



Short communication

Bycatch and directed harvest drive high green turtle mortality at Baja California Sur, Mexico

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ABSTRACT

Evaluating mortality of rare marine megafauna is crucial for conservation planning, but logistically difficult to undertake at sea. From 2006 to 2008 we assessed mortality of endangered green turtles (*Chelonia mydas*) through surveys of beaches and town dumps for stranded and discarded carcasses at nine index sites along the coast of Baja California Sur, Mexico (BCS). We found a total of 778 carcasses, 93% of which were immature. Mortality rates ranged from 0.05 to 9.20 carcasses km⁻¹ year⁻¹ at beaches and 2.84 to 66.75 carcasses year⁻¹ at dumps. All carcasses found at dumps ($N = 339$) were attributed to human consumption, whereas cause of death at beaches was largely unknown (62%), followed by bycatch (30%), and consumption (8%). Over two thirds of total mortality resulted from consumption (48%) and bycatch (20%), and turtles that died from these causes were significantly larger than those that died from unknown reasons. The majority of carcasses at beaches (69%) and dumps (57%) were found during summer months when small-scale gillnet fisheries operate, including 99% of identified bycatch mortality. Three hotspots accounted for 77% of all mortality, which was disproportionately high (40% of total mortality) at one site where mass-bycatch/stranding events occurred annually. Our results demonstrate that many green turtles are being killed from bycatch and directed harvest at BCS despite over two decades of federal protection; thus, highlighting the need to mitigate these threats at mortality hotspots.

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1. Introduction

Marine megafauna such as seabirds, marine mammals, large fish, and sea turtles are subject to multiple anthropogenic threats across different spatial and temporal scales (Boyd et al., 2008; Wallace et al., 2011). Many species are endangered and recovery is difficult because they exhibit delayed life history characteristics (e.g. slow growth, late maturity, and long-lived). Anthropogenic sources of mortality including overexploitation, bycatch, pollution, vessel collisions, and habitat degradation have been known or believed to cause declines in many populations worldwide (Lewison et al., 2004; Koch et al., 2006; Mrosovsky et al., 2009; Wallace et al., 2011; Denkinger et al., 2013). These declines can have widespread ecological consequences, including extensive cascading effects on lower trophic levels (Estes et al., 2011).

Like other marine megafauna, green turtles (*Chelonia mydas*) play an important ecological role by linking nutrient-rich marine

feeding grounds to nutrient-poor nesting beaches during reproduction (Vander Zanden et al., 2012) and as primary consumers of sea-grass and algae in coastal waters (Bjorndal and Jackson, 2002; Moran and Bjorndal, 2005, 2007). Despite decades of widespread international protection, green turtles are still listed as endangered (IUCN, 2013) and populations have been substantially depleted from centuries of overexploitation for meat and eggs, thus limiting their ecological role in many ecosystems (Bjorndal and Jackson, 2002; Allen, 2007). Although some populations have recently been increasing (Balazs and Chaloupka, 2004; Chaloupka et al., 2008a), they remain far below their historical abundances and spatial distribution (Kittinger et al., 2013).

Once considered among the most abundant megafauna species throughout the Mexican Pacific, green turtles have declined dramatically from decades of intense overexploitation for meat and eggs (Delgado-Trejo and Alvarado-Diaz, 2012). From the 1950s to 1970s commercial fisheries in Mexico accounted for 50% of global sea turtle harvest, consisting mainly of green and olive ridley turtles (*Lepidochelys olivacea*) (Marquez, 1990). Coupled with harvest of nesting females and intense egg collection

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(~70,000 eggs per night at Colola, Michoacan), green turtle populations began to plummet during the 1970s (Clifton et al., 1982; Alvarado-Diaz et al., 2001). Following international pressures, in 1990 Mexico closed commercial fisheries and instituted a moratorium on the take of turtles and eggs (Aridjis, 1990). Although nesting females at Colola have since been increasing, they remain at least an order of magnitude below population levels during the mid-1960s (Delgado-Trejo and Alvarado-Diaz, 2012).

Along the coast of Baja California Sur, Mexico (BCS), juvenile green turtles aggregate at coastal foraging areas with abundant seagrass and algae where they spend up to 20 years before reaching maturity and migrating to nesting grounds (Seminoff et al., 2003; Koch et al., 2007). While inhabiting these areas, green turtles exhibit high site fidelity to limited home ranges (Seminoff et al., 2002; Seminoff and Jones, 2006; Senko et al., 2010a,b; López-Castro et al., 2010). Although this life history strategy usually implies good protection from predators and low natural mortality (Koch et al., 2007), it concentrates a sensitive lifestage in coastal environments that are often heavily developed and exploited. Thus, assessing green turtle mortality at BCS foraging areas is necessary for informing conservation planning efforts.

Given the logistical challenges associated with evaluating sea turtle mortality in marine environments, stranded or disposed carcasses offer the most easily accessible data for understanding at-sea mortality (Peckham et al., 2008; Koch et al., 2006, 2013). Prior green turtle stranding research at BCS has assessed general mortality trends (Koch et al., 2006), consumption and black market trade (Mancini and Koch, 2009), and bycatch (Mancini et al., 2012). However, these studies have been limited to a single site or mortality cause, highlighting the need to evaluate multiple sources of mortality across a broader spatial scale. Here, we assess green turtle mortality through monthly and bimonthly surveys of beaches and town dumps at nine index sites along the Pacific and Gulf coasts of BCS, a region that represents among the most important feeding and developmental habitat for green turtles in the Eastern Pacific. To our knowledge, this is the largest green turtle mortality dataset ever compiled from Latin America. Specifically, our goals were to determine: (1) number of carcasses found; (2) causes of mortality; (3) spatial and temporal distribution of mortality; and (4) size frequency distribution and proportion of mature individuals.

2. Materials and methods

2.1. Study site

We conducted monthly and bimonthly mortality surveys at 9 index sites along the Pacific and Gulf of California coasts of BCS. The Mexican state of BCS occupies the southern half of the Baja California peninsula, is approximately 900 km long, and has the longest coastline (~2222 km) of all Mexican states (Mancini and Koch, 2009). The nine index sites included Guerrero Negro (Isla Arena) (GNO), Punta Abreojos (PAO), Laguna San Ignacio (LSI), San Juanico (SJU), Bahía Magdalena (BMA), La Paz (LAP), Loreto (LOR), Mulege (MUL), and Santa Rosalía (SRO) (Fig. 1).

2.2. Mortality surveys

We conducted beach surveys monthly and bimonthly at the study sites from February 2006 to September 2008 (Fig. 1). We surveyed a total of 205 km of shoreline (see [Supplementary material A](#)), representing 9.4% of the total BCS coastline. We also surveyed 9 town dumps bimonthly, representing ~6% of all coastal BCS communities (INEGI, 2013). For each carcass found at beaches and dumps, we identified species, recorded gender (if possible), took digital photographs, and marked all carcasses with spray paint

and/or cable binders to avoid recounts. We measured curved carapace length (CCL) of intact carapaces from the nuchal notch to the posterior marginal tip using a flexible tape measure to the nearest mm. We recorded location of each carcass using a handheld GPS device.

Based on available external evidence, we grouped carcasses into one of four possible cause-specific mortality categories: (1) human consumption (all carapaces found at dumps and carapaces at beaches that were either charred, freshly cleaned, or had harpoon holes); (2) bycatch (whole turtle was found entangled with fishing gear, wounds from fishing gear were visible, signs of drowning were present following on-site necropsies of fresh carcasses (e.g. water in lungs, foam in airways), or direct observation of bycatch mortality (i.e. turtles tossed overboard dead by fishers) adjacent to index beach during the same timeframe it was surveyed); (3) other (e.g. shark predation, disease, boat strike, fibropapillomatosis), and (4) unknown (when there was no obvious cause of mortality). We use “human consumption” versus “poached” because at BCS the latter may imply that the animal was directly hunted for export on the black market. Our mortality categories were based on visual identification of carcasses, many of which were severely decomposed; thus, we acknowledge that laboratory necropsies of fresh carcasses may have identified pathology or other causes of death not revealed here (Chaloupka et al., 2008b).

2.3. Data analysis

We calculated the mean length (CCL) of carcasses and the percentage of mortality type at each site for beaches and dumps. We grouped seasons into summer (May–October) and winter (November–April) following Koch et al. (2007) and López-Castro et al. (2010). We produced length frequency distribution for all carcasses and estimated the percentage of adults. To estimate length at maturity, we used mean size of nesting female green turtles at the major nesting beaches in Michoacán (82 cm CCL; Alvarado and Figueroa, 1990) following Koch et al. (2006, 2007). Size at maturity is close to average nesting size in green turtles (Limpus and Walter, 1980). We calculated annual mortality rates by dividing the number of new carcasses found at index beaches (mean No. carcasses km⁻¹ year⁻¹) and dumps (mean No. carcasses year⁻¹) by the time elapsed between surveys.

We transformed CCL data using an inverse transformation and tested for normality of residuals using the Shapiro–Wilkinson test. We tested homogeneity of variance with a Bartlett’s test on the raw data. We used a one-way nested ANOVA to compare mean inverse CCL between index sites within regions (i.e. Pacific and Gulf). In this model, both region and site were treated as fixed effects because there are environmental differences between regions (e.g. see López-Castro et al., 2010) and we were explicitly interested in quantifying differences between specific sites. We used a one-way ANOVA to compare mean inverse CCL between mortality causes (i.e. bycatch, human consumption, and unknown mortality). When significant differences were detected, we used Tukey’s HSD *a posteriori* mean comparisons test. Analyses were performed in R 2.15.1. Results are presented as mean ± SD and intervals represent absolute ranges. Statistical significance was inferred at a probability of 0.05 or less.

3. Results

3.1. Total mortality

From 2006 to 2008 we encountered a total of 778 carcasses at beaches and dumps (Table 1 and Fig. 2), of which 697 could be measured (see [Supplementary material B](#)). Immature turtles

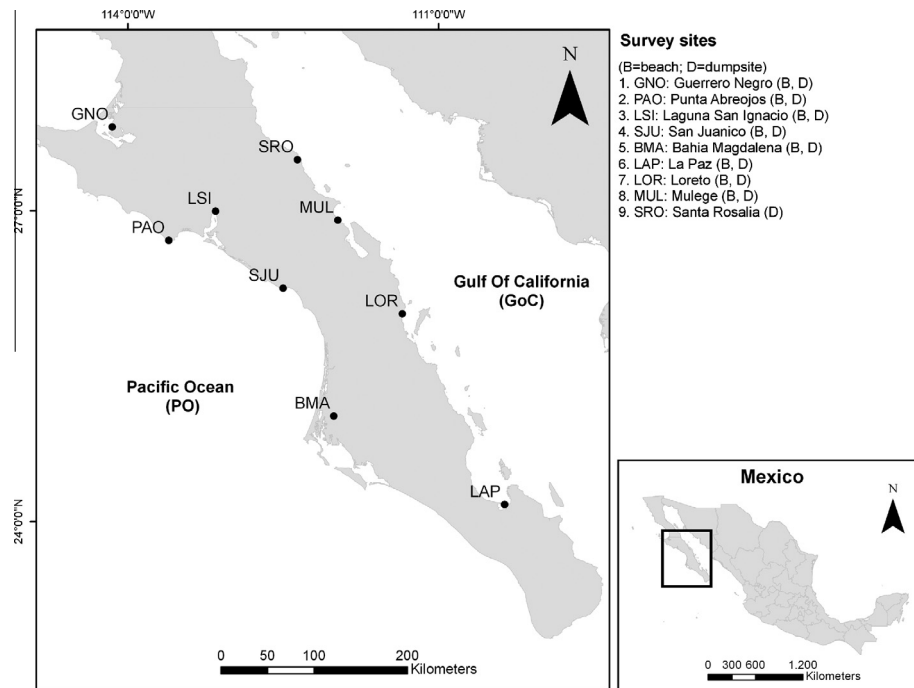


Fig. 1. Map of the study area (Baja California Sur, Mexico) where we conducted green turtle mortality surveys. Beaches (B) and/or dumpsites (D) were surveyed at each index site (marked with black circles). These sites are part of a long-term sea turtle monitoring program at northwestern Mexico by the conservation NGO Grupo Tortuguero and reflect areas of historical abundance and exploitation.

accounted for 93% of all carcasses measured and were dominant at all index sites. The vast majority of dead turtles were in the 50 to 65-cm size class and there was little variation in size distribution amongst mortality causes (Fig. 2). Most mortality (87%) was from the Pacific coast, with LSI accounting for 70% of beach mortality and 40% of total mortality (39% at beaches and 1% at dumps) (Table 1). Three sites along the Pacific coast (LSI, GNO, and BMA) accounted for 77% of all mortality (Table 1). Human consumption accounted for 48% of all mortality, followed by unknown mortality (32%), and bycatch (20%) (Table 1). No carcasses showed clear external signs of “other” mortality, although in many cases decomposition of carcasses was very advanced. While gender determination based on external characteristics is difficult for immature sea turtles, we were able to identify 22 females and 15 males.

3.2. Beach mortality

From 2006 to 2008 we encountered 439 carcasses at eight beaches (Table 1). We recorded 69% ($N = 305$) of carcasses at beaches during the summer months (May–October) (Table 1). Mean CCL at beaches was 58.6 ± 11.2 ($N = 370$, range = 38.5 to 101.0) (see Supplementary material B), and 95% of carcasses were immature. The most common cause of mortality at beaches was unknown (62%), followed by bycatch (30%), and human consumption (8%). Virtually all (99%) bycatch occurred at LSI, which is likely because bycatch was easier to document here due to: (1) the geography of the lagoon (relatively small, shallow, and very narrow); (2) close proximity of the gillnet fishery to the shoreline (~100 m–2 km); and (3) a concurrent bycatch study (i.e. Mancini et al., 2012) that included in-water sampling and interviews with local fishers. The majority of unknown mortality (57%) also occurred at LSI (Table 1). The Pacific coast accounted for almost all carcasses encountered at beaches (94%) (Table 1). Mean stranding rates of carcasses found at beaches ranged from 0.05 carcasses $\text{km}^{-1} \text{year}^{-1}$ to 9.20 carcasses $\text{km}^{-1} \text{year}^{-1}$ (Table 1).

3.3. Dumpsite mortality

From 2006 to 2008 we encountered 339 carcasses at nine dumpsites (Table 1). We recorded 57% ($N = 193$) of carcasses at dumps during the summer months (May–October) (Table 1). Mean CCL at dumps was 62.4 ± 12.6 ($N = 327$, range = 39.7 to 105.4) (see Supplementary material B), and 91% of carcasses were immature. All carcasses found at dumps showed signs of human consumption. The majority (75%) of carcasses were found at dumps on the Pacific coast (Table 1) and more than half of all mortality was encountered at two sites (GNO, 37%; BMA, 22%) (Table 1). Carcasses at dumps were encountered at mean discard rates ranging from 2.84 carcasses year^{-1} to 66.75 carcasses year^{-1} (Table 1).

3.4. Trends in overall mortality

Mortality attributed to bycatch was only identified in June and July (Fig. 3), where one site (LSI) accounted for 99% of bycatch mortality. Unknown mortality also peaked in June (Fig. 3). Human consumption at beach and dumpsites both peaked in October, although dumpsite consumption saw large annual variations (Fig. 3). We found a significant difference amongst carcass size between sites within regions (i.e. Pacific and Gulf) ($F = 2.65$; $df = 2.23 \times 10^{-5}$; $p = 0.0157$). Tukey's *post hoc* comparisons revealed a significant difference ($P < 0.05$) between BMA and LAP, where carcasses from LAP were significantly larger than carcasses from BMA (Table 2). We found significant differences between the three mortality causes ($F = 10.811$; $df = 2$; $p < 0.0001$), where carcasses from bycatch and human consumption were significantly larger ($P < 0.05$, Tukey's HSD) than carcasses from unknown mortality (Table 3).

4. Discussion

The 778 carcasses reported here likely represent only a small percentage of actual green turtle mortality at BCS because: (1)

Table 1

Cause of mortality and number of green turtle carcasses found at beaches and dumpsites along the Pacific and Gulf coasts of Baja California Sur, Mexico from 2006 to 2008. See Fig. 1 for site abbreviations.

	Pacific						Gulf of California					Grand Total
	LSI	GNO	PAO	SJU	BMA	Total	LAP	LOR	MUL	SRO	Total	
<i>Bycatch</i>												
Summer	156	0	0	0	0	156	0	0	0	N/A	0	156 (99%)
Winter	0	1	0	0	0	1	0	1	0	N/A	1	2 (1%)
Total	156 (99%)	1 (<1%)	0	0	0	157 (>99%)	0	1 (<1%)	0	N/A	1	158
<i>Human consumption</i>												
Summer	4	65	38	1	32	140	23	8	9	27	67	207 (56%)
Winter	7	61	14	0	50	132	12	0	18	0	30	162 (44%)
Total	11 (3%)	126 (34%)	52 (14%)	1 (<1%)	82 (22%)	272 (74%)	35 (9%)	8 (2%)	27 (7%)	27 (7%)	97 (26%)	369
<i>Unknown</i>												
Summer	93	10	5	12	10	130	2	0	3	N/A	5	135 (54%)
Winter	52	38	4	0	15	109	5	1	1	N/A	7	116 (46%)
Total	145 (57%)	48 (19%)	9 (4%)	12 (5%)	25 (10%)	239 (95%)	7 (3%)	1 (<1%)	4 (1%)	N/A	12 (5%)	251
<i>Total beach mortality</i>	306 (70%)	49 (11%)	12 (3%)	12 (3%)	32 (7%)	411 (94%)	7 (2%)	2 (<1%)	19 (4%)	N/A	28 (6%)	439
Mean No. carcasses km ⁻¹ year ⁻¹	9.20	0.81	0.13	0.31	0.63	1.36	0.06	0.05	0.61	N/A	0.14	0.81
<i>Total dump mortality</i>	6 (2%)	126 (37%)	49 (14%)	1 (<1%)	75 (22%)	257 (75%)	35 (10%)	8 (2%)	12 (5%)	27 (8%)	82 (25%)	339
Mean No. carcasses year ⁻¹	2.84	66.75	25.78	N/A*	36.65	121.20	17.19	7.91	17.95	23.30	50.90	159.86
<i>Total overall mortality</i>	312 (40%)	175 (23%)	61 (8%)	13 (2%)	107 (14%)	668 (87%)	42 (5%)	10 (1%)	31 (4%)	27 (3%)	110 (13%)	778

N/A, not applicable because beaches at SRO were not surveyed.

* N/A, not applicable because the SJU dump was only sampled once.

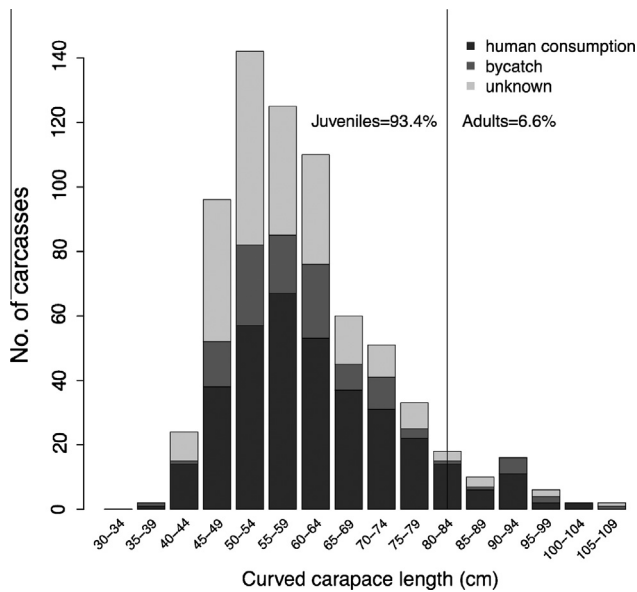


Fig. 2. Size distribution of green turtle carcasses encountered at beaches and dumpsites along the Pacific and Gulf coasts of Baja California Sur, Mexico from 2006 to 2008 by mortality type (N = 778).

surveys were limited to only 9% of the BCS coastline and 6% of BCS coastal communities; (2) green turtles are still exported via black market circuits to local, regional, and even international markets (Mancini and Koch, 2009) and thus would not be discarded at our study sites; (3) surveys were conducted monthly or bi-monthly, meaning that carcasses could have been missed because they became buried in the sand or were eaten by scavengers such as coyotes or vultures (Koch et al., 2006); (4) fishers sometimes destroy carapaces after butchering turtles on the boat; (5) carcasses are often buried, burned, or hidden with trash (Koch et al., 2006; Peckham et al., 2008; Mancini and Koch, 2009); (6) people dispose of carcasses in places other than dumps (e.g. the desert); (7) carapaces are sometimes kept as ornaments; and (8) stranding rates of turtles that wash ashore only represent a small fraction

(usually 5–30%) of actual mortality due to factors such as distance from beach, currents, wind, and season (Hart et al., 2006; Koch et al., 2013).

While only 20% of mortality could be directly attributed to fisheries (i.e. bycatch), it is likely that fisheries are responsible for a large proportion of overall mortality. In particular, bottom-set gillnet fisheries that operate seasonally in BCS coastal waters cause high sea turtle mortality because the nets are usually checked only once every 24 h, preventing entangled turtles from surfacing to breathe (Mancini et al., 2012). These fisheries have caused mass bycatch mortality in both green and loggerhead turtles (*Caretta caretta*) at BCS, producing among the highest sea turtle mortality rates recorded worldwide (Peckham et al., 2007, 2008, 2013; Mancini et al., 2012; Koch et al., 2013). It is thus reasonable to suggest that most consumed turtles were likely taken in gillnet fisheries, either as retained bycatch or from directed hunting, and subsequently discarded at dumps or beaches. Similarly, most unknown mortality during the summer likely resulted from incidental bycatch in gillnets as natural mortality of green turtles is believed to be very low at BCS foraging areas (Koch et al., 2007) and no carcasses we found showed any signs of disease, shark predation, or fibropapillomatosis.

We identified three mortality hotspots (LSI, GNO, and BMA) along the Pacific coast where 77% of all mortality occurred (Table 1). LSI accounted for 40% of total mortality, resulting almost entirely from bycatch and unknown mortality. Mass-stranding events occurred annually at LSI, which accounted for 99% of all identified bycatch mortality recorded. However, the geography of the lagoon, close proximity of the fishery to the shoreline, and a concurrent bycatch study (i.e. Mancini et al., 2012) all made it easier to document bycatch here. By contrast, GNO and BMA had the highest human consumption, accounting for more than half of all consumed turtles (Table 1). Both of these sites were hotspots for legal green turtle fisheries between 1950 and 1990, and currently serve as major circuits for black market trade despite market conditions that provide easier access to other more reliable protein sources (Mancini and Koch, 2009; Senko et al., 2009).

Seasonal trends in mortality were observed, with most carcasses from beaches (69%) and dumps (57%) recovered during the summer months when coastal gillnet fisheries are most active, including 99% of identified bycatch (Fig. 3). Mancini et al. (2012)

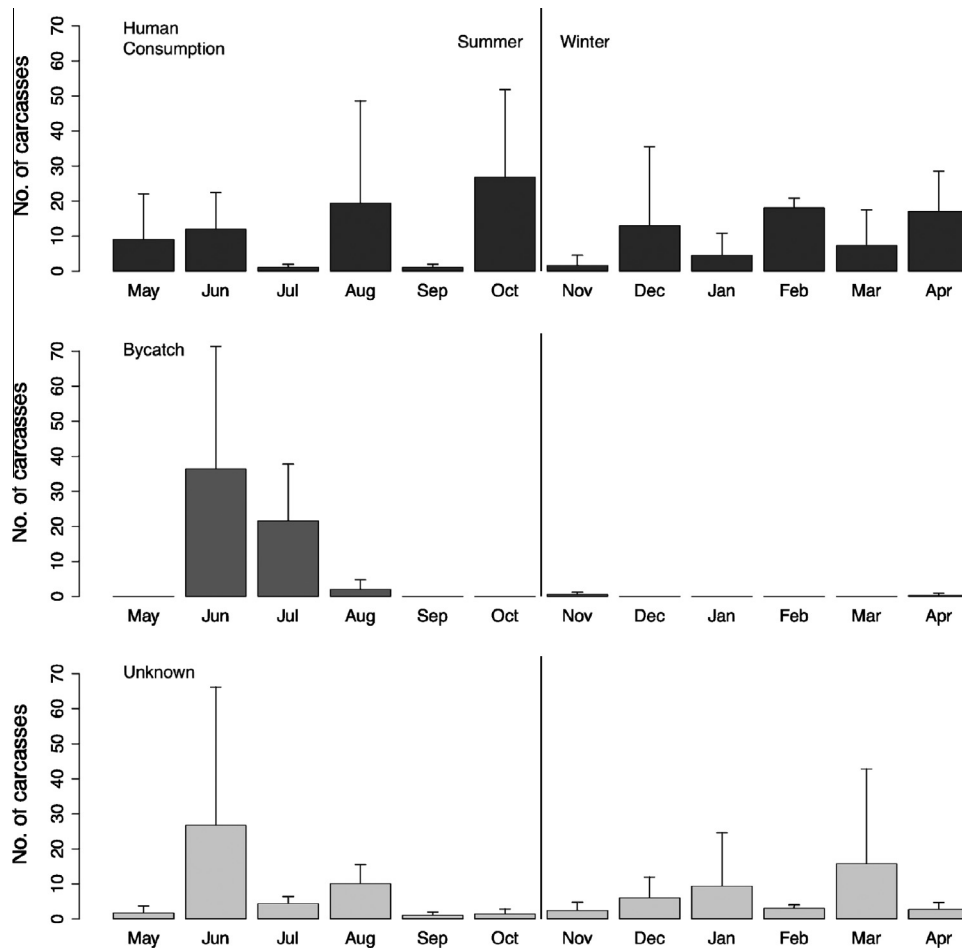


Fig. 3. Monthly and seasonal distribution of green turtle carcasses by each mortality cause encountered at beaches and dumpsites at 9 index sites along the Pacific and Gulf coasts of Baja California Sur, Mexico from 2006 to 2008 (N = 778). Bars represent SD within months.

Table 2

Nested ANOVA comparing inverse curved carapace length between sites nested within region (Pacific or Gulf of California). Site abbreviations are defined in Fig. 1. Significant differences are indicated in bold.

	Df	SS	MS	F	P
Region	1	1.46 × 10 ⁻⁵	1.46 × 10 ⁻⁵	0.657	0.449
Site w/in region	6	1.34 × 10 ⁻⁴	2.23 × 10 ⁻⁵	2.65	0.0157
Residual error	362	3.04 × 10 ⁻³	8.40 × 10 ⁻⁶		
Tukey <i>post hoc</i> test	Site	Homogenous groups			
Gulf of California	LAP	a			
	LOR	ab			
	MUL	ab			
	SRO	ab			
Pacific	BMA	b			
	GNO	ab			
	LSI	ab			
	PAO	ab			
	SJU	ab			

reported that 96% of green turtle strandings at LSI were encountered during summer months when fishers were illegally targeting guitarfish (*Rhinobatus* sp.) and halibut (*Paralichthys californicus*) inside the lagoon. Similarly, Peckham et al. (2008) reported that 70% of loggerhead strandings at BCS occurred during the summer when a bottom-set gillnet fleet was operating in nearby offshore waters. Human consumption at beaches and dumpsites both peaked in October, suggesting that some turtles may have been consumed (and discarded shortly thereafter) at the close of the gillnet fishing season or for a special occasion such as the Mexican independence day celebration (“El Grito”), which is held annually on 16 Septem-

ber. Unlike all other sites, beach mortality was disproportionately high at GNO during the winter when gillnet fisheries are prohibited due to the presence of grey whales (*Eschrichtius robustus*). Stranding surveys by Koch et al. (2013) during 2010–2011 also revealed that comparatively more green turtles stranded at GNO during the winter. GNO is the northernmost index site and experiences cold spells during winter with air temperatures regularly reaching the freezing point (Exportadora de Sal, unpublished data). Thus, unknown beach mortality during winter months at GNO may have resulted from cold-stunning events when water temperatures reached below 10 C (Witherington and Ehrhart, 1989).

Table 3

One-way ANOVA comparing inverse curved carapace length between the three mortality causes at beaches and dumps. Significant differences are indicated in bold.

	Df	SS	MS	F value	P value
Mortality cause	2	2.01×10^{-4}	1.00×10^{-4}	10.811	<0.0001
Residual Error	694	6.44×10^{-3}	9.28×10^{-6}		
Tukey <i>post hoc</i> test	Mortality cause		Homogeneous groups		
	Human consumption	a			
	Bycatch	a			
	Unknown			b	

When all mortality types were pooled together, carcasses from bycatch and human consumption were significantly larger than carcasses from unknown mortality. At BCS, fishers generally target medium to large turtles (Mancini and Koch, 2009), while smaller turtles may be more susceptible to cold stunning, which likely comprised some unknown mortality during the winter. Given that 99% of bycatch came from a single site, it is difficult to draw inferences to other sites. Carcasses found at dumps along both coasts demonstrated virtually the same mean size, suggesting that fishers either have a minimum preferred consumption size, fishers from both coasts fish similarly (e.g. similar gear, depth, bottom substrate), or in-water size distributions of turtles are similar. Although carcasses found at dumps could have originated elsewhere, this is unlikely as the index sites are generally sources, and not destinations, for black market trade. The disparity between carcass size at LAP and BMA is likely driven by habitat differences, as the section of shoreline we monitored at BMA is adjacent to a shallow estuary with predominantly small turtles (see Koch et al., 2007), whereas the index beach at LAP is adjacent to deeper, less protected water. Finally, although mortality data may not represent in-water population structure, we are confident that our size distributions were not skewed by selective mortality, as our data are consistent with previous in-water studies (Seminoff et al., 2003; Koch et al., 2007; López-Castro et al., 2010).

4.1. Conservation implications

Our results indicate that many immature green turtles are being killed at BCS despite over two decades of federal protection. While Mexico has protected major nesting beaches for over 3 decades, inadequate staffing and funding of federal environmental agencies has led to pervasive anthropogenic impacts at coastal foraging areas (Mancini et al., 2011; Senko et al., 2011), including high bycatch mortality and directed harvest observed in this study. Moreover, although the federal ban eliminated commercial harvest and thus substantially reduced overall mortality, it created a network of black market circuits and the perception that turtle meat is a luxury item symbolic of wealth and power (Mancini and Koch, 2009).

The number of nesting females at the largest Mexican nesting rookery at Colola in Michoacan remains at least an order of magnitude below mid-1960s levels (Delgado-Trejo and Alvarado-Diaz, 2012). Approximately 25,000 females nested annually at Colola during the late 1960s when populations were already reduced from intense exploitation along the Mexican Pacific coast that began in the early 1950s (Delgado-Trejo and Alvarado-Diaz, 2012). However, recent reports indicate that nesting females have been increasing over the past decade following near extirpation in the 1980s, with around 1500–2000 females nesting annually at Colola from 2000 to 2007 (Delgado-Trejo and Alvarado-Diaz, 2012). While encouraging, this initial sign of recovery is likely due to the ban on commercial harvest three decades ago and the ongoing protection at major nesting beaches, and may be constrained if high mortality on the feeding grounds persists. Given that the high mortality we observed is likely a gross underestimate of actual mortality,

coupled with nesting numbers that remain well below historical levels, continued mortality of mostly immature turtles could limit population recovery as demographic models of sea turtles indicate that older juveniles are important for population persistence and recovery (Crouse et al., 1987; Crowder et al., 1994).

Circumstantial evidence suggests that the vast majority of mortality likely resulted from gillnet fisheries. Following our study, green turtle strandings at LSI decreased by 97% in 2009 after the presence of law enforcement and subsequent closing of one small bottom-set gillnet fleet (approx. 15 boats fishing for less than 2 months) and has dramatically decreased since (Aaron Esliman pers. comm. 2013), demonstrating the effectiveness of increased law enforcement (Mancini et al., 2012). Nevertheless, while bycatch has largely been mitigated at LSI, high sea turtle bycatch is still occurring in other Mexican bottom-set gillnet fisheries. Recently, a 600% increase in loggerhead turtle strandings (483 turtles) was documented along 43 km of BCS shoreline in July 2012 when a bottom-set gillnet fleet was operating in nearby offshore waters (Peckham et al., 2013), while Mexican federal officials observed average bycatch rates approaching 2 turtles 100 m⁻¹ gillnet 24 h⁻¹ on a government research cruise during the same timeframe (INAPESCA, 2012). Accordingly, in a January 2013 report to Congress the United States cited Mexico under the Magnuson Stevens Reauthorization Act, with the possibility of economic sanctions if high strandings and bycatch continues unabated (NOAA Fisheries MSRA report, 2013).

Given that 77% of all mortality occurred at three sites, conservation action should focus on mitigating bycatch and directed harvest at mortality hotspots. However, continued monitoring of mortality across a broad spatial scale is imperative to assess mortality trends and whether impacts from illegal fishing are being redistributed to other green turtle foraging areas that are more difficult for both researchers and authorities to access. We also recommend partnering with local fishers to develop bycatch reduction solutions (e.g. see Jenkins, 2007, 2010; Wang et al., 2010, 2013).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version, at <http://dx.doi.org/10.1016/j.biocon.2013.10.017>.

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