Journal of Experimental Marine Biology and Ecology 443 (2013) 56–64

Contents lists available at SciVerse ScienceDirect

Journal of Experimental Marine Biology and Ecology

journal homepage: www.elsevier.com/locate/jembe

Fine scale diel movement of the east Pacific green turtle, *Chelonia mydas*, in a highly urbanized foraging environment

Bradley D. MacDonald [a,b,*], Sheila V. Madrak [a], Rebecca L. Lewison [a], Jeffrey A. Seminoff [b], Tomoharu Eguchi [b]

[a] *Department of Biology, San Diego State University, 5500 Campanile Drive, San Diego, CA 92182, USA*
[b] *Protected Resources Division, Southwest Fisheries Science Center, NMFS, NOAA, 8901 La Jolla Shores Drive, La Jolla, CA 92037, USA*

ARTICLE INFO

Article history:
Received 22 August 2012
Received in revised form 18 February 2013
Accepted 19 February 2013
Available online 19 March 2013

Keywords:
Acoustic telemetry
Coastal management
Conservation
Power plant
Sea turtle
Spatial ecology

ABSTRACT

Protection of endangered species requires an understanding of their spatial ecology in relation to human activities. Recent improvements in monitoring technologies, such as automated acoustic telemetry, have enabled the collection of these data for mobile marine organisms such as sea turtles. The east Pacific green sea turtle *Chelonia mydas* uses San Diego Bay, CA, a heavily developed ecosystem, as a year-round foraging ground. We used a combination of manual and automated acoustic telemetry from 2009 to 2011 to elucidate the distribution of green turtles throughout South San Diego Bay and to understand their diel behavior. Tracked turtles (n = 20) ranged in size from 54.9 to 102.5 cm straight carapace length and had fidelity to two sites: the warm-water effluent channel of a waterfront power plant and an eelgrass meadow. Turtles tracked manually during the night were more sedentary (mean swimming speed ± SE: 0.38 ± 0.03 km h^{-1}) and generally restricted their activity to waters near the power plant. During the day, turtles swam at higher speeds (0.67 ± 0.07 km h^{-1}) and were mainly found in eelgrass meadows where they are known to forage. Turtles were occasionally found near a shipping terminal, which occurred almost exclusively during the daytime. Turtles in areas of increased boat traffic are at risk of vessel strikes, and future monitoring should investigate the potential for turtle–human interactions in other heavily-used areas of San Diego Bay. Future monitoring should also characterize how turtle behavior may change following the decommissioning of the power plant, which occurred six months before the end of this study.

1. Introduction

The protection of coastal environments inhabited by at-risk species is a conservation topic that is receiving increasing attention. Sea turtles, marine mammals, and other protected species are subject to numerous anthropogenic stressors in the coastal zone, including shoreline development, vessel traffic, alteration of habitat, and pollution (Colwell, 2010; Eckert et al., 1999; Lusseau, 2006). Effective conservation requires knowledge of both an organism's habitat use as well as the spatial and temporal distribution of anthropogenic threats, which may be diverse and synergistic (Ross et al., 2011; Thompson et al., 2000). However, the acquisition of such data has frequently been hampered by the prohibitive cost and logistical difficulties of monitoring mobile, marine species at fine scales and across meaningful temporal windows (Grothues, 2009; Hazel, 2009). For example, manual radio and ultrasonic telemetry are extremely time and labor intensive (Heupel et al., 2006), while traditional satellite transmitters prove problematic for marine species that spend only short amounts of time at the surface (Schofield et al., 2007) and provide limited precision at fine spatial scales. Often managers must therefore make decisions about the allocation of limited resources based on minimal data amid diverse stakeholder interests. This data gap reinforces the need for studies and techniques that yield fundamental data on the biology and habitat use of threatened species.

Recent technological advances in marine monitoring (e.g., automated telemetry stations, FastLoc GPS) have greatly improved the study of the fine-scale spatial ecology of sea turtles and other cryptic marine organisms (Grothues, 2009; Schofield et al., 2007). Arrays of automated telemetry stations provide continuous, round the clock monitoring, having recently been used to assess the feeding and resting areas of green turtles (Taquet et al., 2006), movement across marine reserve boundaries by kelp bass (Lowe et al., 2003) and changes in the habitat use patterns of white tip sharks (Heupel et al., 2004). Continuous, fine-scale tracking (such as that provided by manual acoustic telemetry and FastLoc GPS) has also been particularly instrumental in the characterization of sea turtle movements between feeding and resting areas in relation to marine reserve boundaries and localized anthropogenic threats (Blumenthal et al., 2010; Schofield et al., 2007). Nonetheless, human uses of coastal areas are diverse, and therefore turtle habitat use may vary substantially among foraging grounds based on the proximity of feeding and resting areas to hotspots of human activity (Hazel, 2009; McClellan and Read, 2009; Renaud et al., 1995). As a result, much

* Corresponding author at: Protected Resources Division, Southwest Fisheries Science Center, NMFS, NOAA, 8901 La Jolla Shores Drive, La Jolla, CA 92037, USA. Tel.: +1 858 334 2837.
E-mail address: bradley.macdonald@gmail.com (B.D. MacDonald).

0022-0981/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jembe.2013.02.033

remains to be understood about the fine-scale behavior of sea turtles in areas where human activities are abundant (Eckert et al., 1999), particularly where such information will enable local management strategies to be tailored to individual foraging grounds.

Green turtles (*Chelonia mydas*) in San Diego Bay (SDB), a natural bay that lies adjacent to metropolitan San Diego, CA, have been documented since the 1800s and studied since the 1970s (McDonald et al., 1994; Stinson, 1984). Green turtles in SDB belong to an endangered Mexico breeding population that is considered part of the east Pacific stock that occupies Pacific coastal waters from southern North America to South America (National Resource Council, 2010). The Bay currently serves as a year-round foraging site for approximately 60 green turtles (Eguchi et al., 2010) and is also home to a high density of industrial, military, and recreational activities. The vast majority of these activities take place in the central and northern sections of the Bay. These areas contain deep shipping channels and dock/marina access that are closer to the mouth of SDB, while boat traffic in South SDB is primarily restricted to recreational boaters and fishers. Boats operating within South SDB, which is classified as a National Wildlife Refuge, are restricted by a 5 knot speed limit as a precaution against vessel strikes of turtles and harassment of endangered shorebirds inhabiting the area (U.S. Department of the Navy et al., 2010).

Green turtles in SDB were known to aggregate during colder months near the warm water effluent of the South Bay Power Plant, a waterfront power plant situated at the southern terminus of SDB that operated between 1960 and 2010 (Duke Energy South Bay and LLC, 2004; Eguchi et al., 2012; Turner-Tomaszewicz and Seminoff, 2012; Fig. 1). Turtle aggregation near this effluent channel was thought to be concurrent with a decrease in water temperatures in the more northern portions of SDB (McDonald et al., 1994; Stinson, 1984). Green turtle home ranges were restricted to South SDB, where core activity areas co-occurred with the power plant outfall during winter months and with eelgrass meadows during non-winter months (MacDonald et al., 2012).

In this study, we used a combination of manual and automated acoustic telemetry to characterize the spatial and temporal extent of green sea turtle habitat use in South SDB. The goals of the study were to identify the daily movement behaviors of resident green turtles and to assess the daily and seasonal patterns of turtle distribution. We discuss our data in the context of potential local anthropogenic stressors in SDB as well as the broader utility of these data for the conservation of endangered marine megafauna inhabiting the coastal zone.

2. Methods

2.1. Turtle capture

Turtles were captured seasonally from November to April of 2009–2010 (Year 1, hereafter) and 2010–2011 (Year 2, hereafter) as part of a long-term study conducted by the NOAA National Marine Fisheries Service (see Eguchi et al., 2010) and the same turtles were tracked during a simultaneous home range study (MacDonald et al., 2012). Weighted entanglement nets were deployed in waters adjacent to the South Bay Power Plant (N32°36″ W117°06″) from aboard a 6-m Boston Whaler and were checked at 30-min intervals. When a turtle was captured, it was immediately removed from the net and moved to shore for measurements. Captured individuals were checked for external flipper tags and internal PIT tags. Inconel flipper tags (Style 681, National Band and Tag Co., Newport, KY) were applied to the trailing edge of one front flipper and an internal PIT tag was injected into one of the front flippers of untagged individuals. A Sonotronics© CT-Series acoustic transmitter was attached to the carapace of captured turtles using fiberglass cloth and resin laminate, similar to Balazs et al. (1996). Each transmitter emits a unique, cyclical pattern of pulses on a frequency between 35 and 40 kHz, which enables the identification of individual turtles. All turtles were released in the waters adjacent to the South Bay Power Plant.

2.2. Automated telemetry data collection

Sonotronics© Submersible Ultrasonic Receivers (SURs) were deployed in South SDB to determine daily and seasonal patterns of turtle presence at an array of monitoring sites. SURs scanned for acoustic transmitters and recorded the date, time, and transmitter ID to a flash memory when a transmitter was detected. SURs were deployed in South San Diego Bay at six sites from December 2009 to June 2010 and at 14 sites from December 2010 to June 2011 (Fig. 1).

Acoustic monitoring sites in South SDB were selected based on known areas of turtle activity, such as the effluent channel of the South Bay Power Plant (Stinson, 1984); within eelgrass meadows, where green turtles in SDB are known to forage (Lemons et al., 2011); and in areas of increased human activity, such as boating channels, a shipping dock, and a marina entrance (Fig. 1). Stations were secured using one of three methods: anchored to the bottom and secured to shore via weighted lines, secured to boat channel markers at a depth of five meters, or anchored to the bottom and marked by surface buoys. SURs were retrieved at approximate twelve-week intervals for maintenance, battery replacement, and data retrieval.

2.3. Automated telemetry range tests

Range tests were conducted in South SDB to estimate the probability of detecting a transmitter present at distances approximately 0–100 m from an SUR. Two sites were chosen for testing: (1) the shallow, constricted effluent channel of the South Bay Power Plant, which ranged in depth from 1 to 3 m (PP1, Fig. 1), and (2) an open-water eelgrass meadow that ranged in depth from 3 to 5 m (E1, Fig. 1). Each site was tested at high tide and low tide. Two to four SURs (based on equipment inventory at time of test) were placed at a testing location and set to scan constantly on one frequency. An acoustic transmitter operating on the chosen frequency was then submerged to a depth of one meter at approximate distances of 5, 25, 50, and 100 m from the SUR for five minutes at each distance. The geographic coordinates of the SUR and transmitter were recorded using a handheld Garmin GPS unit (accuracy <5 m) and were later used to calculate the exact distance between transmitter and SUR.

A SUR scans a programmed frequency for the presence of a transmitter, which takes approximately five seconds and involves the detection and recording of transmitter information to the SUR's flash memory. The probability of detecting a transmitter during a scan by a SUR (P(D)) was calculated as:

$$P(D) = \frac{(\text{number of recorded detections})}{(\text{number of possible detections})}.$$

The number of possible detections was determined by a bench test of SURs placed adjacent to a transmitter. The probability of not detecting a transmitter that was present in the area was calculated as $P(D') = 1 - P(D)$. The probability of not recording any detections of a present transmitter during *n* scans of that frequency was defined as $P(D' = n) = P(D')^n$. Therefore, the probability of recording at least one detection of a present transmitter during *n* scans of a frequency was $P(D \geq 1) = 1 - P(D' = n)$. Using this method, we estimated the probability of recording at least one detection by an SUR during 1–15 scans ($n = 1, \ldots, 15$). This provided a probability distribution of detecting a tag present at a site for different tides and distances from the SUR (Fig. 2). From this distribution, we selected the number of scans that yielded a mean probability of 0.95 ($P(D \geq 1) \geq 0.95$) of detecting a transmitter if it was present.

Based on the probability distribution created with the above criteria, nine scans were necessary at PP1 ($P(D \geq 1) = 0.955 \pm 0.024$) and six scans were necessary at E1 ($P(D \geq 1) = 0.961 \pm 0.009$). For the determined number of scans, we found that the values of $P(D \geq 1)$ were consistent at different distances and tidal heights. The time for an SUR to