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

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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

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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, …, 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

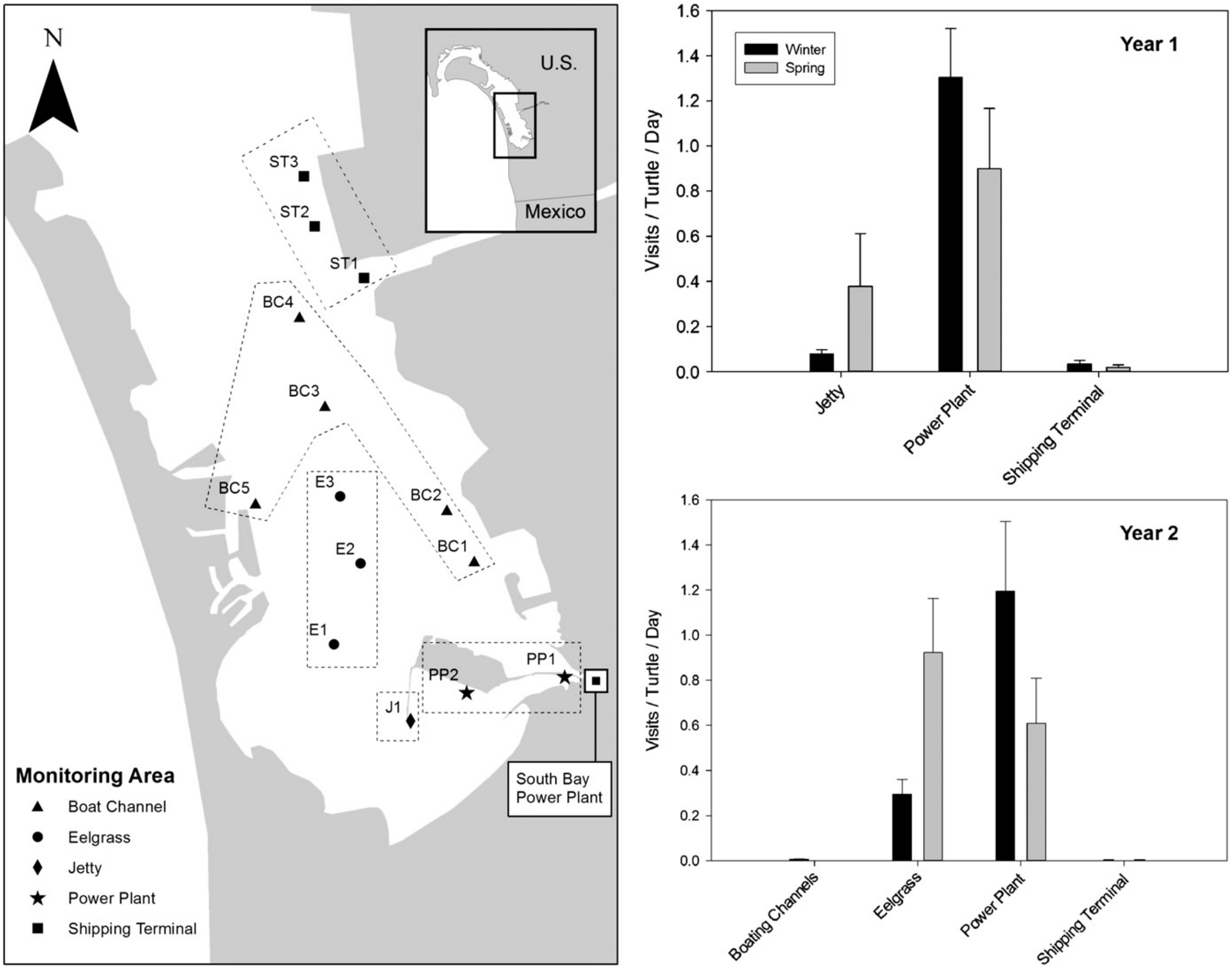


Fig. 1. (Left) Locations of automated receivers in San Diego Bay, CA; grouping of monitoring areas are enclosed by dotted lines. (Right) mean visits per turtle per day to automated telemetry monitoring areas during Year 1 (top) and Year 2 (bottom); black bars indicate visitation during winter months (December–March) and gray bars indicate visitation during spring months (April–June). Error bars indicate standard error.

complete one full scan of the six frequency channels to which we assigned transmitters was two minutes; this included delays between scans of each frequency channel and a delay at the end of each scanning cycle. Therefore, the time to complete nine full scans was eighteen minutes and the time to complete six full scans was twelve minutes. Although not all SUR sites were directly range tested, we believe that the mean scanning time from our two range test sites (fifteen minutes) provided sufficient scanning duration for determining the presence of a turtle transmitter.

2.4. Automated telemetry data analysis

Data from each SUR were processed to find a turtle's presence at every site, termed a ‘visit’. Based on our range tests, we concluded that a turtle visited a site if it was detected at least once every 15 minutes. In addition to the range tests that determined our detection criteria, SUR placement and subsequent analysis of raw data ensured that turtles were not simultaneously detected by two or more SURs. All data were further examined to confirm that no “overlapping” visits occurred; that is, there were no instances in which a visit at one site began before a turtle's visit to a different site had ended. Battery drainage, equipment malfunction, and disappearance of SURs resulted in variable monitoring effort among monitoring sites during the study. To account for variable monitoring, a turtle's total number of visits to a site during an SUR deployment (season, year) was divided by the number of days the site was monitored. The resulting number, visits per monitoring day, was used in subsequent analyses. The majority of data were collected between December and June, the time period that corresponded to when turtles were captured and to the general retention time of acoustic transmitters on captured individuals. This time period provided data for winter and spring. We defined these seasons based on ambient water temperatures at the intake of the South Bay Power Plant,[1] a method also used in MacDonald et al. (2012), because turtle presence in the effluent channel is thought to decrease when ambient temperatures in the rest of the Bay become warmer (Turner-Tomaszewicz and Seminoff, 2012). Mean water temperatures were 16.4 ± 0.2 °C (range 11.1–21.9 °C) between December and March (winter, hereafter) and 22.3 ± 0.2 °C (range 16.6–27.7 °C) between April and June (spring, hereafter).

We grouped monitoring sites into five general areas based on location and habitat type (Fig. 1): 1) power plant (PP), 2) jetty, 3) eelgrass, 4) boating channels (BC), and 5) shipping terminal (ST). Inter-site

[1] Tom Liebst, Dynergy South Bay LLC, 990 Bay Blvd., Chula Vista, CA 91911, USA.

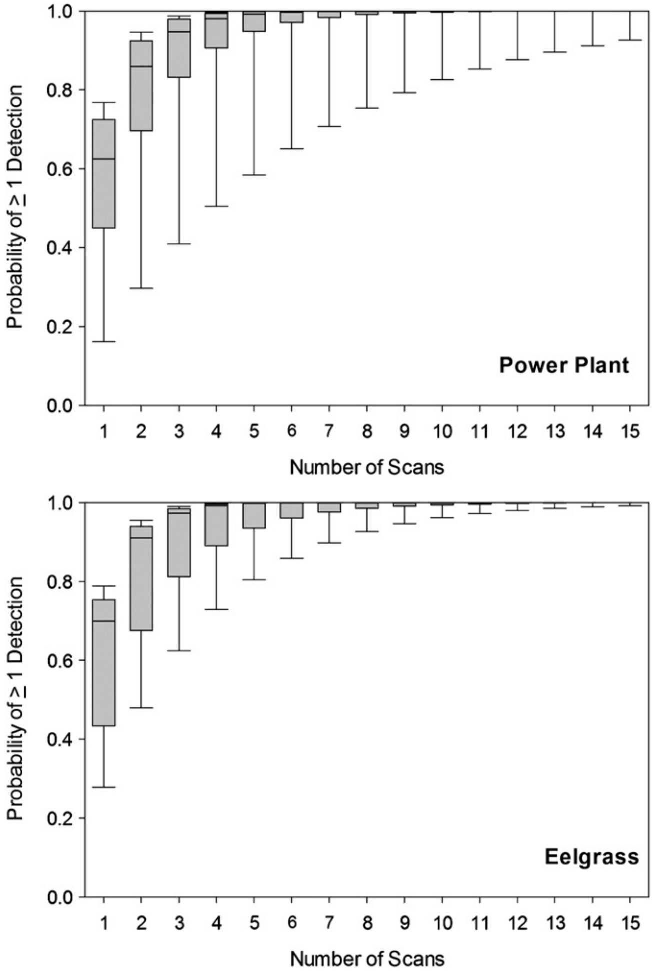


Fig. 2. Range tests of Submersible Ultrasonic Receivers (SURs) at the South Bay Power Plant effluent outfall and an eelgrass bed. Probability of recording at least one detection of a transmitter present within 100 m of the SUR is listed on the ordinate. The number of scans of the transmitter frequency necessary to achieve that probability is presented on the abscissa.

differences were determined using a generalized linear model. Each year was tested separately because SURs were deployed at additional sites in Year 2. Monitoring area, season (winter/spring), and an area–season interaction were modeled as repeated measures for each turtle to acknowledge correlated measures within individual turtles. Visits-per-day was used as the dependent variable. The model was based on a gamma distribution with an inverse link function to account for positive skew in the raw data. Diel variation within sites was examined using histograms of the number of site visits occurring at each hour of the day. Data were analyzed using SPSS 19.01.00, graphics were created in Sigma Plot 12.0, and maps were created in ArcGIS 9.3. Statistical significance was evaluated at a Type I error rate of 0.05. Means ± standard errors are reported unless otherwise stated.

2.5. Manual telemetry data collection

From December 2009 to June 2011, we conducted 50 tracking events at dawn (n = 12), day (n = 16), dusk (n = 12), and night (n = 10) to investigate the movement behavior of turtles throughout the day. Dawn and dusk (crepuscular periods) were defined as one hour preceding and one hour following sunrise and sunset, respectively; day and night were defined as the hours occurring between crepuscular periods. At the outset of a tracking period, tagged turtles were located opportunistically from aboard a 6-m Boston Whaler with an 85-hp outboard motor. A Sonotronics TH-2 omni-directional hydrophone was used to detect the acoustic transmitters of tagged turtles in areas of known turtle activity in San Diego Bay. Once the identity of a tagged turtle could be determined, tracking commenced. When multiple turtles were found, we gave priority to the monitoring of a turtle that had not been tracked in that time period. We used a Sonotronics DH-4 directional hydrophone to approach within 15–20 m of the turtle (Seminoff et al., 2002; Senko et al., 2010) and maintained this approximate distance for the duration of the tracking period to minimize observer effect on the turtle's movements (Brill et al., 1995). The boat's outboard motor was turned off when turtles were sedentary in one location to minimize disruption of turtle behavior. Geographic coordinates were recorded on a handheld Garmin GPS unit (accuracy <5 m) at 10-min intervals. Tracking periods were variable depending on time period and weather conditions and ranged from 2 to 6 h.

2.6. Manual telemetry data analysis

Spatial data from tracking periods were analyzed in Arc GIS 9.3 using the Hawth's Tools extension (Beyer, 2004). Speed (km h^{-1}) was calculated at each time step. Movement-straightness index (MSI), a metric of movement linearity, was calculated for each tracking period by dividing the total linear displacement between the starting and end locations by the total distance traveled during the track. Values close to one represented linear movement, whereas values close to zero represented non-linear movement. Activity area (km^2 h^{-1}) was computed as the area of the minimum convex polygon of the tracking period divided by

Table 1
Automated telemetry. Summary of p-values of generalized linear model post-hoc pairwise comparisons of visitations to SUR monitoring areas.

Year	Season	Area	Jetty	Power plant
1	Winter	Jetty	–	–
		Power plant	<0.001[a]	–
		Shipping terminal	0.104	<0.001[a]
	Spring	Jetty	–	–
		Power plant	<0.001[a]	–
		Shipping terminal	0.124	0.001[a]

Year	Season	Area	Boating channel	Eelgrass	Jetty	Power plant
2	Winter	Boating channel	–	–	–	–
		Eelgrass	<0.001[a]	–	–	–
		Power plant	<0.001[a]	0.006[a]	0.002[a]	–
		Shipping terminal	0.066	<0.001[a]	0.004[a]	<0.001[a]
	Spring	Boating channel	–	–	–	–
		Eelgrass	<0.001[a]	–	–	–
		Power plant	0.002[a]	0.311	–	–
		Shipping terminal	0.285	<0.001[a]	–	0.002[a]

[a] Indicates significant differences between sites.

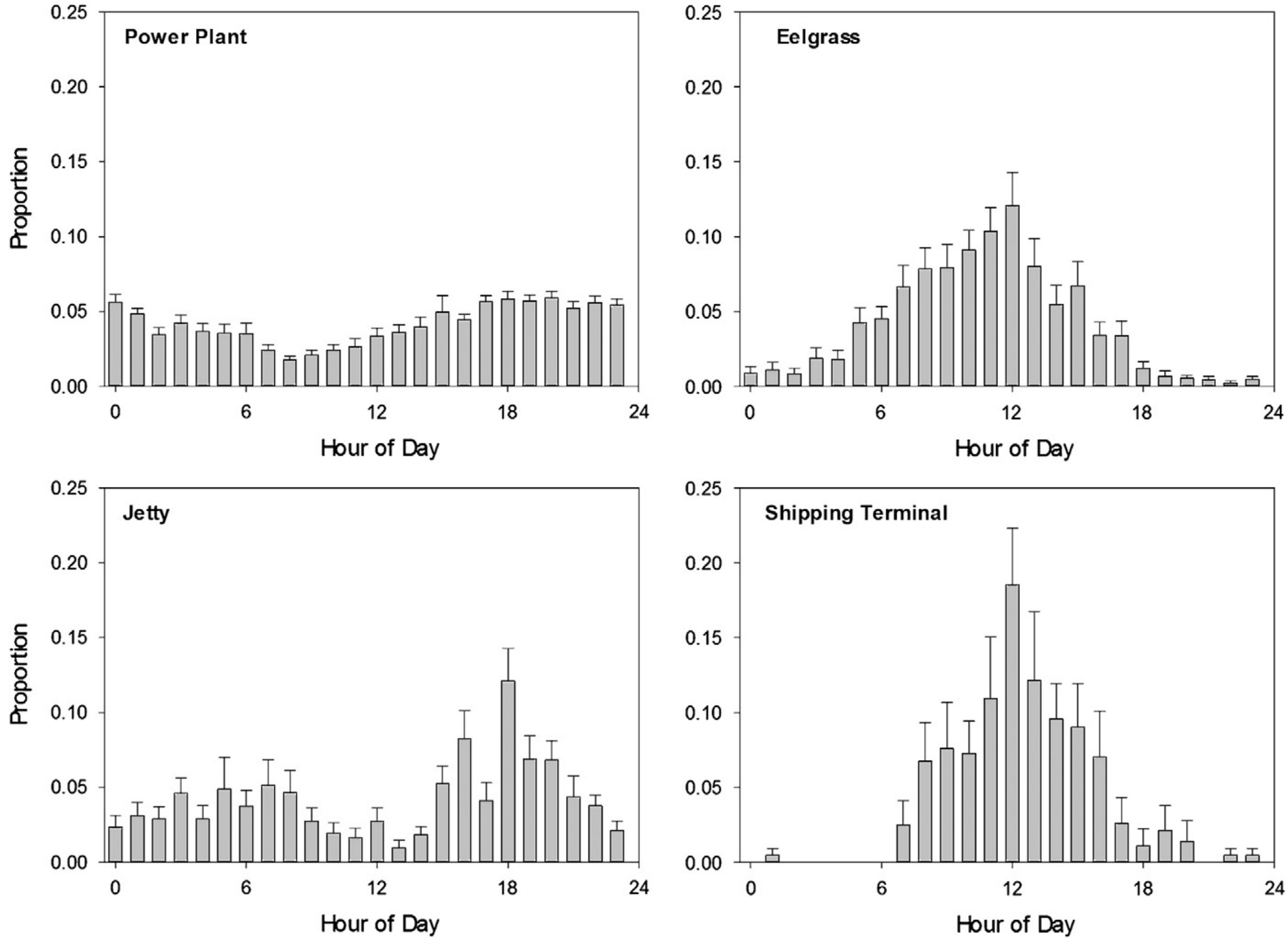


Fig. 3. Daily patterns of visitations by green turtles, *Chelonia mydas*, to automated telemetry monitoring areas in South San Diego Bay. Time of day (hour) is listed on the horizontal axis and proportion of total visits is listed on the vertical axis, presented as mean values ± standard error of individual turtles. No graphic was presented for the boating channel monitoring area due to insufficient data.

the number of hours the turtle was tracked. A generalized linear model was used to determine differences in movement behavior among time periods. The model was based on a gamma distribution with an inverse link function to account for positive skew in the raw data. Time periods were treated as repeated measures for individual turtles. Speed, MSI, and activity area were treated as dependent variables.

3. Results

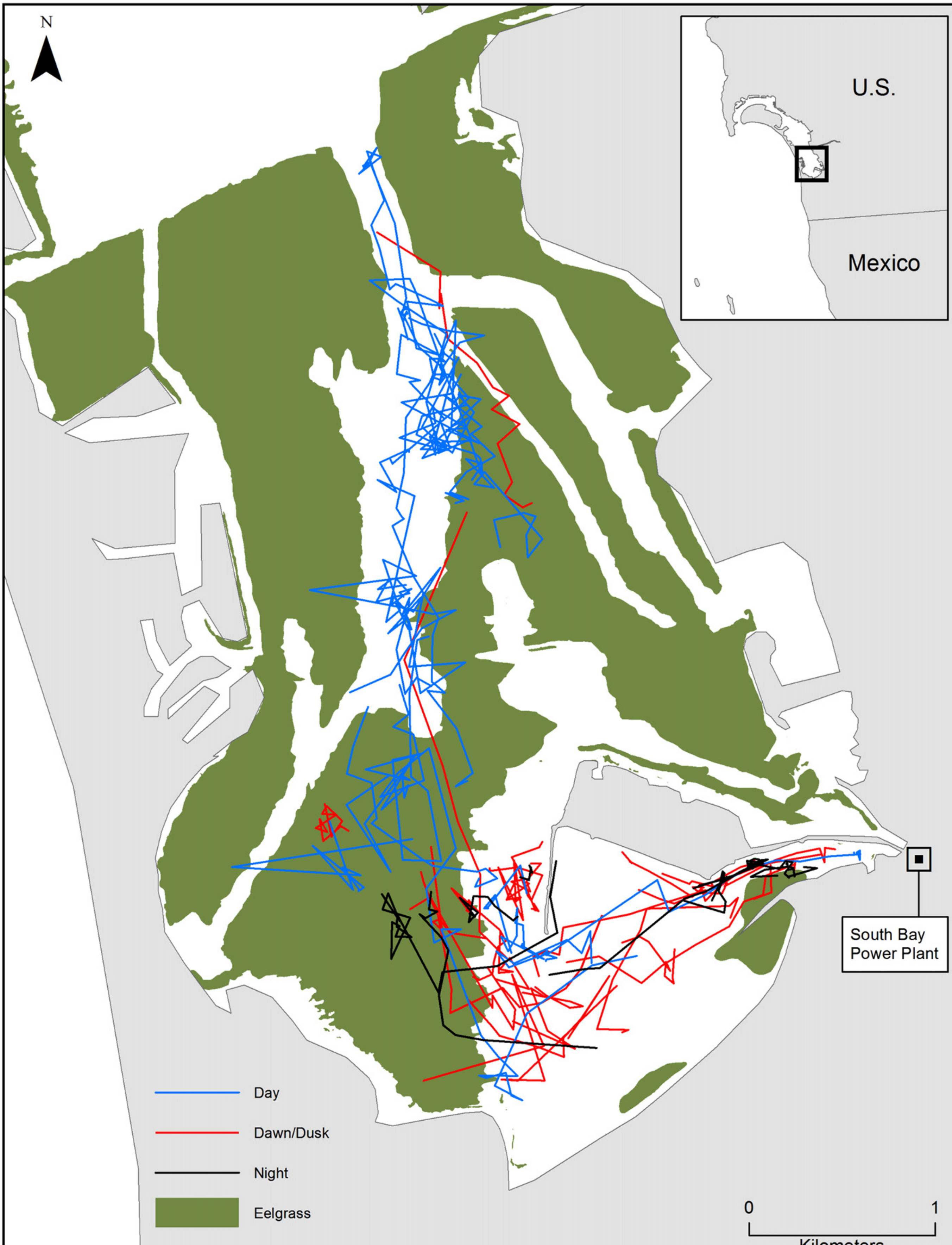
3.1. Automated telemetry

In Year 1, 18 turtles were captured and 14 were monitored by acoustic telemetry. Four turtles whose transmitters were dislodged shortly after attachment (<2 weeks) or were otherwise not detected by SURs were excluded from analysis. Significantly more visits per day (v d^{-1}) were recorded per turtle at the PP than at the jetty and ST monitoring areas (Table 1, Fig. 1; $p < 0.001$). Seasonal, within-area differences were also observed, as turtle visits to the power plant were significantly greater in the winter (1.305 ± 0.216 v d^{-1}) than in the spring (0.900 ± 0.267 v d^{-1}).

In Year 2, 10 turtles were captured (five were recaptures from Year 1) and eight (including four of five recaptures) were monitored by acoustic telemetry. Turtles monitored in Year 2 similarly visited the PP area significantly more than any other monitoring area during winter (Table 1, Fig. 1; $p < 0.01$). During spring, the PP and the eelgrass monitoring area were visited significantly more than other monitoring areas ($p < 0.05$), but were not significantly different from each other ($p = 0.31$). Seasonal, within-area differences were also observed. As in Year 1, turtles visited the power plant significantly less during the spring (0.609 ± 0.199 v d^{-1}) compared to the winter (1.194 ± 0.309 v d^{-1}). Additionally, turtle visits to the eelgrass area were significantly greater during the spring (0.922 ± 0.240 v d^{-1}) than in the winter (0.296 ± 0.064 v d^{-1}). No spring data were collected at the jetty in Year 2 due to equipment failure and loss and thus it was excluded from Year 2 analyses. Visits to monitoring areas and generalized linear model results are summarized in Fig. 1 and Table 1, respectively.

Visits to the PP were most frequent during the night and decreased during daytime, showing inflection points in the early morning and late afternoon (Fig. 3). Visits to eelgrass meadows were always greatest

Fig. 4. Colored lines indicate manual telemetry tracks of green turtles, *Chelonia mydas*, during dawn ($n = 12$), day ($n = 16$), dusk ($n = 12$), and night ($n = 10$). Dark green shading indicates cumulative annual distribution of eelgrass (*Zostera marina*) from 1994 to 2008.


N
U.S.
Mexico
South Bay
Power Plant
Day
Dawn/Dusk
Night
Eelgrass
0
1
Kilometers

during the day, where peaks occurred at midday. Turtles visited the jetty primarily during crepuscular periods. Visits to the ST, though rare in both study years, took place almost exclusively during the daytime. Insufficient visits were recorded to analyze diel variability of turtle visits to the BC area.

3.2. Manual telemetry

All tracked turtles stayed within the southern portion of SDB (Fig. 4). Turtles tracked during the daytime ranged across the entirety of South San Diego Bay, including areas of known eelgrass distribution (U.S. Department of the Navy et al., 2010) and along the effluent channel of the South Bay Power Plant. Significant differences were found among times of day (Table 2). The daytime movement of tracked turtles was characterized by localized activity areas (0.03 ± 0.01 km^2, Table 3) that were significantly smaller than areas used at dusk and dawn (with no significant difference between day and night (0.02 ± 0.01 km^2 h^{-1})). Tracked individuals swam faster during daytime hours (0.67 ± 0.07 km h^{-1}) than nighttime (0.38 ± 0.03 km h^{-1}). During the day, movements were significantly less linear (MSI $= 0.19 \pm 0.04$) than all other time periods. Turtles appeared to transition between daytime and nighttime activity areas during crepuscular periods, exhibiting high swimming speeds, higher linearity, and large activity areas. Turtles were observed to make their most linear movements at dawn (MSI $= 0.52 \pm 0.11$) and dusk (MSI $= 0.45 \pm 0.09$). Nighttime tracks were limited in range to the effluent channel and jetty extending west from the South Bay Power Plant and were frequently marked by long periods of inactivity interrupted by short, directed movements to a new location.

4. Discussion

Understanding the effects of human impacts on sea turtles and other marine vertebrates that inhabit the coastal zone is a topic of increasing management concern. Protected marine species may be affected by multiple threats from human activities because the geographic distribution of these activities is unlikely to be spatially or temporally uniform (Ross et al., 2011). This clustering of human impacts highlights the need for fine-scale tracking studies that identify an animal's primary use areas in the context of protective measures and anthropogenic stressors (Eckert et al., 1999; Schofield et al., 2007). Here we demonstrate the utility of automated acoustic telemetry as a valuable tool for collecting necessary data to evaluate changes in the habitat use of a mobile, marine organism. Our data indicated that during two years of tracking, green turtles in SDB showed fidelity to eelgrass habitat during the day and to the thermal effluent channel of a waterfront power plant at night. Turtles appeared to shuttle between these two activity areas (located approximately 3 km apart) in the early morning and late afternoon. The movements of all tracked turtles were confined within South SDB.

Daytime foraging has been reported extensively in green turtle literature (e.g., Bjorndal, 1980; McClellan and Read, 2009; Taquet et al., 2006) and has also been noted for other sea turtle species, including leatherback and hawksbill turtles (Fossette et al., 2010; van Dam and Diez, 1997). Turtles tracked in our study visited eelgrass meadows primarily during the day (Fig. 3) and are known to consume a mix of eelgrass and invertebrates in SDB (Lemons et al., 2011). Turtles manually tracked during the day exhibited non-linear, rapid swimming speeds, which is characteristic of foraging behavior (Bovet and Benhamou, 1991). The mean daytime swimming speeds of turtles tracked in our study (0.670 km h^{-1}) were similar to those reported for green turtles in Australia (0.679 km h^{-1}; Hazel, 2009) but greater than reported for green turtles in Baja California (0.390 km h^{-1}; Seminoff and Jones, 2006). The significant seasonal increase in visits to this area in spring months (Fig. 1) seems to suggest that turtles accessed foraging habitat more frequently as ambient water temperatures became warmer. In the winter, turtles could also be found near the power plant effluent channel during the day; this suggests that turtles may rest between diurnal foraging excursions, as has been reported for turtles in Florida (Mendonca, 1983) and the Caribbean (Blumenthal et al., 2010).

The use of the power plant effluent channel as a resting area was indicated by small activity areas and low swimming speeds, as well as because turtles rarely visited any other monitored areas during the night (Fig. 3). The mean night swimming speed of turtles (0.380 km h^{-1}) was comparable to those reported by Hazel et al. (2009); (0.279 km h^{-1}) and Seminoff and Jones (2006); (0.270 km h^{-1}). Our findings thus add to a growing body of evidence suggesting that green turtles not only rest at night, but that some individuals show fidelity to specific resting spots (Makowski et al., 2006; Mendonca, 1983; Taquet et al., 2006). Not all studies have found this trend, however, indicating a behavioral plasticity in green turtles that may depend on local environmental features such as the relative availability of resting habitat and its proximity to feeding areas (Hazel, 2009; Senko et al., 2010). Turtles visited the effluent channel more often during the winter, a behavior which has long been hypothesized to be associated with the power plant's thermal discharge (Stinson, 1984) due to green turtles' affinity for warm water (Spotila et al., 1997). Green turtles have also been reported near thermal effluents in Long Beach, CA (Lawson et al., 2011) and in Chile (Donoso and Dutton, 2000), and similar behaviors have been documented for Florida manatees (Laist and Reynolds, 2005; Reynolds and Wilcox, 1994). A common concern among these studies is the potential behavioral responses of thermally sensitive species to power plant retirement, many of which are slated for decommissioning as their technologies become obsolete. The South Bay Power Plant was permanently shut down on December 31, 2010, such that its decommissioning serves as a natural field experiment. Monitoring turtle behavior following power plant closure allows for an evaluation of the behavioral changes of a species in response to changing water temperatures and expected changes in human use of the waterfront. Turtles tracked in this study did not show notable changes in habitat use following decommissioning, although over time it is possible that changes in behavior may result from the loss of thermal effluent. The data collected in this study will therefore be a useful reference against which to compare turtle behavior in the years following power plant closure.

Though rare, turtles sporadically visited the Sweetwater Marine Terminal, a major shipping terminal at the northeastern edge of South SDB (Fig. 1). Turtle visitation to this area occurred almost exclusively during the day, when human activities are also higher (Fig. 3). The possible negative effects of vessel activity, including injury, mortality, and altered behavioral patterns on marine mammals such as whales, dolphins, and manatees are thought to be at least partially due to the amount of time spent at shallow depths or near the surface (Lusseau, 2006; Nowacek et al., 2004; Vanderlaan and Taggart, 2006). Green turtles foraging in shallow areas – water depths in south SDB are generally less than 5 m – have been reported to be similarly vulnerable to vessels, particularly those traveling at high speeds (Hazel et al., 2009). Vessel traffic is lower in South SDB than in the rest of the bay and posted signs restrict boaters to speeds of 5 knots as a precaution against turtle strikes (U.S. Department of the Navy et al., 2010). Nonetheless, vessel strikes have been reported for green turtles in SDB (NMFS and USFWS, 1998) and sub-lethal propeller scarring and tissue damage have been observed for some captured individuals (Eguchi et al., 2010). It is not clear if turtles sustained these injuries in South SDB, in higher traffic portions of SDB, or outside of the bay. Numerous studies present evidence for conservation via the precautionary principle precisely because of the scientific uncertainty associated with quantifying the cumulative negative impacts of numerous, interacting anthropogenic stressors (Ewers and Didham, 2006; Ross et al., 2011; Thompson et al., 2000). Although direct observation of boat strikes is unlikely, an invocation of the precautionary principle for conservation would be grounds for enforcement of boat speeds within the protected regions of SDB.

Table 2
Manual telemetry. Summary of p-values of generalized linear model post-hoc pairwise comparisons of speed (km h^{-1}), movement straightness index, and activity areas (km^2 h^{-1}) among time periods (dawn, day, dusk, and night).

Movement metric	Season	Dawn	Day	Dusk
Speed	Dawn	–	–	–
	Day	0.199	–	–
	Dusk	0.068	0.516	–
	Night	0.154	<0.001[a]	<0.001[a]
Movement straightness index	Dawn	–	–	–
	Day	0.015[a]	–	–
	Dusk	0.663	0.016[a]	–
	Night	0.599	0.041[a]	0.883
Activity area	Dawn	–	–	–
	Day	0.166	–	–
	Dusk	0.787	0.070	–
	Night	0.023[a]	0.226	0.017[a]

[a] Indicates significant differences between time periods.

5. Conclusions

The delineation and enforcement of protected areas continue to represent a challenge to the conservation of sea turtles and marine species in coastal environments (Gaos et al., 2012; Schofield et al., 2010; Wilson et al., 2004). Human activities in coastal areas, because they can undergo periods of rapid change and development, will affect existing and future protective measures (Burgman et al., 2005). Effective conservation of green turtles in SDB and other impacted coastal foraging grounds depends upon the protection of priority habitat, such as eelgrass meadows, as well as the limitation of boating activity or monitoring of boater behavior in core activity areas. Characterizing turtle use areas is an ongoing process, and continued monitoring and modeling of how turtle movements relate to in-water threats are needed. The daily and seasonal patterns of movement and site presence discussed in this study represent an assessment of co-occurrence of turtles and human activities in SDB. We also demonstrate that a combination of manual and automated acoustic telemetry accommodates the cost-effective collection of fine-scale information of animal movements as well as the long-term monitoring of essential habitat — a high priority for the conservation of threatened marine vertebrates in dynamic, human-dominated environments.

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Table 3
Manual telemetry. Summary of average speed (km h^{-1}), movement straightness index (MSI), and activity areas (km^2 h^{-1}) for green turtles tracked during dawn, day, dusk, and night. Means ± standard errors are reported.

Time	Number of tracks	Average speed	MSI	Activity area
Dawn	12	0.51 ± 0.08	0.52 ± 0.11	0.06 ± 0.02
Day	16	0.67 ± 0.07	0.19 ± 0.04	0.03 ± 0.01
Dusk	12	0.77 ± 0.10	0.45 ± 0.09	0.07 ± 0.02
Night	10	0.38 ± 0.03	0.43 ± 0.10	0.02 ± 0.01

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