over areas of seagrass for each of the six green turtles tracked in Laguna San Ignacio, BCS, Mexico. Data are partitioned by diurnal (0500 to 1859) and nocturnal (1900 to 0459) periods of activity.

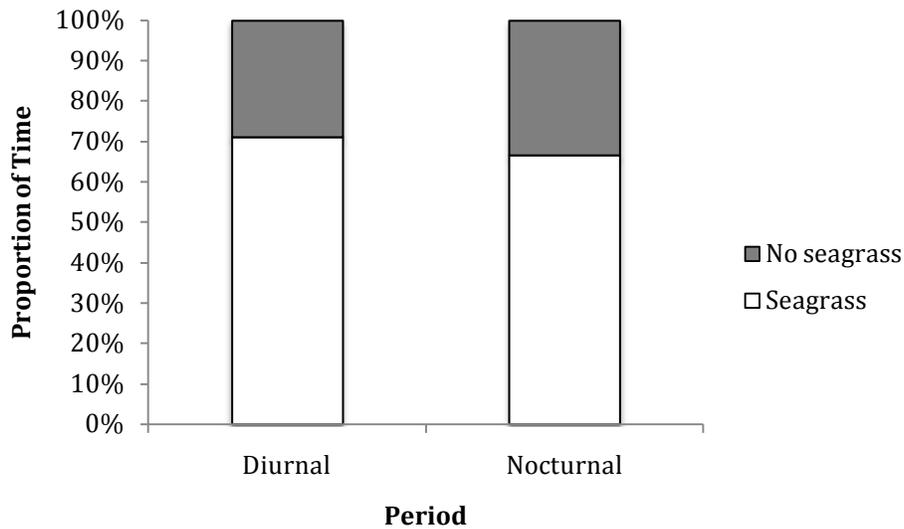


Figure 1-10. Proportion of time spent over areas of seagrass by diurnal (0500 to 1859) and nocturnal (1900 to 0459) periods of activity for six green turtles tracked in Laguna San Ignacio, BCS, Mexico.

Table 1-5. Summary of *Chelonia mydas* MCP home/activity ranges and vagility (km traveled per day) reported here and from other green turtle foraging areas. \* Short-term activity ranges analogous to our study; \*\* Different units

Location	MCP	Vagility	Source
Laguna San Ignacio, BCS, Mexico	404 ± 386 ha	13.2 ± 4.5 km (summer)	Present study
Moreton Bay, Australia	662 ± 294 ha *	n/a	Hazel (2009)
Bahia Magdalena, BCS, Mexico	n/a	18.6 ± 11.4 km (summer)	Brooks et al. (2009)
Bahia de los Angeles, BC, Mexico	458 ± 202 ha *	8.21 ± 1.61 km (summer)	Seminoff and Jones (2006)
Palm Beach, FL, USA	238 ± 178 ha	n/a	Makowski et al. (2006)
Bahia de los Angeles, BC, Mexico	1662 ± 324 ha	n/a	Seminoff et al. (2002)
Bahia de los Angeles, BC, Mexico	n/a	9.54 ± 3.2 km (summer)	Seminoff (2000)
Mosquito Lagoon, FL, USA	288 ± 146 ha	2.62 ± 0.96 km (summer)	
Tague Bay, St. Croix, US Virgin Islands	n/a	8.2 ± 1.75 km (winter)	Mendonca (1983)
Kaneohe Bay, Oahu, Hawaii, USA	n/a	~ 2 km	Ogden et al. (1983)
Texas, USA	n/a	3 km <sup>2</sup> area for 13 d **	Brill et al. (1995)
		1.2 km	Renaud et al. (1995)

CHAPTER 2  
TETHERED VHF-GPS TELEMETRY: AN IMPROVED, LOW COST TOOL FOR THE  
FINE SCALE TRACKING OF A LONG-LIVED MARINE MEGAVERTEBRATE

**Introduction**

Biotelemetry is increasingly being used to study the fundamental biology of free-living animals (Cooke 2008) such as sea turtles. Understanding the factors that influence animal movements are important aspects of conservation biology and behavioral ecology (Castilla 2000). Regional, national and international threat assessments require a basic understanding of animal behavior, distribution and habitat use, which can usually be obtained through biotelemetry studies (Cooke 2008). Explicit data on spatial ecology is often required for many species when designing conservation and management plans. These data are often hard to obtain because many species are cryptic and tracking studies are expensive as well as labor and time consuming. Understanding the movements of sea turtles are important because these animals perform key ecological roles as consumers, prey, competitors, hosts for parasites and pathogens, substrates for epibionts, seascape and marine substrate engineers and nutrient transporters (Bjorndal 2003; Bjorndal and Bolten 2003; Bjorndal and Jackson 2003). Fine scale movement data are especially important as increased knowledge may provide critical information towards establishing dynamic and adaptive conservation strategies (Castilla 2000) for these endangered marine vertebrates.

For several decades, flipper tagging was the main tool used to study the movements of sea turtles (Hendrickson 1958). However, flipper tagging requires large numbers to ensure sufficient captures, does not provide fine scale data and it may be difficult to determine whether tags were recovered en route or from final destinations. In addition, the likelihood of tag recovery is typically low and tag recovery locations may be

biased towards areas with active fisheries or capture effort and recovery (Godley et al. 2003b). Since the late 1970s, however, satellite telemetry has been used to track the oceanic and migratory movements of sea turtles. Despite progressive size reductions, the costs to purchase and operate satellite telemetry remain high (Fuller et al. 2008). Today, the majority of broad scale studies use Platform Transmitter Terminals (PTTs) with the Argos data service. Accuracy of locations is not important for these studies because they often focus on long distance movements; however accuracy is essential for fine scale movements (Hays et al. 2001). Given the ease of access to sea turtles at nesting beaches and their comparatively large size which is advantageous to device attachment, it is not surprising that > 75% of published sea turtle tracking studies have focused on adult females (Godley et al. 2008). To date, fine scale studies employing sonic and radio tracking, as well as traditional mark and recapture methods have provided the most value for money (Seminoff et al. 2002; Godley et al. 2008). Radio and sonic tracking has been used to determine inter-nesting movements (Starbird et al. 1999), movement direction when departing a rookery (Addison et al. 2002) and home ranges (Seminoff et al. 2002). However, fundamental spatial information exists for only a handful of green turtles inhabiting coastal foraging areas (i.e. Mendonca 1983; Whiting and Miller 1998; Seminoff et al. 2002; Makowski et al. 2006; Seminoff and Jones 2006; Hazel 2009) and continuous fine scale tracking (Mendonca 1983; Seminoff and Jones 2006; Brooks 2009; Hazel 2009) remains comparatively limited (Hazel 2009).

While GPS loggers are beginning to show detailed movement patterns for a number of terrestrial and aerial species (Wegge et al. 2007), technical constraints have largely limited the use of GPS loggers for aquatic organisms such as marine turtles

(Schofield et al. 2009). This is largely because saltwater blocks the transmission of radio signals, thereby limiting prospects for acquiring satellite-based tracking data to very brief intervals when a turtle surfaces. Hays (2008) identified improved resolution of tracking as one of two key approaches to understanding what drives the movements of free-living sea turtles. However, there are several challenges to tracking marine turtles at coastal foraging areas. Unlike adult sea turtles that are migrating or usually moving comparatively large distances, turtles on neritic foraging areas typically move less and their diving behavior leads to very few, if any, high quality locations (Plotkin 1998; Godley et al. 2003b). Additionally, green turtles at our study site and other foraging areas along the Baja California peninsula rarely, if ever, expose their carapace when surfacing for air. Rather, they only elevate their head slightly out of the water for a quick breath before immediately descending underwater (J. Senko, pers. obs.).

We were able to overcome challenges inherent with fine scale tracking marine turtles inhabiting coastal foraging areas by using a floating buoy attached to the turtle via a tether that housed a GPS logger and VHF transmitter modified after Brooks et al. (2009). We tested this tracking method both in the laboratory and in the field on free-living East Pacific green turtles resident at a dynamic marine environment. Here, we document the effectiveness of our tracking device and discuss the benefits and challenges associated with this method, as well as provide recommendations for future use of this tracking technique.

## **Methods**

### **Tracking Device**

The 2007 telemetry package consisted of hand-carved, self-righting, floating buoys (22 x 5 cm; 200 g total package;  $\leq 1\%$  of average turtle body mass) made out of

high density Styrofoam (see figure 1). I placed a small GPS receiver (Trackstick, Telespatial Systems, California, USA) and data logger (10.3 x 2.8 cm) and a VHF transmitter inside the floating buoy. Before placing the GPS device in the buoy, I sealed the unit in a latex condom. A plastic rudder (6 cm) placed in the back of the buoy acted as a directional stabilizing mechanism while half of a Compact Disc built into the bow as a plane prevented pitching down at speed.

The 2008 telemetry package consisted of hand-carved, self-righting, floating buoys made out of balsa wood (26 x 9 cm; 250 g total package;  $\leq 1.5\%$  of average turtles body mass). Before placing the GPS device in the buoy, we vacuum-sealed the unit in Ziploc brand vacuum freezer bags to protect from saltwater intrusion. The buoy had a built-in rudder that acted as a directional stabilizing mechanism with an enlarged bow to prevent pitching down at speed.

### **Field Trials**

Field trials were conducted in November/December 2007 and June 2008 at Laguna San Ignacio, a tidally driven lagoon located on the Pacific coast of Baja California Sur, Mexico. GPS-VHF transmitter devices were deployed on 13 free-living East Pacific green turtles using two different buoy designs (red, 2007; green, 2008). Movement data obtained from the turtles tracked during this time period are not presented here (see Senko 2009).

Turtles were tracked using VHF radio (148.103 – 148.146 MHz) and GPS telemetry. Both buoys were attached to the turtles via a monofilament floating line (10 m length, 30-pound test) as a tether, a weak link and a carapace attachment point. The weak link was comprised of three separate eight-pound monofilament test lines of

differing lengths (3, 4 and 5 cm) connected to a snap-swivel. This was used to facilitate the turtles escape should the buoy or tether became entangled. The attachment point was a small, dissolving, magnesium hook that was glued to the middle of the first central scute using 5 min quick set epoxy. The high-frequency VHF transmitters (F1835B, Advanced Telemetry Systems; Isanti, MN) were 48 mm in length, 18 mm in width, and transmitted at 164-165 MHz. Turtles were tracked w/ a Yagi antenna using VHF (148.103 – 148.146 MHz) and GPS telemetry. GPS units were configured to receive and record locations ( $\pm 1$  m) every minute. Turtle positions were triangulated from shore approximately every two hours to maintain constant contact. Tracking was terminated when the tether broke naturally at the weak link.

### **Laboratory Trials**

Increased drag from attached tracking devices has been shown to affect animal behavior (Shepard et al. 2008) and negative effects have been reported for many marine animals, including but not limited to king penguins, Antarctic fur seals, polar bears and leatherback turtles (Sherrill-Mix and James 2008; Shepard et al. 2008). Therefore, we tested the drag exerted on the turtle by the tags in the laboratory using a flow tunnel and an instrumented beam. The tag was connected by a short length of monofilament line to the end of the beam such that the line made an angle of 45 degrees with the water's surface, approximating the observed towing angle exhibited by the tagged turtles in the wild. The water flow was incremented stepwise, and the resulting bending force was measured on the beam. Drag force was plotted as a function of the square of flow velocity for the two tag designs employed during the course of our study.

## **Results and Discussion**

All buoys remained intact and all GPS loggers and VHF transmitters remained watertight and in the same position within the buoy. We tracked a total of 13 turtles for periods of 0 to 184 h. For the flow velocities that are relevant to turtles in everyday life, there were no differences between the two tag designs. At high velocities beyond 0.8m/s, the flow in the tank became so turbulent that the readings were difficult to interpret.

### **Effects of Tracking**

We measured force (N) imposed on the turtles by the 2007 and 2008 telemetry unit using a flow tank. As the buoys increased in size (from 2007 to 2008) there was a slight increase in drag. In 2008, the shape of the buoys became more hydrodynamic, but to hold the larger batteries these tags were heavier, thus accounting for the increased drag. The tags generated a force of ~ 0.5 N at the average velocity of the turtle (see Figure 2-3). In terms of drag, there appeared to be very little real difference between the two designs. The overall drag (in N) is small compared to the thrust being developed by the turtle.

Without a control group, it is unclear what impact this system had on green turtle behavior and we cannot be certain that the behaviors exhibited by tracked turtles are normal. Sherrill-Mix and James (2008) reported that leatherback turtles satellite tracked off Canada did not commence foraging until a median of 12.7 d after being tagged. Nevertheless, I believe the tracking device used in this study most likely had minimal effects on the movements and behaviors of tracked turtles. Tracked turtles returned to their initial capture locations, were seen in areas with other turtles and demonstrated seemingly normal swimming behavior. In addition, the telemetry device was ~ 1% of

mean body mass for all tracked turtles. Seminoff et al. (2002) and Brooks et al. (2009) indicated that the maximum mass of their telemetry unit was 1.2% of the mass of tagged green turtles. The tag: mass ratio achieved in this study is comparable to that of other green turtle telemetry studies in BCS, Mexico and less than the 2% ratio recommended for telemetered fish (Mellas and Haynes 1985). Moreover, sea turtles swim using their front flippers for propulsion (Wyneken 1997) and the present system does not appear to affect their swimming ability as the tether is almost always behind the turtle. Nevertheless, the system creates some drag and its effect on diving behavior might be substantial if the turtle were to attempt to dive deeper than the length of the tether. However, without the use of time-depth recorders it is unclear if, or how often, turtles are diving deeper than our 10 m tether.

### **Challenges, Limitations, and Prospects for Future Studies**

Recent developments in satellite linked GPS technology (i.e. Yasuda and Arai 2005) have provided quicker acquisition times that may provide insights into fine scale tracking of animals such as juvenile sea turtles that move short distances over long time periods (Godley et al. 2008). Schofield et al. (2007) used novel TrackTag™ GPS loggers housed in plastic casing to record the movements of inter-nesting loggerhead turtles (*Caretta caretta*). However, this method is evidently only suited to sea turtles that bask at the surface with their carapace exposed, such as loggerhead turtles or sea turtles that are migrating or in the oceanic stage (Bolten 2003). The use of data loggers and transmitters are now just beginning to shed new light on habitat use for sea turtles resident at neritic foraging areas (Schofield et al. 2009). Hazel (2009) used a 0.6 m neutral buoyant tether-attached Fastloc GPS tracking tag attached to the posterior

margin of the carapace to record fine scale movements and habitat use of green turtles in Australia and Fastloc GPS was considerably more accurate than Argos PTT. However, no information was presented on the price of each unit or why tracking was ultimately terminated.

Reasons for early termination of tracking in our tests included: (1) the tether detaching from the carapace attachment point either naturally or purposefully; (2) the GPS data logger failing; (3) the batteries failing; (4) salt water fouling the GPS logger switch and (5) the epoxy not being applied correctly. One tether was snapped at the weak link upon release in deep water ( $> 10$  m). Initial release should therefore occur in shallow water (preferably  $\leq 2$  m) to prevent substantial drag, which increases as an accelerating function of speed (Boyd et al. 1995), from breaking the tether at the weak link. Although the red tags (2007) appeared to exhibit lower drag than the green ones (2008), the larger green tag was able to record for longer and stood up better to the punishment of being cast ashore after detaching from the turtle.

There are obvious limitations to the present system, including several situations in which the present device will not be useful. First, the device only works when the animal is moving forwards. Second, the current set up has limited battery life ( $\sim 2$ -10 days depending on configuration). The largest improvement would be to strengthen the tether to include the use of high strength, flexible monofilament line that is flexible but less likely to break. However, although the weak link can probably be strengthened with higher test monofilament, we cannot recommend this until we are absolutely certain that the fail-safe would work if the turtle were to become tangled. Second, the device is

useful in habitats with relatively few obstacles (i.e. large rocks, outcrops, ledges, etc) and thus may not be appropriate in freshwater or reef habitats.

One of the advantages of satellite tracking is that it allows researchers to follow turtles in near real time, no matter where they go (Godley et al. 2008). Although a major advantage to our method is that turtles do not need to be continually followed (which is typically the case in radio-tracking studies), individuals should be monitored regularly during the entire tracking duration. While monitoring a tracked turtle during June 2008, we noticed irregular swimming behavior. Upon further investigation, we realized that the turtle's tether had become tangled with another turtle. We were able to capture, untangle and free both turtles. Although seemingly rare, this observation highlights the importance of monitoring turtles that are being tracked at least once per day.

### **Conclusions and Implications for Conservation**

Understanding the fine scale spatial requirements of green turtles during this vulnerable and important life stage is critical to their conservation, as broad scale conservation strategies (i.e. complete moratorium on the use of sea turtles and widespread nesting beach protection) have failed to provide adequate conservation gains throughout many regions of the world, including our study site and other foraging areas along the Baja California peninsula. We described a novel method for tracking the fine scale movements of free-living endangered East Pacific green turtles on their neritic foraging grounds. The system we developed and tested is relatively cheap, easy to use and retrieve and the data can be downloaded and analyzed on site. In addition, turtles do not need to be continuously followed; the tracking device exerts little drag on turtles and does not appear to negatively affect free-living turtles tracked in the field. Data gained from future studies utilizing the present system will ideally improve our

understanding of fine scale behaviors and movement patterns of a cryptic and important life stage of an endangered marine megavertebrate.

Given the limited amount of funds for conservation research (Myers et al. 2000; Halpern et al. 2006), it is critical to consider that the most cost effective research methods are used. Cooke (2008) recommends that authors include data on the cost of their studies and resources required (staff, equipment, time). We believe this system holds promise for fine scale tracking of free-living sea turtles and possibly even other aquatic animals. Considering that most species of sea turtles are endangered and satellite telemetry is costly and largely ineffective for tracking sea turtles inhabiting coastal foraging areas, we hope that future studies use and improve upon our methods.

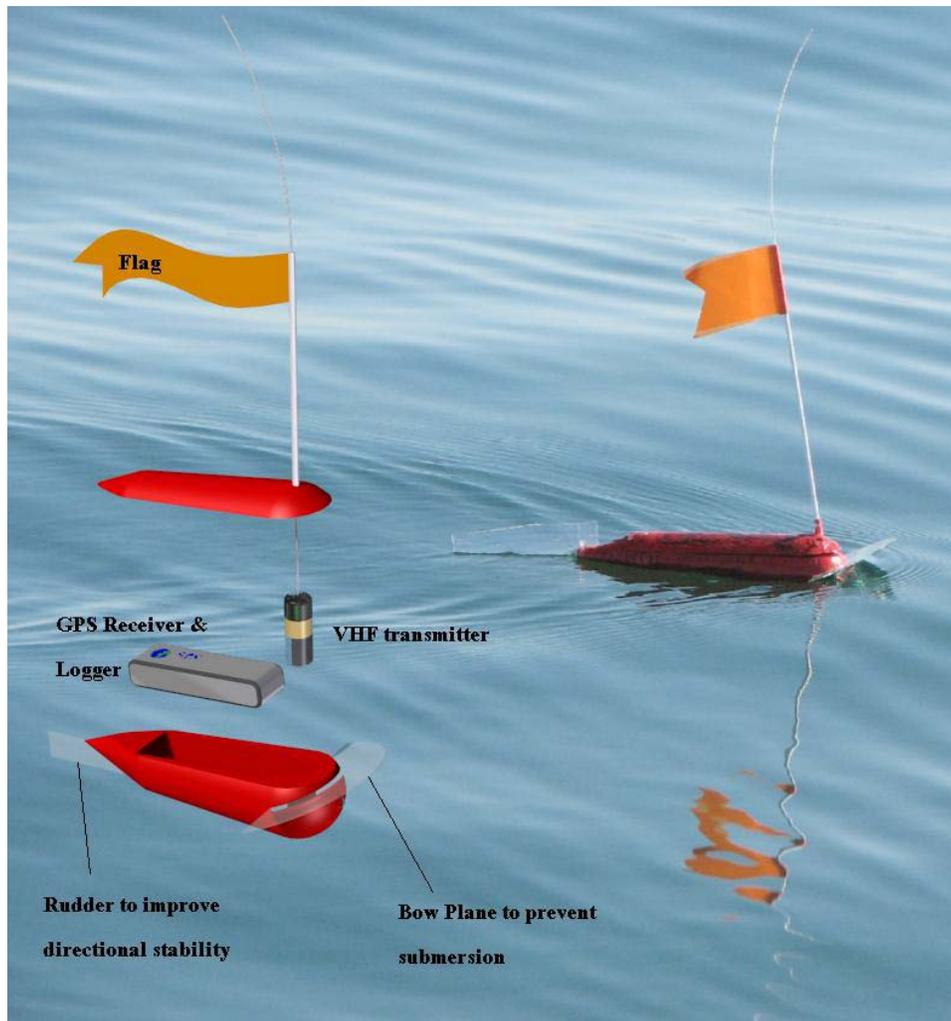


Figure 2-1. Annotated diagram of 2007 floating buoy (22 x 5 cm; 200 g total; 1% of average turtles body mass) that houses GPS device and VHF transmitter

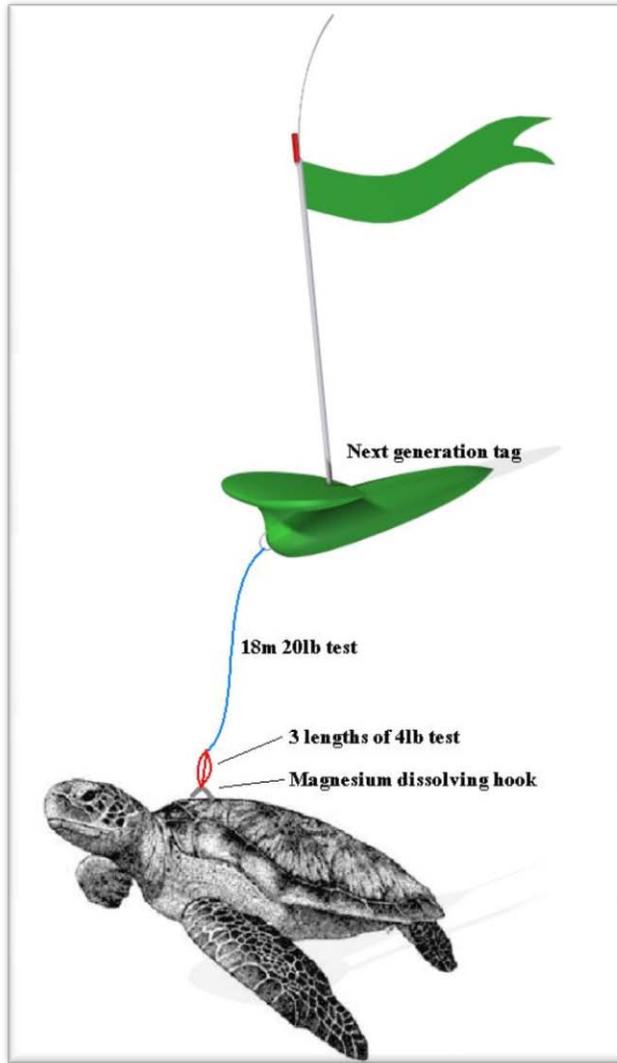


Figure 2-2. Schematic drawing of 2008 floating buoy (26 x 9 cm; 250 g total; 1.5% of average turtles body mass) that houses GPS device and VHF transmitter

Table 2-1. Costs associated with the two iterations of our tracking device.

Tracking Components	Make/Model	Quantity	Cost (US \$)
<u>Red (2007)</u>			
GPS logger	Trackstick	4	600
VHF transmitters	Sirtrack	4	240
Yagi Antenna	Asanti	1	150
Line (tether)	Spider wire	2	20
Buoy	Styrafoam	4	30
Battery	AA NiMH rechargeable	16	50
Protective Packaging	Latex condoms	4	20
Attachment material	5 min quick set epoxy	4	20
			\$1,125 total
<u>Green (2008)</u>			
GPS logger	GeoChron	4	600
VHF transmitters	Sirtrack	4	240
Yagi Antenna	Asanti	1	150
Line (tether)	Spider wire	2	20
Buoy	Balsa wood	4	50
Battery	AA Li-ion rechargeable	8	320
Vacuum sealer	Wal-Mart	1	50
Protective Packaging	Zip-Loc	4	25
Attachment material	5 min quick set epoxy	4	20
			\$1,475 total

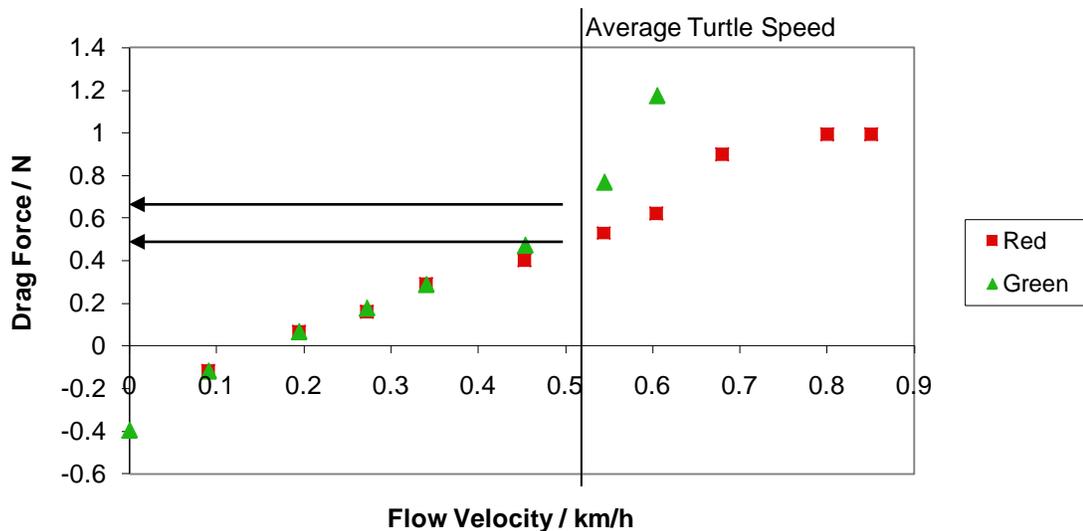
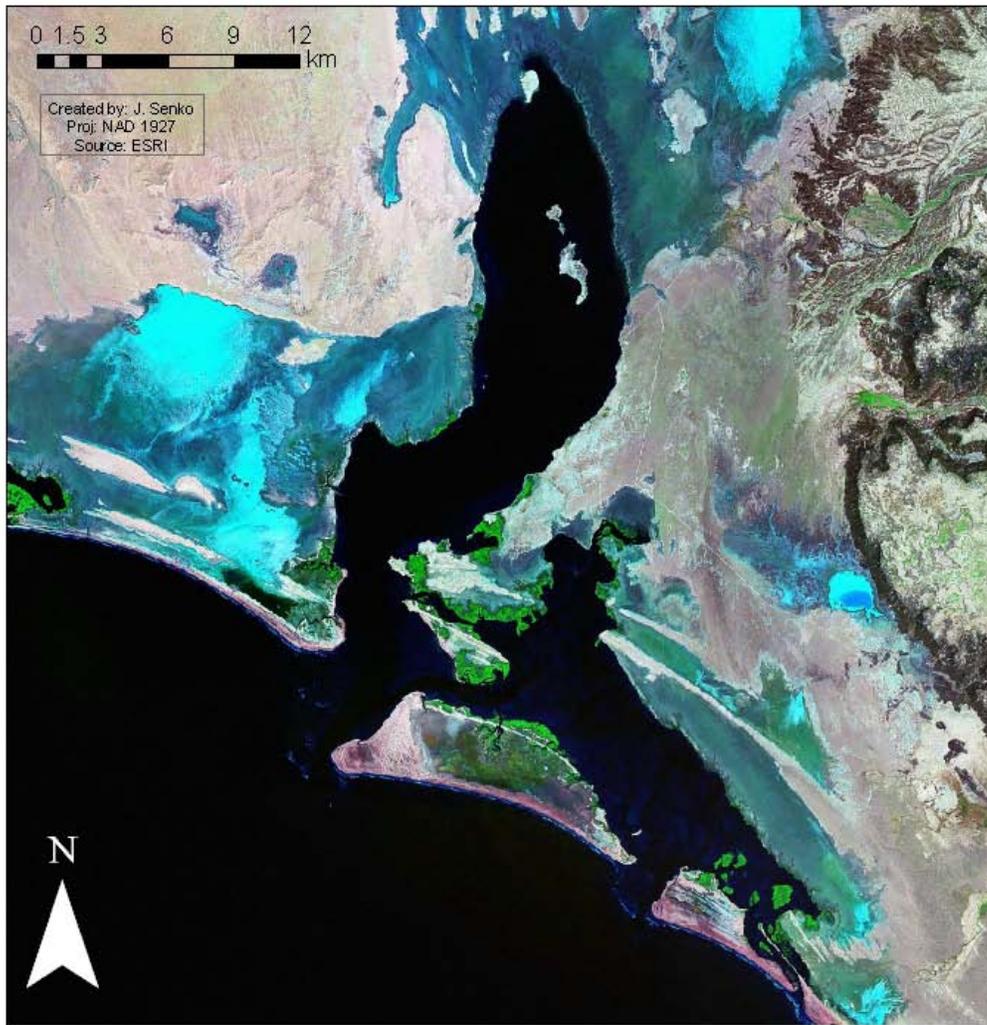


Figure 2-3. Force (N) imposed by telemetry unit at increasing current speeds measured in a flow tank. Average speed for all turtles tracked in June 2008 = 0.54 km/h.

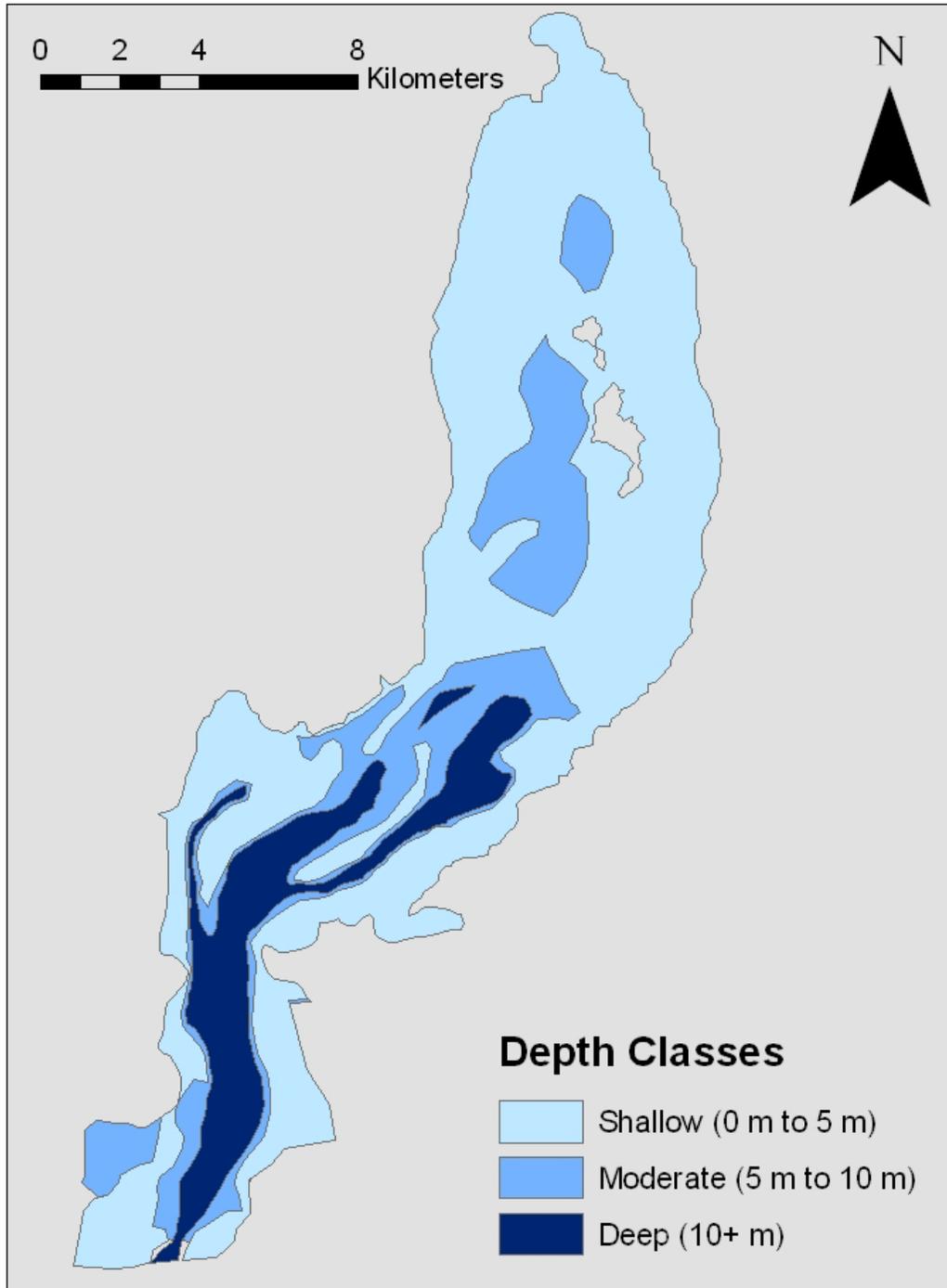
Table 2-2. Summary of tracking effort and device performance for 13 turtles tracked during the course of the study. Red and green buoys were used for turtles tracked during 2007 and 2008 respectively.

Turtle ID	SCL (cm)	Mass (kg)	Tracking Interval	Total Hours	Reason for Termination	Break Point
CM 1	49.00	15.20	11/21/07-11/22/07	23.80	Natural Break	Weak Link
CM 2	50.20	14.10	11/22/07-11/23/07	19.50	Natural Break	Weak Link
CM 3	50.70	17.50	11/23/07-11/24/07	37.60	Terminated	Weak Link
CM 4	48.80	15.60	11/23/07-11/24/07	21.90	GPS failure	Weak Link
CM 5	59.20	26.90	6/20/08-6/24/08	98.50	Natural Break	Weak Link
CM 6	69.90	43.50	6/20/08-6/21/08	41.50	Natural Break	Weak Link
CM 7	62.40	31.20	6/19/08-6/22/08	75.50	Natural Break	Weak Link
CM 8	83.50	75.60	6/25/08-6/27/08	56.10	Natural Break	1 m from Weak Link
CM 9	44.60	10.90	6/18/08-6/21/08	86.0	Natural Break	Weak Link
CM 10	56.20	24.00	6/11/08-6/19/08	184.00	Natural Break	Weak Link
CM 12	54.90	21.90	6/10/08-6/10/08	0.00	Broke during release	Glue
CM 13	81.10	71.90	6/11/08-6/11/08	0.00	Broke during release	Weak Link

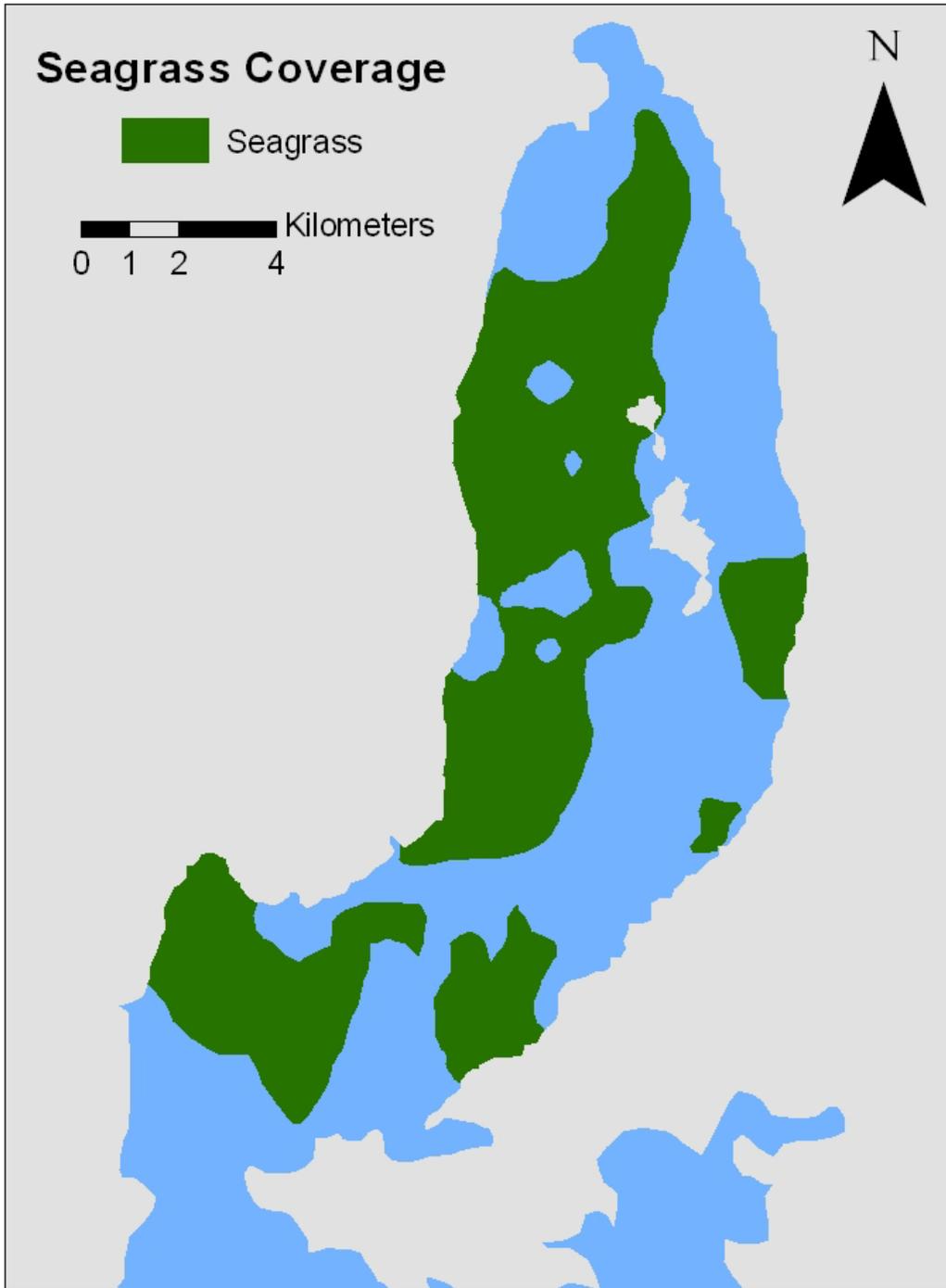
# APPENDIX A STUDY AREA



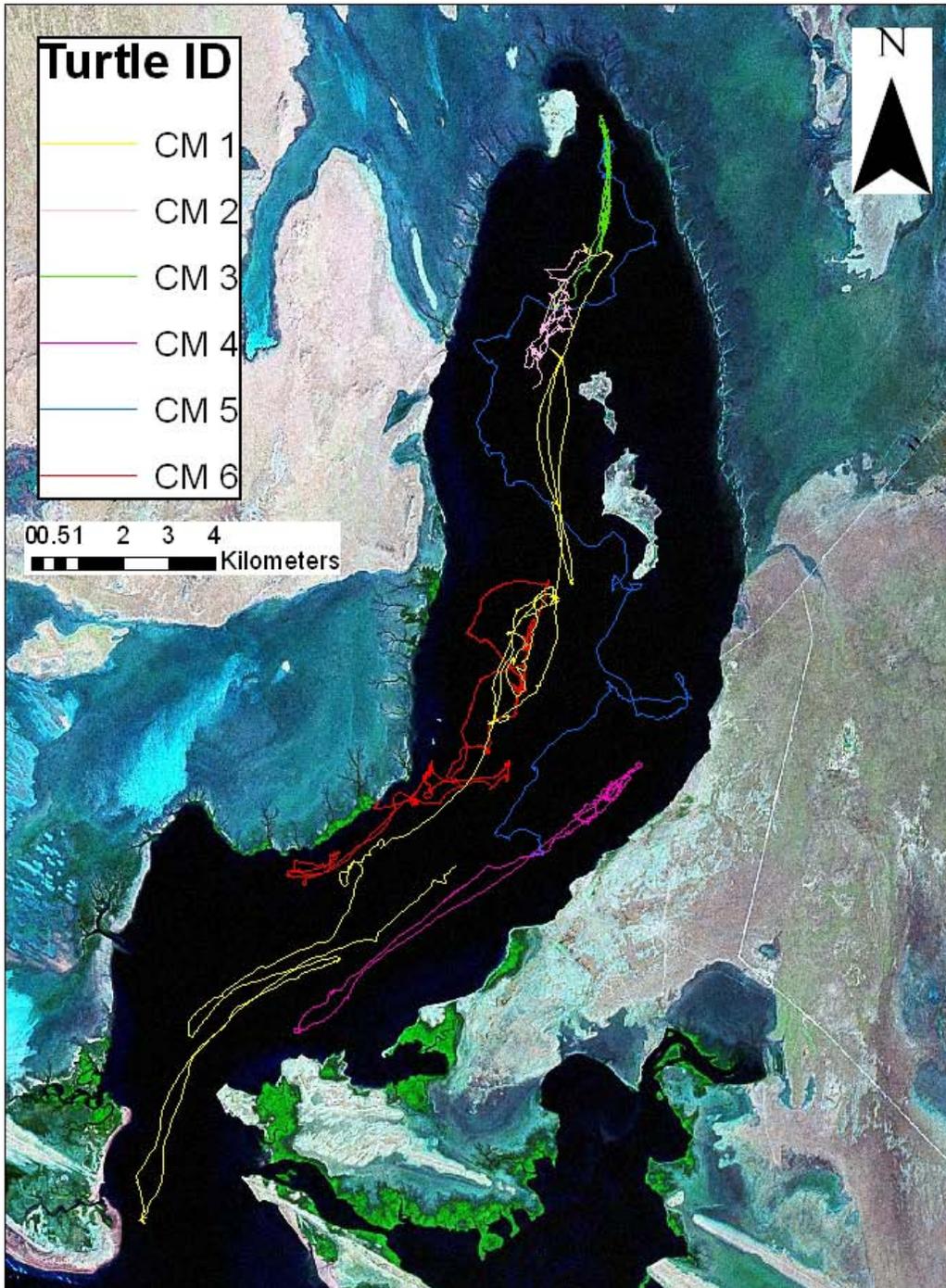
APPENDIX B  
DEPTH CLASSES



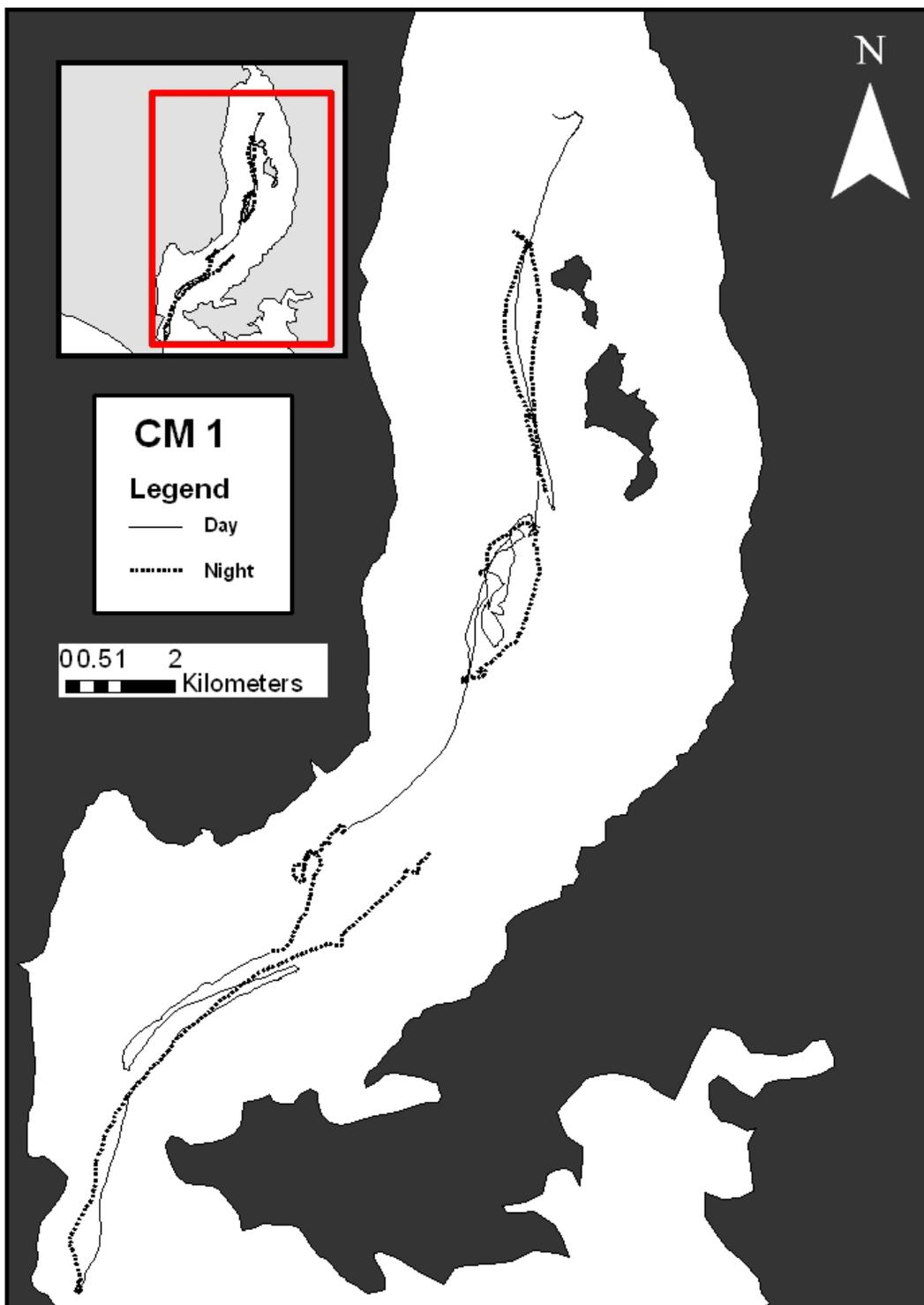
APPENDIX C  
SEAGRASS COVERAGE



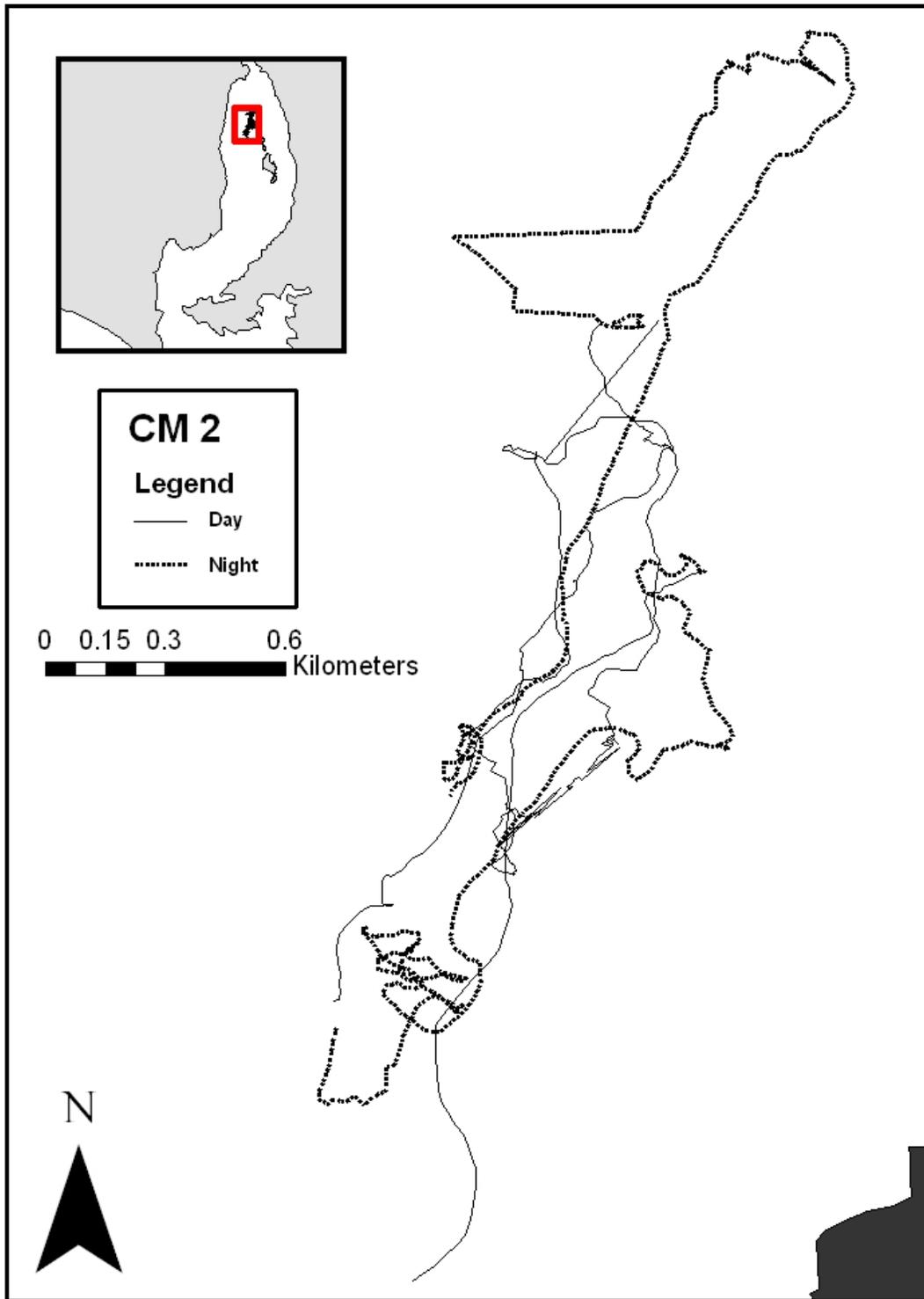
APPENDIX D  
ALL TURTLES



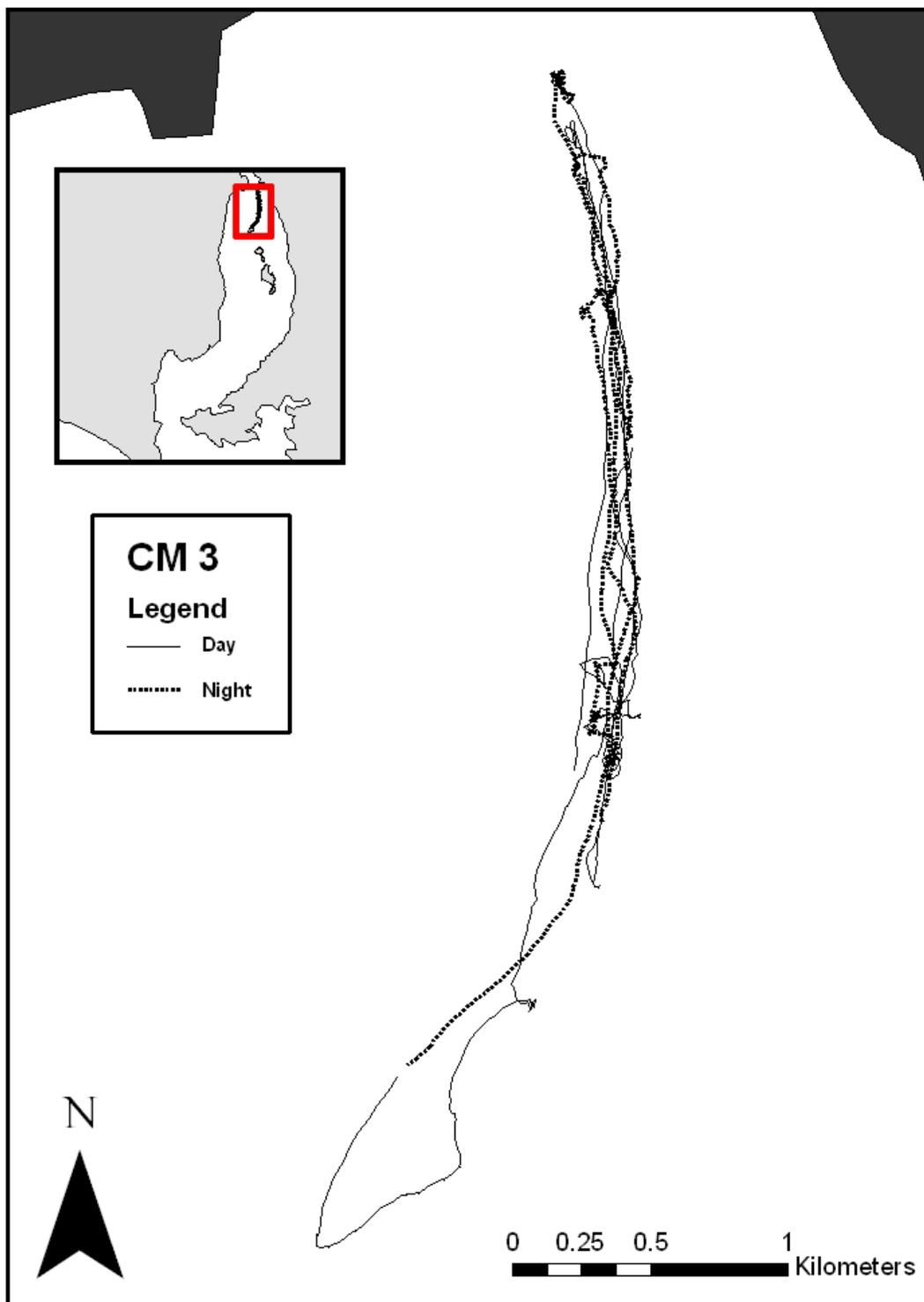
APPENDIX E  
CM 1



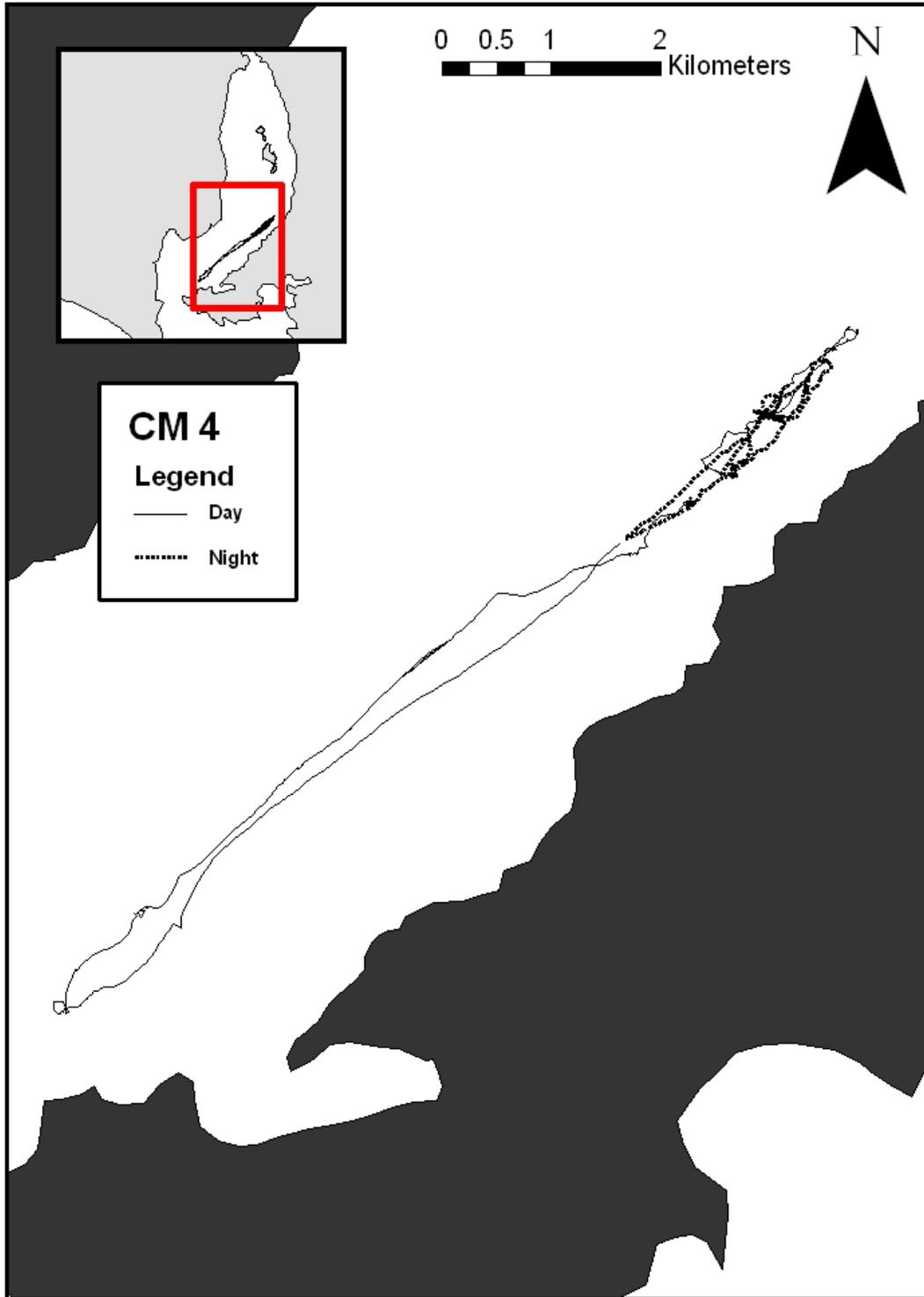
APPENDIX F  
CM 2



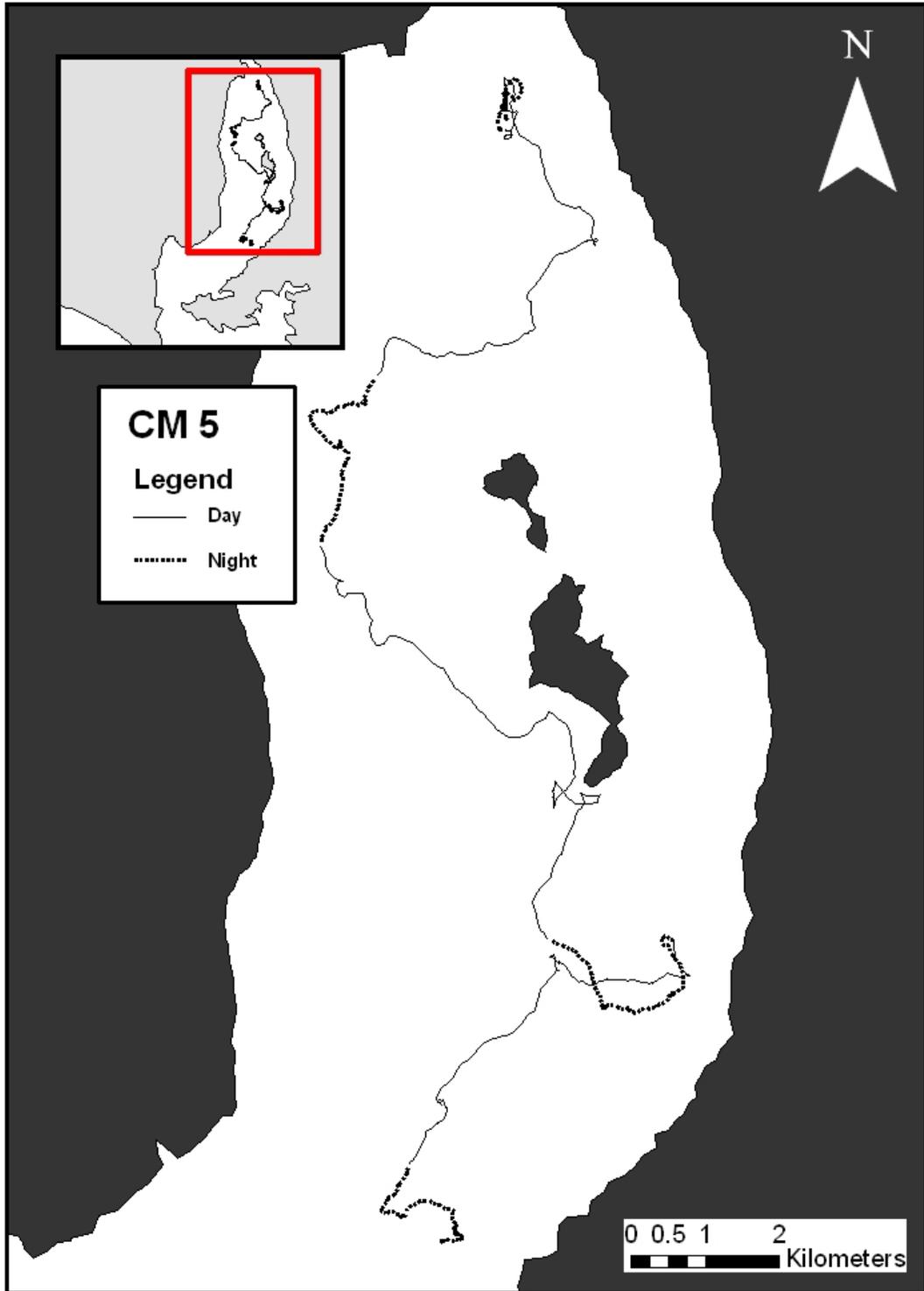
APPENDIX G  
CM 3



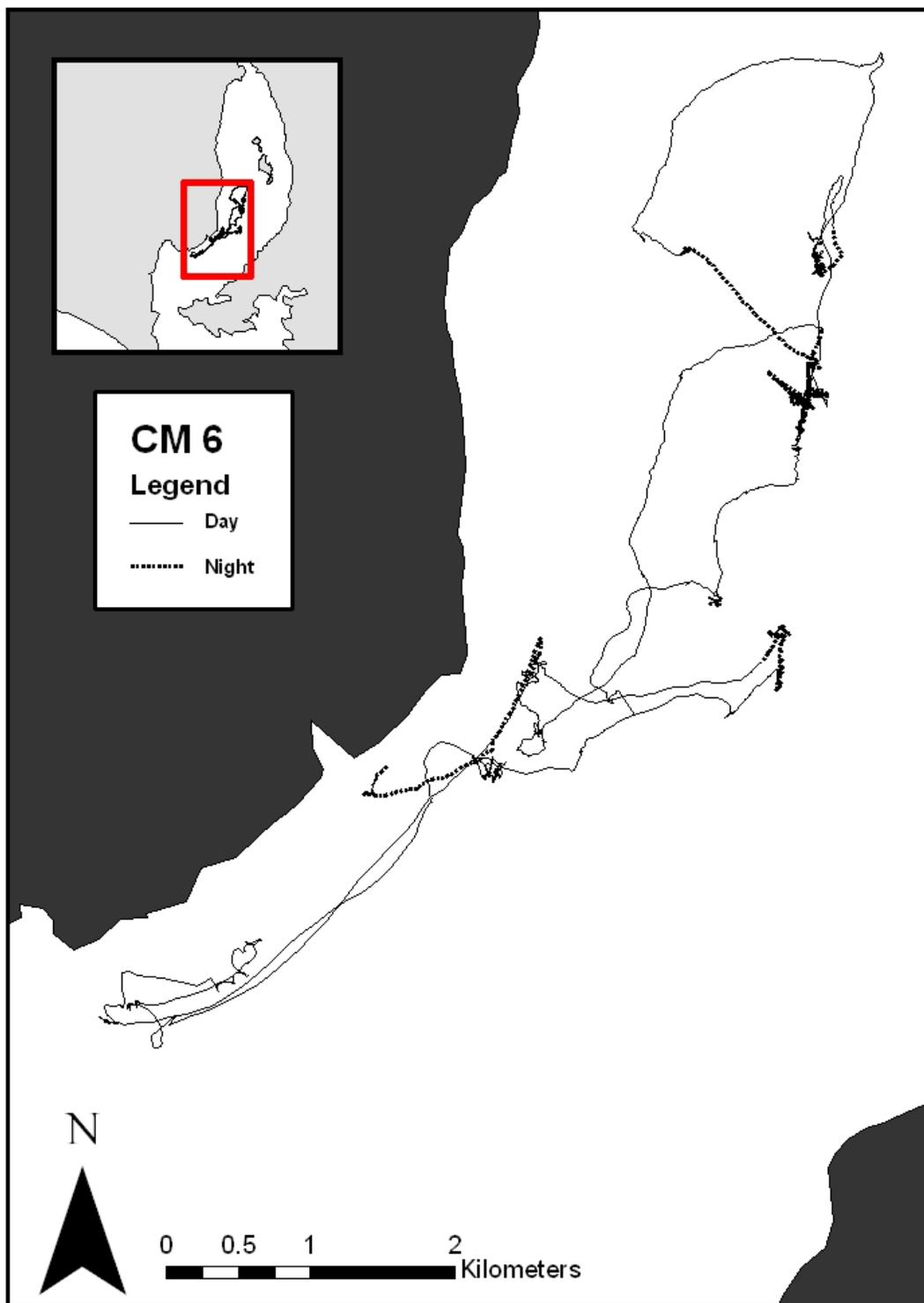
APPENDIX H  
CM 4



APPENDIX I  
CM 5



APPENDIX J  
CM 6



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Jesse Senko grew up in Monroe, CT and attended the University of Connecticut at Storrs where he received a BS in fisheries and wildlife sciences. Jesse has been conducting research focused on sea turtle ecology and community-based conservation in Baja California Sur, Mexico since 2004. His research interests are broad and encompass the natural and social sciences. He is particularly interested in: (1) the application of ecology to practical conservation issues; (2) multidisciplinary approaches to better understand and improve conservation efforts and (3) using novel conservation tools. His specific interests include conservation biology and policy, vertebrate ecology, landscape and spatial ecology, behavioral ecology, fisheries bycatch, herpetology and human dimensions of wildlife conservation.