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# Loggerhead sea turtle abundance at a foraging hotspot in the eastern Pacific Ocean: implications for at-sea conservation

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ABSTRACT: The Pacific Coast of the Baja California Peninsula (BCP), Mexico, is a hotspot for foraging loggerhead turtles *Caretta caretta* originating from nesting beaches in Japan. The BCP region is also known for anthropogenic sea turtle mortality that numbers thousands of turtles annually. To put the conservation implications of this mortality into biological context, we conducted aerial surveys to determine the distribution and abundance of loggerhead turtles in the Gulf of Ulloa, along the BCP Pacific Coast. Each year from 2005 to 2007, we surveyed ca. 3700 km of transect lines, including areas up to 140 km offshore. During these surveys, we detected loggerhead turtles at the water's surface on 755 occasions (total of 785 loggerheads in groups of up to 7 turtles). We applied standard line-transect methods to estimate sea turtle abundance for survey data collected during good to excellent sighting conditions, which included 447 loggerhead sightings during ~6400 km of survey effort. We derived the proportion of time that loggerheads were at the surface and visible to surveyors based on *in situ* dive data. The mean annual abundance of 43 226 loggerhead turtles (CV = 0.51, 95% CI range = 15 017 to 100 444) represents the first abundance estimate for foraging North Pacific loggerheads based on robust analytical approaches. Our density estimate confirms the importance of the BCP as a major foraging area for loggerhead turtles in the North Pacific. In the context of annual mortality estimates of loggerheads near BCP, these results suggest that up to 11% of the region's loggerhead population may perish each year due to anthropogenic and/or natural threats. We calculate that up to 50% of the loggerhead turtles residing in the BCP region in any given year will die within 15 yr if current mortality rates continue. This underscores the urgent need to minimize anthropogenic and natural mortality of local loggerheads.

KEY WORDS: Baja California Peninsula · Mexico · *Caretta caretta* · Distance sampling · Line-transect analysis · $g(0)$ · Abundance · Density



## INTRODUCTION

Understanding the abundance and distribution of threatened species is crucial for effective conservation and management (Hamann et al. 2010, NRC 2010, NMFS 2013). Knowledge about these aspects is useful in gauging population-level impacts of local anthropogenic threats such as directed harvest and fisheries bycatch mortality (Koch et al. 2006) as well as natural threats such as biointoxication (Buss & Bengis 2012). This information can also help pinpoint priority areas for conservation (Sobel & Dalgren 2004, Jones 2011). However, estimating population size and distribution for threatened species is often hindered by the inability to consistently sight animals over broad spatial regions. This is particularly true of

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marine animals, including sea turtles, that live in oceanic and neritic habitats where they spend vast periods submerged and thus 'unavailable' during survey monitoring efforts.

The North Pacific loggerhead sea turtle *Caretta caretta* underwent steep declines in the 20th century and was recently uplisted to 'endangered' status under the US Endangered Species Act (NMFS & USFWS 2011). Despite nesting exclusively in Japan, these loggerheads undertake juvenile developmental migrations that can last over 20 yr and span the entire North Pacific Basin. To date, juvenile foraging areas have been identified in the Central North Pacific (Polovina et al. 2006, Abecassis et al. 2013) and off Mexico's Baja California Peninsula (BCP), where they are subject to high anthropogenic mortality, an issue that is now of international conservation and diplomatic concern (e.g. Peckham et al. 2007, Peckham & Maldonado Díaz 2012, Koch et al. 2013, NOAA-Fisheries 2013). The loggerheads observed at the BCP foraging hotspot are primarily large juveniles of high reproductive value that are thought to reside in the area for years and possibly decades before returning to Japan as adults to reproduce (Nichols et al. 2000, Peckham et al. 2008, Ishihara et al. 2011). Evaluating the conservation implications of the mortality observed at BCP is thus of urgent importance.

Peckham et al. (2008) encountered 2385 loggerhead carcasses during stranding surveys along a 44.3 km index beach in BCP from 2003 to 2007, representing apparently the highest sustained stranding rate documented worldwide for any sea turtle species. They estimated that ~2200 loggerhead turtles (95% CI = 1516–2951) died each year in the region due to bycatch in bottom-set gillnet and longline fisheries targeting halibut *Paralichthys californicus*, grouper *Mycteroperca* sp., and assorted shark species. Hundreds of loggerheads also die each year near BCP due to direct human consumption (Koch et al. 2006, Mancini & Koch 2009), and an unknown level of loggerhead mortality may also be related to harmful algal blooms (Mendoza-Salgado et al. 2003), although more information is needed to substantiate this possibility.

The bycatch problem at the BCP hotspot became broadly known in the late 1990s, yet while community-based conservation efforts have resulted in dramatic decreases in direct harvest in some communities and reductions in bycatch by some fleets (Peckham & Maldonado Díaz 2012, Peckham et al. 2012), loggerhead mortality continues at extreme rates. The Mexican fisheries and wildlife management agencies documented 841 loggerhead turtles stranded along the 43 km Playa San Lazaro Beach from 2011 to 2012 (PROFEPA 2012), which coincided with extraordinarily high bycatch rates averaging 2 loggerheads caught per 100 m of net per 24 h (INAPESCA 2012). This ongoing mass mortality prompted the US Government to cite Mexico in January 2013 under the Magnusson-Stevens Reauthorization Act for Mexico's inadequate management of sea turtle bycatch in its coastal fisheries at the Gulf of Ulloa (NOAA-Fisheries 2013).

These high levels of mortality are apparently unprecedented for an endangered sea turtle population, and for this reason community-based bycatch mitigation efforts were initiated in 2003 (Peckham & Maldonado Díaz 2012). However, an essential management need is to determine abundance at the hotspot to evaluate the consequences of the high mortality occurring there; observed beach strandings of dead loggerhead turtles must be evaluated against the total abundance in the area.

Abundance of loggerhead turtles in the area was estimated at ~15 000 individuals by Ramirez Cruz et al. (1991) based on shipboard surveys. While this figure suggests that thousands of loggerheads are present in the area at any given time, the estimate of Ramirez-Cruz et al. (1991) was based on surveys of only a small portion of the BCP region (6600 $km^2$ versus ca. 66 000 $km^2$ in our study), and they did not account for turtles that were submerged during survey efforts. Clearly, newer information based on more robust survey techniques is needed on loggerhead abundance in the area.

Aerial surveys are useful for estimating at-sea density and abundance of sea turtles because these animals need to surface for breathing. This tool has been used to estimate parameters of foraging populations of sea turtles in several areas worldwide (e.g. Epperly et al. 1995, Braun & Epperly 1996, McDaniel et al. 2000, Benson et al. 2007, Lauriano et al. 2011). However, while aerial surveys are useful for characterizing density and abundance of sea turtles at sea, the precision of such estimates can be improved by incorporating the proportion of time that animals are at the surface and are available for counting, termed sightability and denoted as $g(0)$ (Thomas et al. 2009, 2010). For marine species, independent data on diving behavior and correction factors such as $g(0)$ define the presence of surface-visible fractions of the population. Without this information, aerial survey efforts are only able to count the number of turtles at the surface rather than estimate total abundance.

We conducted 3 years (2005–2007) of systematic aerial surveys for loggerhead turtles in the Gulf of

Ulloa along the west coast of BCP. We combined line-transect density estimates with a correction factor derived from *in situ* dive studies to account for submerged animals (Peckham et al. 2012). We provide the first robust estimates of loggerhead density and abundance in the BCP region and define the high-use areas where loggerheads were present each year. We also evaluated the magnitude of annual mortality estimates for loggerheads near BCP based on beach surveys relative to loggerhead abundance in the area. Taken together, these aerial surveys, population estimates, and the bycatch summary are used to examine regional-level impacts to loggerhead turtles in the BCP.

## MATERIALS AND METHODS

### Study area

This study was conducted in the Gulf of Ulloa along the Pacific coast of Baja California Sur, Mexico (Fig. 1). The Gulf of Ulloa is a semi-enclosed bight located at the southern extent of the California Current Large Marine Ecosystem. It is bounded in the north by the Vizcaino Peninsula (27° 50′ N, 115° 05′ W) and in the south by Bahía Magdalena (24° 30′ N, 112° 00′ W; Fig. 1). This region is influenced by seasonal upwelling that is strongest from April to June and gradually relaxes between July and October (Zaytsev et al. 2003). The region is highly productive (Wingfield et al. 2011) and is a hotspot for a variety of ecologically and economically important species, including sea turtles, seabirds, sharks, tuna, and whales (Etnoyer et al. 2004, Peckham et al. 2007, Schaefer et al. 2007, Wolf et al. 2009). The seasonal presence of large blooms of pelagic red crabs *Pleuroncodes planipes* (Aurioles-Gamboa 1992), constitutes a primary diet component for loggerhead sea turtles (Ramirez-Cruz et al. 1991). Artisanal fishing is widespread, with fleets targeting a variety of shark and bony fish species (Ramírez-Rodríguez & Ojeda-Ruíz 2012). Among the most numerous fleets are those targeting California halibut *Paralichthys californicus* and grouper *Mycteroperca* spp. with bottom-set gillnets and longlines (Peckham et al. 2007).

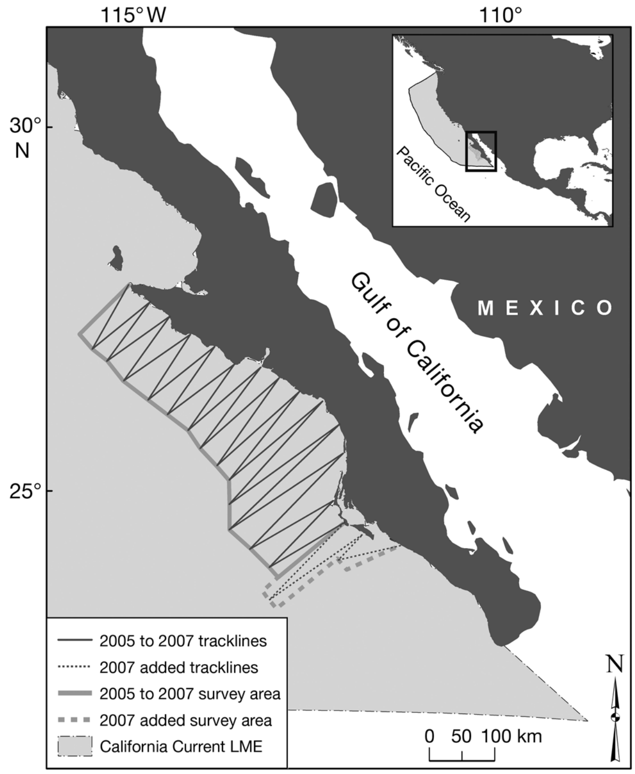


Fig. 1. Locations of survey transect lines in the Baja California, Mexico, study area. Shaded area indicates waters within the California Current Large Marine Ecosystem (LME)

### Aerial survey methods

Aerial line-transect surveys for loggerhead turtles were conducted between 8 September and 3 October of 2005 to 2007 (Table 1). This survey period corresponds with warm surface waters and peak logger-

Table 1. Summary of turtle sightings from 2005 to 2007 under all survey conditions. Surveys included ca. 3700 km of track line each (see Fig. 1). CC: loggerhead turtle *Caretta caretta*; LO: olive ridley turtle *Lepidochelys olivacea*; CM: green turtle *Chelonia mydas*; DC: leatherback turtle *Dermochelys coraicea*; UH: unidentified hardshell turtle. Fishing boats include open-hull skiffs ('pangas'), shrimp trawlers, and industrial long-line and purse-seine vessels

| Survey year | Start date | End date | CC | LO | CM | DC | UH | Fishing boats |
|---|---|---|---|---|---|---|---|---|
| 2005 | 8 Sep | 30 Sep | 246 | 37 | 10 | 1 | 15 | 34 |
| 2006 | 24 Sep | 3 Oct | 309 | 34 | 3 | 0 | 32 | 20 |
| 2007 | 14 Sep | 27 Sep | 230 | 79 | 25 | 0 | 48 | 25 |

head presence in the area; it is also a period that typically has calm survey conditions, which is vital for aerial surveys. The total study area encompassed 66 471 km$^2$, and was surveyed along a series of 26 transect lines from 100 to 220 km in length, totaling approximately 3700 km of trackline (Fig. 1). Transects were arranged in a saw-tooth pattern between the coast and the 92 m (50 fathom) isobath; the endpoint of the longest transect line was 140 km from shore. Our survey track lines were arranged to overlap with the highest density of turtles based on previous shipboard sighting information (NMFS unpubl. data) and satellite-tracked loggerhead movement data (Peckham et al. 2007). Four additional transect lines south of the main study area were surveyed in 2007, encompassing an additional 7843 km$^2$ of survey area (Fig. 1).

The survey aircraft was a de Havilland DHC 6 Twin Otter turbo prop operated by the National Oceanic and Atmospheric Administration (NOAA). This platform is a 2-engine, high-wing survey aircraft with 2 bubble windows for lateral viewing and a belly window for downward viewing; the aircraft can safely fly at low altitude and slow airspeeds. Surveys were conducted at an altitude of 152 m (500 ft) and airspeeds of 165 to 175 km h$^{-1}$ (90–95 knots). Our survey crew consisted of 2 pilots, 3 on-effort observers (left, right, and belly), 1 data recorder, and 1 off-effort (resting) observer position. The observer team systematically rotated through on- and off-effort positions to minimize fatigue. Sightings were verbally reported to a data recorder who entered sighting and environmental information into a laptop computer receiving real-time GPS position and flight altitude information. Observers were trained in loggerhead identification techniques each year. Species identification was based on surface behavior, body shape, head size, and color (loggerheads are bright orange and sharply contrast with the deep blue color of local surface waters). Loggerhead turtles were easily distinguished from olive ridley turtles *Lepidochelys olivacea* and green turtles *Chelonia mydas*, the 2 other species that occur in the study area though at much lower density.

The survey methodology for this study follows protocols established in previous aerial surveys (Forney et al. 1991, 1995, Forney 1999, Benson et al. 2007, Carretta et al. 2009). When turtles and other animals (e.g. marine mammals, sharks), were sighted, observers measured the declination angle to the animals abeam of the aircraft using hand-held clinometers (Model PM-5/360, Suunto). Declination angles were converted during analysis to perpendicular sighting distances, based on the altitude of the aircraft. Sighting information and environmental conditions, including Beaufort sea state, % cloud cover, and horizontal sun position (to measure glare direction), were recorded and updated throughout the survey, using a laptop computer connected to the aircraft's GPS navigation system. We also recorded the presence of artisanal and industrial fishing vessels such as open skiffs, shrimp trawlers, long-liners, and purse seiners.

### Line-transect analysis

Transect data were analyzed in the program Distance 6.0 (Thomas et al. 2009), which was used to estimate turtle density ($D$) and abundance ($N$). Only transect data collected under good to excellent survey conditions (Beaufort sea state ≤3 and belly observation conditions of 'good' or 'excellent') were used to estimate turtle density and abundance. As whitecaps greatly reduce the probability of detecting sea turtles from the aircraft, we did not use Beaufort 4 or higher data in our analysis. However, we did use Beaufort 3 data, as their inclusion was necessary to achieve representative spatial coverage of the entire study area, because relatively little survey effort in the northern portion of the study area was collected in Beaufort 0 through 2 sea states. The detection function, $f(x)$, was estimated by pooling all sightings from transect segments meeting these environmental criteria, rather than estimating separate detection functions for each environmental category or modeling sea state and glare as covariates. We also evaluated the pooling robustness of this strategy by estimating density and abundance for only line transect segments surveyed during Beaufort 0 through 2 conditions (see 'Results'). Generally, detection functions are considered 'pooling robust' if data can be aggregated over multiple environmental factors and still provide reasonable estimates of density (Buckland et al. 1993). Half-normal, uniform, and hazard-rate models with simple cosine adjustment terms were fit to the perpendicular sighting distance data to estimate $f(x)$ and the effective strip width (ESW). The ESW is that perpendicular distance from the transect line at which the number of objects detected beyond this distance equals the number missed within the same distance (Thomas et al. 2009, 2010). Perpendicular sighting distances were right-truncated at 253 m (which eliminated the largest 5% of perpendicular distances) to avoid fitting extreme values in the tail of the distribution. The model fit with the lowest Akaike's Information Criterion (AIC) was selected by the program Distance to estimate turtle density.

Turtle density ($\hat{D}$) in year $y$ was estimated as:

$$\hat{D}_y = \frac{n_y \cdot f(0) \cdot S_y}{2 \cdot L_y \cdot g(0)} \quad (1)$$

where

$n_y$ = number of turtle sightings in year $y$,

$f(0)$ = probability density function (km$^{-1}$) evaluated at 0 perpendicular distance,

$S_y$ = mean group size of turtle groups in year $y$,

$L_y$ = length of transect line (in km) surveyed in year $y$,

$g(0)$ = probability of detecting a turtle on the transect line.

Values for $g(0)$ used in this analysis are based on dive data from loggerheads equipped with video-time-depth recorders (Peckham et al. 2012) and *a priori* estimates of depths at which loggerheads are detectable on the transect line during calm (Beaufort 0–2) and moderate (Beaufort 3) sea states. To determine the proportion of time spent within sightable depths, data from 9 loggerhead turtles were used to create cumulative density distributions and then averaged together to plot inter-individual variation in sightability at each depth increment (Peckham et al. 2012). Dive data were collected during warm-water seasons (July and August, 2002 to 2004) in the center of our aerial survey study area. These data were collected during years preceding our aerial surveys, but we conclude that the spatial overlap and similarity in water temperatures makes them suitable for determining $g(0)$ in this study. Dive data were censored so as to eliminate the first half-hour of deployment from data analysis to account for capture stress during these short-term deployments (Thomson & Heithaus 2014). Peckham et al. (2012) found that loggerheads spent 13% of the time at the surface and 39% of the time within 2 m of the surface, with no significant diel variation in these values. In calm sea states, we assumed that loggerhead turtles could be detected immediately below the aircraft to a maximum depth of 2 m (corresponding $g(0)$ = 0.390). In moderate sea states characterized by occasional whitecaps (Beaufort 3), this depth is thought to be only 1 m (corresponding $g(0)$ = 0.308). Benson et al. (2007) reported that small, light-colored Secchi discs were visible to aerial observers at a maximum depth of 1 m in central California waters under such Beaufort conditions; however, we expect that this depth would increase in the clearer sub-tropical waters where our surveys were conducted. Our survey effort represents a mix of calm and moderate sea states, and thus the maximum depth of detectability is somewhere between 1 m and 2 m. We calculated a weighted maximum depth of detectability of 1.57 m from our survey effort data, based on the ratio of kilometers surveyed in calm (Beaufort 0–2) and moderate (Beaufort 3) sea states. The time-at-depth data from Peckham et al. (2012) indicated that loggerheads spent 35.5% of their time within 1.57 m of the surface (SD = 0.177). Our estimate of $g(0)$ for the surveys was therefore 0.355 (SE = 0.177; CV = 0.5). This estimate of $g(0)$ addresses only availability bias (the turtle is too deep to be seen by observers) and not perception bias (turtle is visible, but the observer fails to see it). For this reason, our estimate of $g(0)$ may be positively biased, which would result in underestimation of turtle density by an unknown amount.

Total abundance ($\hat{N}$) in year $y$ was estimated as:

$$\hat{N}_y = \sum \hat{D}_y \cdot A \quad (2)$$

where $\hat{D}_y$ is estimated turtle density in year $y$ and $A$ is the size of the study area in km$^2$. Pooled density and abundance for the 3 yr period 2005 to 2007 were calculated as the mean density and abundance for 3 annual surveys, weighted by the amount of survey effort in each year (Thomas et al. 2009). Encounter rate ($n/L$) variance was estimated empirically within Distance 6.0 from the individual survey effort segments. The CV of the abundance estimate in year $y$ was calculated as the square root of the sum of the squared CVs of the parameters group size, encounter rate, detection function, and trackline sighting probability:

$$\mathrm{CV}(\hat{N}_y) = \sqrt{\mathrm{CV}^2(S_y) + \mathrm{CV}^2\left(\frac{n_y}{L_y}\right) + \mathrm{CV}^2(f(0)) + \mathrm{CV}^2(g(0))} \quad (3)$$

The variance and CV of the pooled 2005–2007 abundance estimate was calculated as:

$$\mathrm{Var}(\hat{N}_{\mathrm{pooled}}) = \sum_{y=2005}^{2007} (\mathrm{CV}(N_y) \cdot N_y)^2 \quad (4)$$

and

$$\mathrm{CV}(\hat{N}_{\mathrm{pooled}}) = \frac{\sqrt{\mathrm{Var}(\hat{N}_{\mathrm{pooled}})}}{\hat{N}_{\mathrm{pooled}}} \quad (5)$$

We estimated 95% confidence intervals for abundance estimates by simulating a log-normal distribution for each point estimate and associated CV and using the 2.5th and 97.5th percentiles, respectively, as lower and upper limits.

### Distribution mapping

We estimated the distribution of loggerhead turtles using fixed kernel density estimation (KDE; Silverman 1986, Worton 1989) in the geospatial modeling environment 0.6.2 for ArcMap version 10.1 geographic information system software (Environmental Research Systems Institute). Kernel distributional ranges were calculated with a Gaussian (bivariate normal) smoothing parameter with the 'Plug-in' algorithm and mapped using the North American Alvers Equal Area Conic coordinate system. A 95% KDE utilization distribution (UD) was used to estimate the overall range of loggerheads, whereas a 50% KDE UD was used to establish the core areas of loggerhead presence each year (Worton 1989). We also mapped loggerhead distribution using 9 KDE auto-selected isopleths to provide a more resolved view of loggerhead density throughout the region. Each sighting was treated as an independent position.

## RESULTS

### Survey summary

From 2005 to 2007, 6441.6 km of transect line were surveyed in Beaufort sea states 1 to 3 and belly observer conditions of 'good' to 'excellent.' Average weather conditions were different each year, and strongly influenced the level of survey coverage completed during optimal sea states (Beaufort 1–3), which ranged from 1577.3 km (2006) to 3022.7 km (2005; Table 2). Loggerhead turtle encounter rates were highest during Beaufort 1 conditions (9.9 sightings per 100 km), and decreased with each worsening sea state category; the loggerhead encounter rate during Beaufort 3 was approximately half (4.1 sightings per 100 km) of that in Beaufort 1 and 2 conditions (Table 2).

Table 2. Number of kilometers surveyed by Beaufort sea state, number of loggerhead sea turtle *Caretta caretta* sightings, and encounter rates by sea state category. Values represent survey effort during which the aircraft belly-window observer conditions were 'excellent' or 'good'

| Year | Beaufort 1 | Beaufort 2 | Beaufort 3 |
|---|---|---|---|
| All years | 1561.3 | 2110.5 | 2769.8 |
| 2005 | 701.6 | 1042.6 | 1278.5 |
| 2006 | 291.4 | 465.1 | 820.8 |
| 2007 | 568.2 | 602.6 | 670.4 |
| No. of sightings | 155.0 | 178.0 | 114.0 |
| Sightings 100 km$^{-1}$ | 9.9 | 8.4 | 4.1 |

During the 3 yr of survey effort, we encountered loggerhead turtles at the water's surface on 755 occasions (total of 785 loggerheads, encountered in groups of up to 7). The number of loggerheads sighted each year ranged from 230 to 309 (Table 1). We also sighted 150 olive ridley turtles, 38 green turtles, 1 leatherback turtle *Dermochelys coriacea*, and 95 sea turtles of unknown species over the 3 yr of the study. The abundance estimates of these other sea turtle species will be reported elsewhere and are not included in the present analyses. A total of 79 active fishing vessels were seen during surveys, including open-hull skiffs, shrimp trawlers, industrial long-liners, and purse-seiners (Table 1).

Because our abundance analyses only included loggerheads sighted during good to excellent viewing conditions, our analyses effectively filtered out survey effort and sightings that were made during high sun glare and cloud cover, both of which erode an observer's ability to sight turtles. Including only survey effort conducted during good to excellent sighting conditions resulted in a total of 6441.6 km of survey effort and 447 loggerhead sightings (Table 2), from which we estimated the detection function.

### Loggerhead density and abundance

The half-normal model was selected because it provided the best fit to the perpendicular distance data over competing uniform and hazard rate models (Table 3). Based on these analyses, we calculated $f(0)$ of 0.00634 m$^{-1}$, and a mean ESW of 157.6 m (CV = 0.04) (Fig. 2). Over the 3 yr of the survey, the number of loggerhead sighting events during Beaufort 1–3 sea states ranged from 117 (2007) to 205 (2005), with a mean group size of 1.05 loggerheads per sighting event (SE = 0.0126; range = 1 to 7 turtles per sighting; 96% of sightings were single turtles). Uncorrected densities ranged from 0.205 to 0.228 loggerheads

Table 3. Akaike's Information criterion (AIC) values for competing detection function models considered in this analysis

| Model | AIC | $\Delta_{AIC}$ |
|---|---|---|
| Half-normal | 1648.4 | 0 |
| Hazard rate | 1652.8 | 4.4 |
| Uniform | 1739.6 | 91.2 |

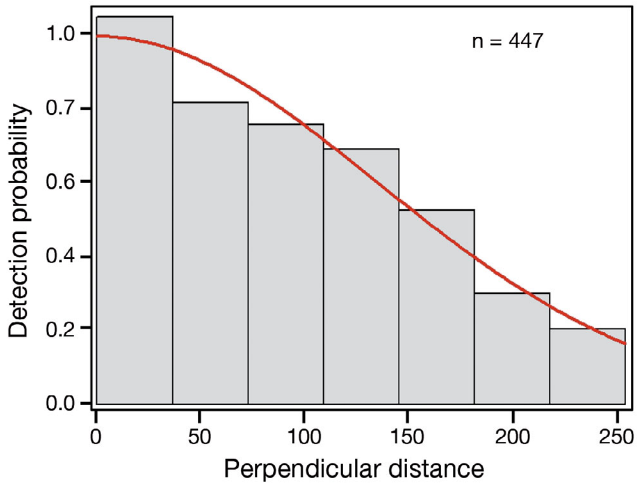


Fig. 2. Perpendicular sighting distances (m) and half-normal detection model fit. The resulting effective half-strip width (ESW) was calculated to be 157.6 m ($f(0)$ = 0.00634 m$^{-1}$); n: number of loggerhead sea turtle *Caretta caretta* sightings

km$^{-2}$ and uncorrected abundance (i.e. excluding turtles too deep to be detected) ranged from 13 627 to 17 643 loggerhead turtles. Correcting estimates for the amount of time turtles were diving ($g(0) < 1$) based on Peckham et al. (2012) increased raw density estimates by a factor of 2.8, which represents the inverse value of $g(0)$ , with associated CV of 0.5. Corrected estimates of loggerhead density ranged from 0.577 to 0.747 (mean = 0.650) loggerheads km$^{-2}$. Corrected estimates of total abundance ranged from 38 396 loggerheads (CV = 0.53) in 2007 to 49 712 (CV = 0.57) in 2006. The best estimate of mean loggerhead annual turtle abundance is 43 226 (CV = 0.51, 95 % CI range = 15 017–100 444; Table 4).

Based on analysis outputs from Distance 6.0, the largest source of uncertainty in our abundance estimates resulted from our $g(0)$ correction for diving, which contributed between 92 and 96 % of the variance in both the annual and pooled estimates. By comparison, encounter rate variance contributed approximately 5 % of the overall variance, while the parameters for group size and detection function contributed negligible amounts. With respect to the data used to derive our estimates, excluding Beaufort 3 data from our analysis would have resulted in density estimates approximately 9 % higher than we report here. This suggests that pooling of Beaufort 0 through 3 data did not result in large biases in density estimation, with the added benefit of gaining uniform spatial coverage of the study area by including Beaufort 3 data while providing a more conservative estimate of total abundance.

## Loggerhead distribution

A primary goal of our survey design was to encompass the entire loggerhead range in the Gulf of Ulloa. Based on the latitudinal distribution in sightings (Fig. 3a) it is apparent that our survey captured the entire north–south extent of loggerhead distribution. The highest densities of loggerhead sightings were found in the center of our survey area, and the northern and southern boundaries of the study area included the 'tails' of loggerhead distribution. Similarly, the longitudinal boundaries of the survey area encompassed the primary west–east distribution of loggerheads (Fig. 3b).

Kernel density analyses give a mean annual range of 55 468.5 km$^2$ (95 % UD range = 49 629.7–64 990.9 km$^2$; Table 5) and a mean annual core area of 5098.1 km$^2$ (50 % UD range = 3742.9–5931.8 km$^2$; Table 5). The locations of high-density areas shifted from year to year (Fig. 4). Whereas the core area of loggerheads in 2005 was found in the southern portions of the Gulf of Ulloa, in 2006 it was more dispersed and extended farther north towards Punta Eugenia. The broadest distribution

Table 4. Estimated density and abundance of loggerhead sea turtles *Caretta caretta*. Uncorrected density estimates use the assumption that turtles are always at the surface and are detected on the transect line: $g(0)$ = 1. Corrected density and abundance are calculated using $g(0)$ = 0.355, $f(0)$ = 0.00634 m$^{-1}$, and ESW = 157.6 m as discussed in the 'Results'

| Year | n sightings | Km surveyed | Mean group size | Uncorrected density | Uncorrected abundance (CV) | Corrected density | Corrected abundance (CV) | 95 % confidence interval |
|---|---|---|---|---|---|---|---|---|
| 2005 | 205 | 3041 | 1.07 | 0.228 | 15185 (0.20) | 0.643 | 42786 (0.54) | 13614–100989 |
| 2006 | 125 | 1578 | 1.06 | 0.265 | 17643 (0.27) | 0.747 | 49712 (0.57) | 15508–128657 |
| 2007 | 117 | 1841 | 1.02 | 0.205 | 13627 (0.18) | 0.577 | 38396 (0.53) | 12837–88302 |
| All years | 447[a] | 6460 | 1.05 | 0.231 | 15341 (0.08) | 0.650 | 43226 (0.51) | 15017–100444 |

[a]After data filtration for best-viewing conditions

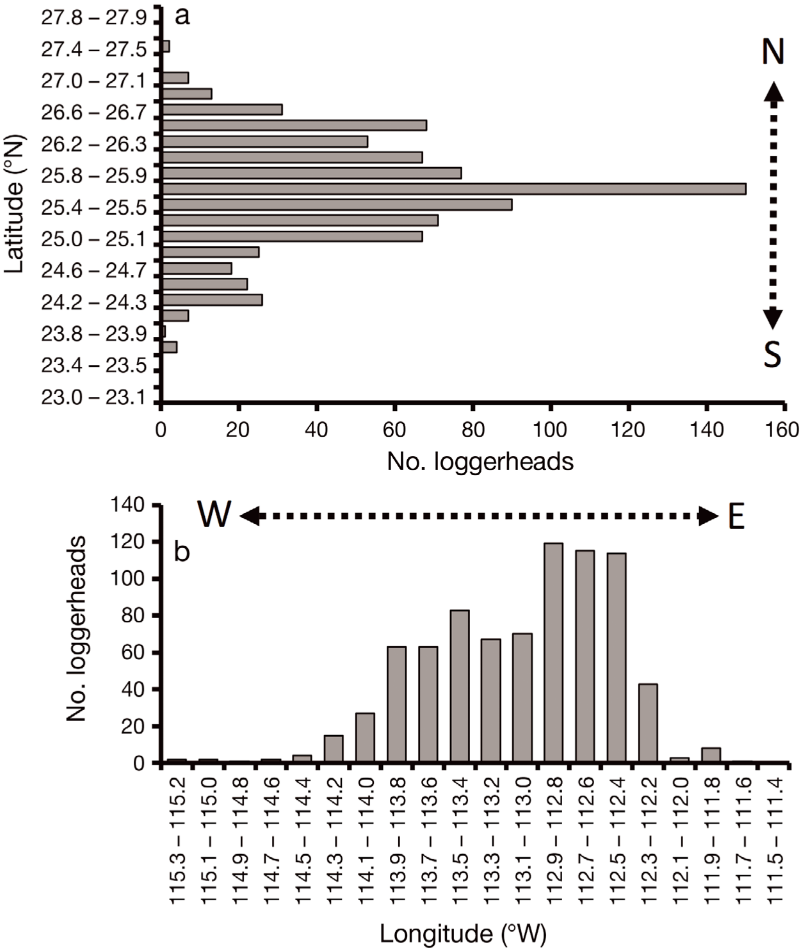


Fig. 3. Number of loggerhead sea turtle *Caretta caretta* sightings organized by (a) latitude and (b) longitude

Table 5. Total range area (km$^2$) of loggerhead distribution (95 % kernel density estimator, KDE, area) and core areas of activity (50 % KDE area). Determined using KDE with Jenks optimization

| | 95 % KDE area (km$^2$) | 50 % KDE area (km$^2$) |
|---|---|---|
| 2005 | 49629.7 | 3742.9 |
| 2006 | 51785.0 | 5619.6 |
| 2007 | 64990.9 | 5931.8 |
| Mean | 55468.5 | 5098.1 |
| SE | 4801.7 | 683.6 |

occurred in 2007, when the core area and overall distribution extended to the south, outside of the primary study area. This more southern distribution is perhaps revealed due to the added survey effort in 2007; however, if we eliminate these data, the core areas of density are still the farthest south of all years.

## DISCUSSION

### Loggerhead density and abundance

At more than 43 000 loggerheads, our mean annual estimate of population size for the BCP loggerheads is triple that of the only prior estimate by Ramirez-Cruz et al. (1991). Our aerial surveys also integrated a $g(0)$ correction factor derived from loggerhead dive behavior in BCP waters. The expanded survey area in our aerial study versus that covered during boat-based surveys by Ramirez-Cruz et al. (1991; 66 000 km$^2$ versus 6600 km$^2$, respectively), combined with the $g(0)$ availability correction factor, undoubtedly contributed to the higher abundance estimates reported here. These results substantiate the BCP region as a major hotspot for loggerhead turtles in the North Pacific, and further underscore the value of using aerial platforms rather than water-based vessels for estimating density and abundance of sea turtles in foraging areas.

There are divergent opinions about the overall value of the BCP to the entire North Pacific loggerhead population. Studies by Kobayashi et al. (2008) and Van Houtan & Halley (2011) depicted the BCP region as relatively insignificant for North Pacific loggerhead turtles, whereas studies by Peckham et al. (2007, 2008) and Koch et al. (2013) found that this area was of vital importance to a major proportion of the entire North Pacific loggerhead population. We do not attempt to quantify the proportion of the North Pacific loggerheads that is represented by BCP turtles due to lack of information on sex ratio and population age structure of turtles at the BCS hotspot and complete absence of quantification of juvenile loggerheads elsewhere in their range. However, considering that our estimate of annual abundance (ca. 43 000) is almost 20× greater than the current annual number of nesting females in Japan (ca. 2300 females; Matsuzawa 2011), the loggerhead cohorts found in BCP waters likely represent a significant portion of the entire North Pacific loggerhead population.

### Loggerhead distribution

The extent of latitudinal and longitudinal distributions in sightings illustrate that our survey area

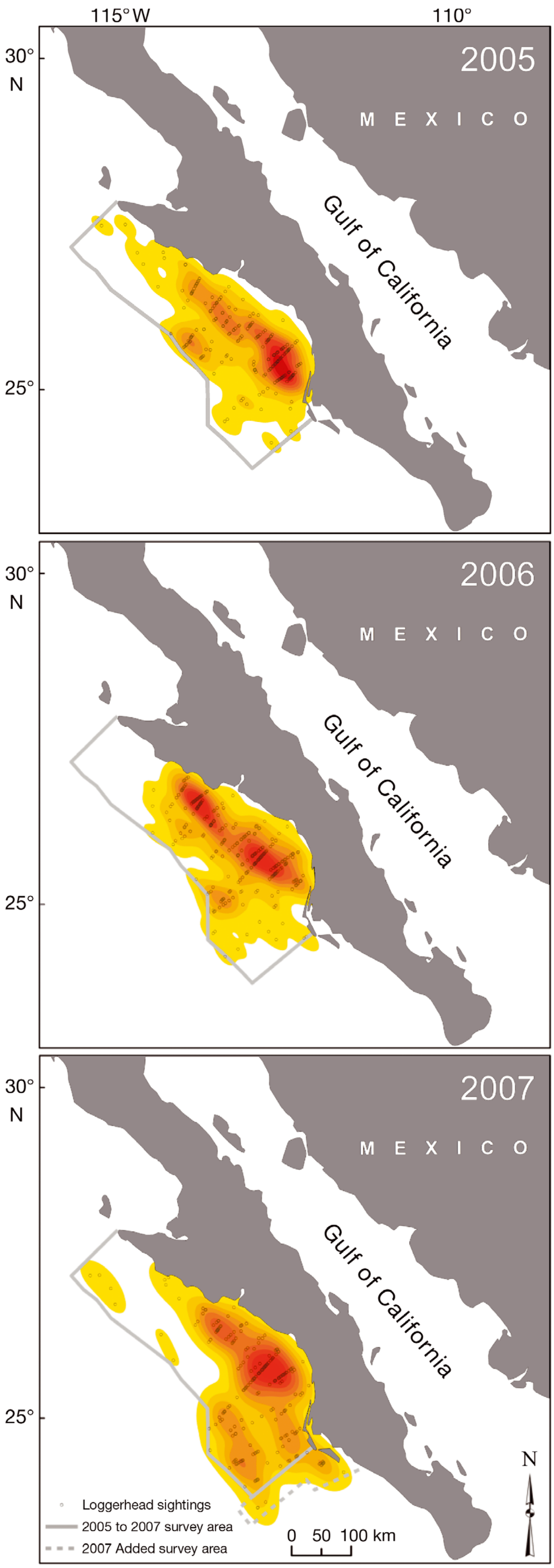


Fig. 4. Fixed kernel density plot for loggerhead sea turtle *Caretta caretta* sightings during the 2005 to 2007 aerial surveys along the Pacific Coast of the Baja California Peninsula, Mexico. Warmer colors indicate higher loggerhead density. Gray marks within each density plot indicate sighting locations of loggerhead turtles during survey efforts.

encompassed the entirety of the BCP loggerhead hotspot. Despite variation in spatial distributions among years (Fig. 4), the extents of spatial surveys clearly included the tails of the N–S and W–E distributions (Fig. 3). Nevertheless, we did detect a small number of loggerheads in the most offshore portions of our study area, and it remains unknown whether substantial numbers of loggerheads also occurred west of our survey area. The extent to which turtles travel between inshore and offshore regions near the Gulf of Ulloa is unclear, although satellite-tracked movements of 45 loggerheads from 1996 to 2007 indicate that such movement is minimal (Peckham et al. 2011).

The density of loggerheads that we found in the Gulf of Ulloa (0.650 km$^{-2}$) is the second-highest aerial survey-derived density for any sea turtle foraging population reported to date (Table 6), rivaled only by sea turtles in Chesapeake Bay, USA, where Keinath et al. (1996) reported a density of 3.5 turtles km$^{-2}$. Of note, however, is the fact that the density reported by Keinath et al. (1996) includes multiple turtle species, whereas our estimate is for loggerheads only. Possible reasons for the high density and sustained presence of loggerhead turtles in the Gulf of Ulloa are the relative consistency in food availability and/or preferred thermal conditions. The region hosts enhanced upwelling, and the Ulloa Bight promotes retentive circulation and heightened year-round primary production (Zaytsev et al. 2003, Etnoyer et al. 2004, Wingfield et al. 2011), which help sustain high prey density (e.g. Aurioles-Gamboa 1992) and increased foraging opportunities. Indeed, Peckham et al. (2011) contrasted BCP neritic habitats with Central North Pacific pelagic habitats and suggested that juvenile loggerheads in the BCP encounter more favorable food quality and availability that could potentially yield faster juvenile growth and larger body size.

The core areas of loggerhead presence remained in the center of the Gulf of Ulloa, although there were some north–south shifts in core areas of loggerhead presence from year to year (Fig. 5). These annual core areas of loggerhead presence are relatively small (<6000 km$^2$; Table 5, Fig. 5) and are likely tied to the spatial distribution of optimal habitat and prey availability, both of which may shift slightly from

Table 6. Summary of key parameters derived from previous aerial surveys for sea turtles in marine habitats. The $g(0)$ calibration value indicates $g(0)$ corrected for the turtle-at-surface availability value. Only maximum turtle density is reported in cases where multiple season and habitat-specific turtle densities are reported. ESW: estimated strip width; na: not an appropriate metric; nr: appropriate metric, but not reported

| Species | Location | Years | Survey area (km$^2$) | Offshore extent (km) | No. observations | $g(0)$ calibration | ESW (m) | Density (turtles km$^{-2}$) | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Loggerhead | NW Atlantic | 4 | 721[a] | na | 2 | Yes | 250 | 0.377 | Byles (1988) |
| Multiple | NW Atlantic | 3 | 278350 | ~200[b] | 2 | No | nr | 0.0051 | Shoop & Kenney (1992) |
| Multiple | NW Atlantic | 3 | 4700 | na | 2 | No | 300 | 0.372 | Epperly et al. (1995) |
| Multiple | NW Atlantic | 1 | nr | 10 | 2 | No | nr | 0.620[c] | Braun & Epperly (1996) |
| Mulitple | NW Atlantic | 7 | 1527 | 27.8 | 2 | Yes | 250 | 3.5[d] | Keinath et al. (1996) |
| Multiple | NW Atlantic | 4 | 3408 | na | 2 | Yes | 134 | 0.093[a] | Mansfield (2006) |
| Multiple | Gulf of Mexico | 3 | nr | 200 | 3 | No | nr | 0.047 | McDaniel et al. (2000) |
| Loggerhead | W Mediterranean | 1 | 477 | 36 | 2 | No[e] | 290 | 0.082 | Cardona et al. (2005) |
| Loggerhead | W Mediterranean | 2 | 32000 | 112 | 2 | Yes[f] | 130 | 0.592 | Gómez de Segura et al. (2006) |
| Leatherback | NE Pacific | 10 | 31885 | <50 | 3 | Yes | 224 | 0.077 | Benson et al. (2007) |
| Loggerhead | NW Mediterranean | 1 | 88268 | 120 | 2 | No | 202 | 0.046 | Lauriano et al. (2011) |
| Loggerhead | E Pacific | 3 | 66471 | 140 | 3 | Yes | 158 | 0.650 | This study |

[a]Maximum reported value among survey years. [b]Estimated based on reported extents of 9.3 km seaward of the 1000 fathom (1829 m) isobath. [c]Based on very small sample size (n = 3 loggerhead turtles). [d]Derived for a study of turtles within nearshore waters of Chesapeake Bay. [e]This paper reports % surface time for loggerhead turtles (35.1 ± 19.7%), but this value is not used to estimate aerial survey $g(0)$. [f]Although absolute density estimates are reported, the specific surface proportions are not reported

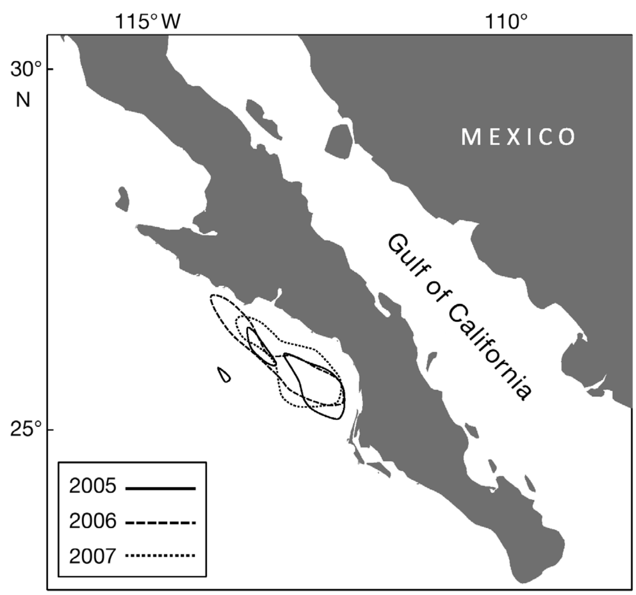


Fig. 5. Boundaries for the 50% kernel density estimator utilization distribution (KDE UD; core area of distribution) of loggerhead sea turtles *Caretta caretta* for each year of the study

year to year due to annual differences in the location of retentive circulation eddies and blooms of key prey such as pelagic red crabs (Aurioles-Gamboa 1992). Hotspots for sea turtles in other areas have also been shown to correspond with localized abundance of their prey (Houghton et al. 2006, Polovina et al. 2006, Witt et al. 2007).

### Uncertainty in estimates

Although the 95% CI range for the estimated abundance of loggerheads (15 017–100 444) is wide, we believe our mean annual estimate is accurate for 4 primary reasons: (1) surveys from 3 successive years (2005–2007) yielded a relatively low CV (0.51) for a similar magnitude of turtle sightings across years (2005: 42 786; 2006: 49 712; 2007: 38 396), (2) our abundance estimate is based on a line-transect method that integrates environmental and observer bias parameters to derive a robust detection function; (3) our $g(0)$ estimate (i.e. turtle availability) is derived from dive records of loggerhead turtles gathered from within our study area during water temperature conditions similar to those observed when surveys were conducted; and (4) there was no significant diel variation in surface times for loggerheads (Peckham et al. 2012), thus minimizing within-day temporal errors in our $g(0)$ estimate. We are confident in these results, although we do acknowledge that greater precision in our estimates could have been gained from conducting repeat surveys a few days apart along the same transect lines. Unfortunately, logistical and financial constraints precluded such an effort.

Whereas our estimates of $g(0)$ corrected for availability bias (animals diving too deep to be seen), they did not account for perception bias (animals available to be seen but missed by the observer). Perception bias is usually corrected for by an independent observer approach, i.e. some or all of the surveys are undertaken with more than 1 observer independently searching the same area and recording data separately, known as the 'double platform' approach (see Thomas et al. 2010). However, the size of our aircraft precluded the additional persons needed to apply this approach in the present survey. No estimate of perception bias is available for loggerhead turtles; however, in an aerial survey for dugongs *Dugong dugon* and sea turtles, observers missed over 80% of turtles visible within the transect (Marsh & Sinclair 1989). Forney et al. (1995) reported that small groups of small dolphins and porpoises are missed about 33% of the time. Therefore, it is likely that the detection of available loggerheads along the transect line is less than 100%, a bias that would result in underestimation of turtle density and abundance by an unknown amount. Other negative biases for density estimation may include (1) that some unidentified turtles were loggerheads, and (2) the area surveyed does not fully encompass the range of loggerheads in this area during the survey period.

Species mis-identification could also be a source of potential uncertainty. After loggerheads, the most commonly identified sea turtle species during our study was the olive ridley turtle *Lepidochelys olivacea*. While these 2 species have been confused by researchers in the past (Frazier 1985), in our study loggerheads were easily distinguished by color and shape. This distinctiveness by species is consistent with Braun & Epperly (1996), who were able to distinguish loggerheads from Kemp's ridley turtles *L. kempii*, which are similar in morphology and color to olive ridleys. Likewise, Epperly et al. (1995) noted the ease with which loggerheads were discerned from green turtles and Kemp's ridleys based on color and body shape.

The assumption that sighted turtles were correctly identified for species is also supported by comparisons of our species-specific sighting proportions with other data from the study area. Whereas olive ridleys constituted from 10 to 24% of identified turtles in each year of our study, Koch et al. (2006) found that 9% of the 1945 turtle carcasses found in the region were olive ridleys. A more recent study by Koch et al. (2013) reported that only 6% of 594 turtles found stranded in the region were olive ridley turtles. It is likely that the proportions of loggerheads to olive ridleys near the BCP may shift each year, but nevertheless these comparisons also suggest that loggerhead density and abundance may be underestimated here.

**Conservation implications: abundance relative to mortality**

Loggerhead mortality in the Gulf of Ulloa is high, and our abundance estimate is crucial for estimating the proportion of turtles that die each year in this area. Peckham et al. (2008) estimated that between 1500 and 2950 loggerhead turtles yr$^{-1}$ died in Baja California Sur from 2005 to 2007. This estimate is based on (1) intensive stranding surveys of a 44.3 km index shoreline, (2) bimonthly surveys of shorelines and towns across the region, and (3) onboard observations of bycatch by 2 small-scale fishing fleets (Peckham et al. 2008). However, the authors noted that their estimates represented minimum loggerhead mortality in only a small portion of the hotspot because nearly a dozen other small-scale plus medium and industrial-scale fleets also operate within the hotspot. There is also the potential for impacts from harmful algal blooms (e.g. Mendoza-Salgado et al. 2003).

Koch et al. (2013) found ca. 320 stranded dead loggerheads along the same index shoreline from 2010 to 2011 and developed a drifter-buoy study to determine the proportion of turtles that would potentially reach this index beach due to currents and tides. In total, Koch et al. (2013) deployed 4752 individually marked drifters during 9 trials from 2010 to 2011, 4 of which occurred in waters directly adjacent to the stranding index beach. In these 4 trials, an overall mean of 6% (range = 4–36%) of the drifters were encountered on shore at the stranding index beach. This indicates that the 320 loggerheads encountered on the San Lazaro index shoreline reflect mortality of a much larger number of turtles, and by extrapolation up to 5300 loggerhead turtles over the 2 yr based on the mean drifter 'stranding' rate, or from 888 to 8000 loggerheads based on the overall range in drifter stranding rates found by Koch et al. (2013).

Based on our estimate of 43 226 loggerhead turtles (Table 4), the minimum annual mortality estimate by Peckham et al. (2008; 2250 loggerheads yr$^{-1}$) suggests that between 2005 and 2007, a minimum of 5.2% of loggerheads in BCS waters may have died annually. When integrating the findings of Koch et al. (2013) with our abundance estimate, the range of mortality we extrapolate from their stranding rates and probabilities (888 to 8000 loggerheads over 2 yr) suggests that 1.2 to 11.0% of the population of loggerhead turtles die each year in the region. Regardless of which estimates are used, and what the actual causes of mortality are, these results suggest that the high levels of mortality reported in BCP waters are unsustainable for the North Pacific loggerhead population.

The fraction of a loggerhead's life cycle that is spent in Baja waters is unknown, but the smallest individuals encountered here were ~45 cm curved carapace length, which corresponds to an age of between 7 and 8 yr (Zug et al. 1995, Chaloupka 1998). Assuming a mean age of 7.5 yr for the initial appearance of loggerheads off Baja and comparing it to the age at first reproduction (25 yr; Van Houtan & Halley 2011), implies that juvenile loggerheads spend at least 16 yr near the BCP before departing for nesting beaches. In context, the anthropogenic threats faced by loggerheads in this region over a 16 yr period are considerable, when one takes into consideration the estimated fraction of the population removed annually by fisheries, direct hunts, and natural causes. Exposure to such threats over such a long time period implies a very low survival probability for individual loggerheads in this region.

The proportion of loggerheads surviving to adulthood (i.e. those that survive to leave BCP waters) will significantly decrease each year if the current mortality rates continue (Fig. 6). Maximum calculated mortality rates suggest that the number of juveniles in the BCP region during year $Y_x$ that will recruit to the adult population will be reduced by 50% within 15 yr (i.e. $Y_{x+6}$; range = 6 to >35 yr; Fig. 6). The 50% decline threshold will be reached even sooner if we account for the mortality related to human consumption (ca. 74 loggerheads yr$^{-1}$; Koch et al. 2006), which includes turtles that would not be encountered on the stranding index beach, and turtles that die due to natural causes. Because the BCP population is composed of 99% juvenile turtles (Peckham et al. 2008), the impacts of the mortality in the region will manifest as a decline in neophytes recruiting to nesting beaches in Japan in the coming decades. Clearly, recovery of the North Pacific loggerhead population will be hindered if BCP mortality rates are not substantially reduced. Our findings underscore the urgent need to mitigate loggerhead mortality on the Baja California Peninsula.

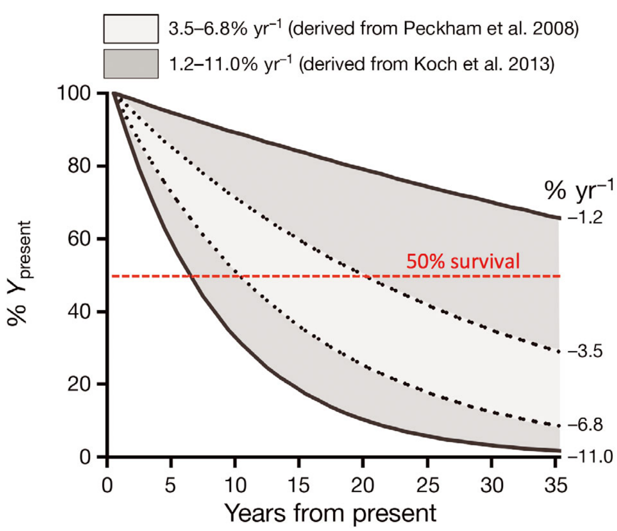


Fig. 6. Cohort survival forecasts for juvenile loggerhead sea turtles *Caretta caretta* in the Baja California Peninsula (BCP) based on published estimates of mean annual mortality in the Gulf of Ulloa. The *y*-axis denotes percent of juveniles present in BCP in the current year that will be alive in year *X* and available for adult recruitment

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