Sustaining Small-Scale Fisheries: Ecological, Social, and Policy Challenges and Solutions

by

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ABSTRACT

Small-scale fisheries are globally ubiquitous, employing more than 99% of the world's fishers and providing over half of the world's seafood. However, small-scale fisheries face many management challenges including declining catches, inadequate resources and infrastructure, and overcapacity. Baja California Sur, Mexico (BCS) is a region with diverse small-scale fisheries; these fisheries are intense, poorly regulated, and overlap with foraging hot spots of endangered sea turtles. In partnership with researchers, fishers, managers, and practitioners from Mexico and the United States, I documented bycatch rates of loggerhead turtles at BCS that represent the highest known megafauna bycatch rates worldwide. Concurrently, I conducted a literature review that determined gear modifications were generally more successful than other commonly used fisheries management strategies for mitigating bycatch of vulnerable megafauna including seabirds, marine mammals, and sea turtles. I then applied these results by partnering with researchers, local fishers, and Mexico's federal fisheries science agency to develop and test two gear modifications (i.e. buoyless and illuminated nets) in operating net fisheries at BCS as potential solutions to reduce bycatch of endangered sea turtles, improve fisheries sustainability, and maintain fisher livelihoods. I found that buoyless nets significantly reduced mean turtle bycatch rates by 68% while maintaining target catch rates and composition. By contrast, illuminated nets did not significantly reduce turtle bycatch rates across day-night periods, although they reduced mean turtle bycatch rates by 50% at night. Illuminated nets, however, significantly reduced mean rates of total bycatch biomass by 34% across day-night periods while maintaining target fish catch and market value. I conclude with a policy analysis of the unilateral identification of Mexico

by the U.S. State Department under section 610 of the Magnusson-Stevens Fishery Conservation and Management Act for failure to manage bycatch of loggerhead turtles at BCS. Taken together, the gear modifications developed and tested here represent promising bycatch mitigation solutions with strong potential for commercial adoption, but fleet-wide conversion to more selective and turtle-friendly gear (e.g. hook and line and/or traps) at BCS, coupled with coordinated international conservation action, is ultimately needed to eliminate sea turtle bycatch and further improve fisheries sustainability.

DEDICATION

To my parents – Fred and Denise Senko – for nurturing my passion, and teaching me the power of a dream.

&

To Rafe Sagarin, for teaching me to find beauty, awe, and interconnectedness in everything around me.

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"...the knowledge that all things are one thing and that one thing is all things — plankton, a shimmering phosphorescence on the sea and the spinning planets and an expanding universe, all bound together by the elastic string of time. It is advisable to look from the tide pool to the stars and then back to the tide pool again." –John Steinbeck, *The Log from the Sea of Cortez*

CHAPTER 1

Introduction

I like turtles. Located along the Pacific coast of Mexico, Baja California Sur (BCS) is a region with abundant and diverse small-scale fisheries (Shester and Micheli 2011) as well as a tradition of utilizing marine megafauna such as sea turtles for food, medicine, and decoration (Mancini and Koch 2009; Senko et al. 2010; Mancini et al. 2011). The coastal waters of BCS provide critical feeding and developmental habitat for five of the world's seven sea turtle species: green turtle (*Chelonia mydas*), hawksbill turtle (*Eretmochelys imbricata*), loggerhead turtle (*Caretta caretta*), olive ridley turtle (*Lepidochelys olivacea*), and leatherback turtle (*Dermochelys coriacea*) (Senko et al. 2011). Despite complete federal protection in Mexico, sea turtles continue to be killed as incidental capture (hereafter termed bycatch) in small-scale fisheries (Peckham et al. 2008) and illegally hunted for personal consumption or black market trade at BCS (Mancini and Koch 2009; Senko et al. 2010; Mancini et al. 2011; Senko et al. 2014). However, the extent of current levels of bycatch and hunting remain largely unknown – and more importantly – creative solutions to curb both while maintaining fisher livelihoods are virtually nonexistent. Here, I use three themes to comprise my dissertation: 1) BCS as a model human-environmental system; 2) the bottom-set gillnet and entangling net fisheries of BCS as a model for improving the sustainability of small-scale fisheries and maintaining fisher livelihoods; and 3) the North Pacific loggerhead and green turtle as model endangered megafauna species that are impacted by both bycatch and human consumption.

Broadly, I use BCS as a model human-environment system where conflicting objectives often exist between resource users and managers or practitioners. BCS has a wide variety of small-scale fisheries, ranging from net fisheries to jig fisheries to hook and line and traps, although the majority of fishing is conducted with nets (Peckham and Maldonado 2012). These net fisheries cause extremely high bycatch of the endangered North Pacific loggerhead turtle, with bycatch rates among the highest documented of any marine megafauna worldwide (Peckham et al. 2008; INAPESCA 2012). Many of the coastal fishing communities of BCS have limited infrastructure, are often isolated, and generally have limited economic opportunities beyond fishing (Peckham and Maldonado 2012). In addition, BCS has poor fisheries management; the only regulations for small-scale fisheries are the number of permits issued by the government, although fishers routinely fish without permits. Fish stocks at BCS are declining (Sala et al. 2004), and the government does not appear to have a comprehensive management plan for declining stocks.

I then use BCS net fisheries as a model small-scale fishery to improve the sustainability of small-scale fisheries while maintaining the livelihoods of fishers, primarily from a bottom-up perspective that seeks to inspire and empower local fishers to improve the sustainability of their fisheries. Nets have become ubiquitous in coastal small-scale fisheries, both at BCS and throughout the world, and play an important socioeconomic role in coastal communities because they are inexpensive, easy to build, fish, and maintain, and can yield high landings of mixed species (Shester and Micheli 2011). However, bottom-set nets are notorious for high bycatch of both target and non-target species due to their low selectivity (Chuenpagdee et al. 2003; FAO 2008). Recent research indicates that bycatch of marine megafauna, such as seabirds, marine mammals, and sea turtles, in small-scale coastal net fisheries might approach or in some cases even exceed bycatch in industrial fleets (Jaramillo-Legorreta et al. 2007; Peckham et al. 2007, 2008; Alfaro et al. 2011; López-Barrera et al. 2012; Mancini et al. 2012). Unlike industrial fisheries, however, artisanal fisheries often lack adequate resources to regulate their bycatch impacts (Shester and Micheli 2011). In some high profile cases, governments have limited or closed net fisheries in order to protect endangered megafauna populations, including an international ban on driftnets in the North Pacific (Wetherall et al. 1993), and restrictions on net use in the Gulf of California to protect the critically endangered vaquita porpoise (D'Agrosa et al. 2000). High bycatch mortality in small-scale net fisheries is documented or believed to cause declines in a number vulnerable air-breathing megafauna populations worldwide (D'Agrosa et al. 2000; Tasker et al. 2000; Read et al. 2006; Peckham et al. 2007, 2008; Crowder and Heppell 2011; Alfaro et al. 2011; Casale 2011; Wallace et al. 2013; Hamer et al. 2013).

Coastal small-scale fisheries bycatch and directed harvest of sea turtles at Baja California Sur, Mexico: past and present exploitation

Sea turtles have historically been an important resource for many coastal communities throughout Mexico and have been used for food, decoration, and medicine (Mancini and Koch 2009; Senko et al. 2010). Consumption of sea turtles increased dramatically upon western colonization of Mexico, and during the mid-19th century whalers hunted marine turtles for fresh meat (Scammon 1970; O'Donnell 1974; Nichols 2003; Mancini and Koch 2009). By the end of the 19th century new markets for turtle soup arose in Europe and Asia (Nietschmann 1995; Fleming 2001; Mancini and Koch 2009). Even so, sea turtles were among the most abundant large vertebrate in the Pacific before, and were still plentiful even during, the onset of commercial harvesting. For example, Townsend (1916) states:

> *"When the 'Albatross' visited San Bartolome on April 11, 1889, a very remarkable catch of green turtle was made. The U. S. S. ' Ranger ' was there at the same time and a seining party was made up consisting of members of the crew of that vessel and of the 'Albatross.' In a single haul of a seine 600 feet long we brought to shore 162 green turtles, many of them of large size. Probably half as many more escaped from the seine before it could be beached; there being a continual loss by turtles crawling over the cork lines during the entire time we were hauling it. There are doubtless other bays around the Peninsula which are frequented by turtles at the egg laying season and where large numbers might be obtained by seining. Turtles are plentiful in the Gulf of California, and the 'Albatross' obtained specimens in the vicinity of Willard Bay, on the Peninsula near the head of the Gulf in 1889. During the present cruise, we found deserted turtle camps and an abundance of turtle shells at Tiburon and other islands in the Gulf. Turtles are said to abound near the mouth of the Rio Colorado where their eggs are deposited in the sands. The inhabitants of the Peninsula seem to have no difficulty in obtaining a supply of them. Turtles are sometimes shipped to San Francisco by steamer from Magdalena Bay."*

Increased demand led to greater exploitation throughout the first half of the 20th century (Caldwell 1963; O'Donnell 1974; Cliffton et al. 1995; Mancini and Koch 2009), and as commercial harvest continued to grow, sea turtle populations in Mexico started to decline sharply in the 1950s due to intense fisheries and egg harvesting (Koch et al. 2006, 2007). From the 1950s to the1970s, commercial fisheries in Mexico accounted for 50% of the global sea turtle harvest, consisting mainly of green and olive ridley turtles (Marquez 1990), peaking in 1968 with over 380,000 turtles harvested (Cantu & Sanchez, 1999). Coupled with harvest of nesting females and intense egg collection (~ 70,000 eggs per night at Colola, Michoacan), sea turtle populations began to plummet during the

1970s (Clifton et al. 1982; Alvarado et al. 2001). Populations began to crash in the 1970s when sea turtles were unable to reproduce fast enough in the face of increasing regional and global demand (Garcia-Martinez and Nichols 2001; Senko et al. 2011). Consequently, the Mexican government implemented a recovery program in 1978 and closed all nesting beaches to the harvest of sea turtle eggs. In 1980, the government issued a quota limiting the number of sea turtles that could be taken commercially (Senko et al. 2011). However, populations continued to drop and in 1990, prodded by growing international pressure, Mexico issued a complete moratorium on the use of sea turtles throughout Mexico (Senko et al. 2011).

Despite over two decades of complete federal protection, sea turtles continue to be killed by humans at BCS either as bycatch in small-scale fisheries (Nichols 2003; Koch et al. 2006; Peckham et al. 2007, 2008; Mancini et al. 2009; Senko et al. 2014) or by directed harvest for food or sale on the black market (Koch et al. 2006; Peckham et al. 2008; Mancini and Koch 2009; Senko et al. 2010; Mancini et al. 2011; Senko et al. 2014). Although Mexico has successfully protected its major sea turtle nesting rookeries since the 1990 moratorium, inadequate staffing and funding of federal environmental agencies (e.g. The Secretary of Environment and Natural Resources ‘SEMARNAT,’ and The Federal Attorney General for Environmental Protection ‘PROFEPA’) has led to insufficient enforcement of the law (Senko et al. 2011).

Today, the primary threats to sea turtles at BCS are bycatch in small-scale net fisheries and illegal harvest. In particular, the overlap of local bottom-set entangling and gillnet fisheries with a loggerhead turtle hotspot at BCS produces among the highest recorded sea turtle bycatch rates worldwide (Peckham et al. 2007, 2008; INAPESCA

2012; see chapters 4 and 5). These fisheries result in high mortality because the nets are checked only once every 24 h, causing most entangled turtles to drown (Peckham et al. 2007). Anthropogenic induced mortality of loggerheads at BCS is primarily limited to bycatch in small-scale net fisheries over the past 30 years, as the turtles are not prized for their meat and consequently are usually tossed overboard dead or alive upon removal from the net (Peckham et al. 2008; see below). By contrast, green turtles are prized for their meat at BCS and continue to be hunted illegally for their meat and shells (Mancini and Koch 2009; Mancini et al. 2011; Senko et al. 2014). Today, despite complete federal protection prohibiting their take, they are hunted for their meat, both for personal consumption and sale on black market circuits (Mancini and Koch 2009; Mancini et al. 2011; Senko et al. 2014). Additionally, green turtles continue to be killed as bycatch in small-scale net fisheries (Mancini et al. 2012; Senko et al. 2014; see chapter 3). Population declines in large megafauna, such as sea turtles, can lead to widespread ecological consequences that include cascading effects on lower trophic levels (Estes et al. 2011).

Developing and testing conservation solutions

Although coastal small-scale net fisheries have the capacity to produce high levels of megafauna and finfish bycatch, only a handful of studies have developed and tested net modifications, and very few bycatch reduction solutions have been developed for net fisheries, especially when compared to other high-bycatch fisheries such as trawls and longlines (Senko et al. 2014; see chapter 2). Developing solutions to reduce bycatch in net fisheries is challenging because nets are inherently non-selective, and changing net characteristics such as mesh size and techniques such as soak time often result in substantial decreases in target catch (Gilman et al. 2009). Developing net modifications to reduce megafauna bycatch is important because more selective fishing practices may be less profitable and reduce a fisher's flexibility to optimize catch value. For example, the inherent non-selectivity of nets allows fishers to retain multiple target, and sometimes even non-target species, which reduces and spreads their overall risk. Given the socioeconomic and nutritional importance of small-scale fisheries at BCS and elsewhere around the world (Shester and Micheli 2011), it is imperative to develop creative solutions that mitigate megafauna bycatch while maintaining net fisheries. In particular, set nets lead to high bycatch mortality of vulnerable megafauna species and may alter ecosystem structure and function (Shester and Micheli 2011). During our collaborative work over the past decade at BCS we have partnered directly with local net fishers, convening workshops and running experimental trials to design, test, and implement bycatch reduction solutions as part of the long-term fisher led community-based conservation initiative *ProCaguama*. Two of our most promising bycatch reductions solutions are discussed in chapters 4 and 5.

Dissertation overview

Broadly, my dissertation focuses on the ecological, social, and policy challenges and solutions of small-scale fisheries bycatch and management. Geographically, I focus my research on BCS, a region with among the highest levels of sea turtle bycatch on the planet. Specifically, my dissertation will: 1) assess and identify the extent of small-scale fisheries bycatch at Baja California Sur, Mexico (BCS), focusing primarily on endangered loggerhead and green sea turtles as model species for endangered marine megafauna, while looking at overall bycatch and fisheries sustainability; 2) develop and test creative conservation solutions (i.e. gear modifications in nets) to mitigate small-scale fisheries bycatch at BCS; and 3) assess the potential of the bycatch reduction solutions to be implemented in operating small-scale fisheries at BCS, both from a top-down and bottom-up management perspective. Below I discuss a brief outline of each chapter.

In chapter 2 I compare three common bycatch mitigation strategies (i.e. closures, take-limits, and gear modifications) for vulnerable marine megafauna. I found that gear modifications were generally more successful than time-area closures, take limits, and buy-outs, which led me to help develop and test two unique gear modifications for reducing bycatch of sea turtles at BCS. In chapters 3 and 4, I outline development and testing of buoyless and illuminated nets, respectively, as a means to reduce bycatch of endangered loggerhead turtles while maintaining fisher livelihoods in operating entangling net fisheries at BCS. In chapter 5, I discuss the policy challenges of managing endangered sea turtles at BCS, with a focus on international governance. In particular, I analyze the 2012 unilateral identification of Mexico by the U.S. State Department under section 610 of the Magnusson-Stevens Fishery Conservation and Management Reauthorization Act, the primary law the codifies marine fisheries management in U.S. federal waters, for failure to manage bycatch of loggerhead turtles in net fisheries at BCS. In chapter 6, I assess anthropogenic mortality, including bycatch in small-scale fisheries, of endangered green turtles at nine index sites along the BCS peninsula. Finally, I conclude in chapter 7 with an assessment of the future of small-scale fisheries bycatch and management at BCS.

CHAPTER 2

Comparing Bycatch Mitigation Strategies for Vulnerable Marine Megafauna

Introduction

Recent research has identified significant declines in fish stocks from global industrial fisheries, with at least half of all fisheries either fully exploited or overexploited (Worm et al. 2009; Branch et al. 2011; Ricard et al. 2011). Fishing effort has increased worldwide over the past few decades (Swartz et al. 2010; Anticamara et al. 2011), leading to concerns over the impacts on non-target animals and habitats (Lewison et al. 2004a; Lewison et al. 2011). Marine megafauna such as seabirds, marine mammals, and sea turtles are often subject to incidental mortality from fishing (Lewison et al. 2004a). Incidental capture of non-target species in fisheries, termed bycatch, is known or believed to cause declines in several marine megafauna populations worldwide (Lewison et al. 2004a; Peckham et al. 2007; Zydelis et al. 2009). These declines can have widespread ecological consequences, including extensive cascading effects on lower trophic levels (Estes et al. 2011).

Marine megafauna are particularly vulnerable to population-level impacts from bycatch due to their life history characteristics (e.g. long lifespans, late maturity, slow reproductive rates, and wide-ranging movements) and propensity to interact with fisheries (Heppell et al. 2005; Peckham et al. 2007; Zydelis et al. 2009). Furthermore, many species frequently occur in close proximity to the coast (Block et al. 2011), and use nearshore habitats throughout their lives or during sensitive life stages (e.g. breeding/nursery areas, foraging hotspots, movement corridors). As human populations continue to rise, fishing effort is increasing in coastal areas worldwide (Stewart et al. 2010), highlighting the importance of evaluating strategies that seek to minimize interactions between marine megafauna and fisheries.

A review of bycatch species and management strategies can provide guidance for future planning and evaluation of mitigation efforts. Here we use three focal species (i.e. leatherback turtle, black-footed albatross, and vaquita porpoise) as case studies to compare management outcomes of four bycatch mitigation strategies (i.e. time-area closures, individual bycatch limits, gear modifications, and buy-outs). Due to inherent difficulties in evaluating mitigation methods across studies (Bull 2007), our goal was to compare how the focal species responded to each management strategy by qualitatively synthesizing management outcomes from available published data. While our three focal species do not represent all marine megafauna-fisheries interactions, they provide detailed examples for each of three major taxa groups that illustrate the range of issues we address. We selected the focal species because they are not targeted in fisheries, use pelagic and coastal habitats, occupy a broad range of positions in the food chain, are flagship species for conservation, encompass small and large distributions, and are jeopardized by bycatch in industrial and small-scale fisheries (Table 2.1). Based on lessons learned from these species, we highlight when and where a particular strategy would work best, provide recommendations for improving each technique, and outline priorities for future research.

Focal species: Leatherback turtle

Life history characteristics and current population status

Leatherback turtles (*Dermochelys coriacea*) are the largest, deepest diving, and most migratory of all sea turtles, exhibiting the broadest geographic range of any living reptile (Eckert et al. 2012). They forage in temperate and subarctic waters worldwide and nest on tropical and subtropical beaches (Eckert et al. 2012). Leatherbacks are currently listed as critically endangered by the International Union for Conservation of Nature (IUCN 2012a). In the Pacific and Indo-Pacific, populations have declined precipitously and face extirpation within the next generation (Spotila et al. 2000), although smaller populations in the Atlantic appear to be increasing (TEWG 2007; Stewart et al. 2011). The last published global population estimate suggested 34,500 nesting females (Spotila et al. 1996), although recent research estimated that the world's largest nesting population in West Africa had 15,730 – 41,373 females (Witt et al. 2009).

Fishery interactions and bycatch impacts

Incidental bycatch in fisheries represents a serious threat to leatherback populations worldwide (Lewison et al. 2004b; Lewison and Crowder 2007; Eckert et al. 2012). In pelagic longline fisheries, leatherbacks are attracted to baited hooks and usually become entangled in the gear, but are also occasionally hooked in the mouth (Gilman et al. 2006a; Read 2007). The best estimate of direct mortality from being entangled or hooked in the mouth ranges from 4–27% (Lewison and Crowder 2007). In passive fisheries such as mesh net and pot fisheries, leatherbacks become entangled (Gilman et al. 2010; Eckert et al. 2012), whereas they are captured in trawl fisheries (Cox et al. 2007). In the year 2000 alone more than 50,000 leatherbacks were estimated to be hooked in Pacific pelagic longline fisheries (Lewison et al. 2004b), and large nesting populations in the Caribbean are jeopardized by persistent bycatch in mesh net fisheries (Eckert et al. 2012). Entanglement in mesh net fisheries may cause higher mortality than longlines (Lewison and Crowder 2007), and leatherbacks frequently encounter these fisheries while inhabiting coastal waters during the breeding season (Eckert et al. 2012).

Black-footed albatross

Life history characteristics and current population status

Black-footed albatross (*Phoebastria nigripes*) reach maturity in 8 – 10 years, live 40 – 50 years, mate for life, and produce one chick per breeding season (Lewison and Crowder 2003). Their range encompasses the North Pacific and approximately 95% of the population nests in the northwestern Hawaiian Islands (Arata et al. 2009). The species is currently listed as vulnerable by the International Union for Conservation of Nature (IUCN 2012b), with the most recent population estimated at 129,000 individuals based on counts from the 2006 – 2007 breeding season (Flint 2007). The species is expected to decline rapidly over the next three generations (2009 – 2065) if bycatch mitigation measures in longline fisheries are inadequate (IUCN 2012b), although the current population is believed to be stable or slightly increasing (Arata et al. 2009).

Fishery interactions and bycatch impacts

Black-footed albatross are taken as bycatch in pelagic and demersal longline fisheries throughout their range, as their foraging distribution frequently overlaps with these fisheries (Fischer et al. 2009). Bycatch also occurs in driftnet fisheries (IUCN 2012b), trawl fisheries (Fischer et al. 2009), and possibly gillnet and troll fisheries

(Lewison and Crowder 2003). In longline fisheries, black-footed albatross are attracted to baited hooks when lines are deployed, and drown after they are hooked and pulled underwater (Lewison and Crowder 2003). Bycatch in US, Japanese, and Taiwanese pelagic longline fisheries may kill 5,000 to 14,000 animals per year (Lewison and Crowder 2003).

Vaquita porpoise

Life history characteristics and current population status

The vaquita porpoise (*Phocoena sinus*) is the world's smallest and most endangered cetacean (Rojas-Brancho et al. 2006; Jaramillo-Legorreta et al. 2007). This critically endangered species (IUCN 2012c) is endemic to shallow waters (<40 m) in the northern Gulf of California and occupies the smallest known range of any cetacean (Rojas-Brancho et al. 2006; IUCN 2012c). Given their cryptic nature and naturally low abundance, little is known about vaquita life history characteristics. The most current population estimates from 2007 range from 150 (Jaramillo-Legorreta et al. 2007) to 226 individuals (Gerrodette and Rojas-Brancho 2011), down from an estimate of 500 – 600 individuals in the late 1990s (Jefferson et al. 2008).

Fishery interactions and bycatch impacts

Vaquita are incidentally taken in mesh net and trawl fisheries throughout their range in the upper Gulf of California, where they drown after being entangled or captured. It is believed that vaquita started declining in the 1940s when large-mesh gillnet fisheries targeting totoaba (*Totoaba macdonaldi*) first became widespread in the Gulf (Rojas-Brancho et al. 2006). Small-mesh gillnet and trawl fisheries targeting shrimp, elasmobranches, and finfish are now the greatest threat to vaquita following the collapse and closure of the totoaba fishery in the early 1980s (D'Agrosa et al. 2000; Rojas-Bracho et al. 2006; Barlow et al. 2010). The only known statistical bycatch rate estimated that at least 39 individuals were taken per year from 1993 – 1995 in just one of three main fishing areas in their range (D'Agrosa et al. 2000), and recent research suggests that vaquita bycatch needs to be eliminated in order to prevent their imminent extinction (Jaramillo-Legorreta et al. 2007; Gerrodette and Rojas-Brancho 2011).

Overview and synthesis of fishery management strategies

Time-area closures

Many marine megafauna form spatially and temporally predictable aggregations that become focal areas for both conservation and fisheries. Time-area closures are employed for marine megafauna to reduce bycatch or protect sensitive life stages (Grantham et al. 2008; Vanderlaan et al. 2008; Game et al. 2009; Armsworth et al. 2010), and vary in jurisdiction, timing, and size. Time-area closures may prohibit fishing, allow fishing only within specific areas or at specific times, or permit fishing for non-target species. In general, time-area closures are easier to monitor and enforce within the Exclusive Economic Zones of the regulating nation; regulation in international waters is restricted to the fisheries of the regulating nation or international agreements (Leathwick et al. 2008). Table 2.2 summarizes published data for time-area closures for each case study.

Leatherback turtle

Time-area closures have been employed in a few fisheries to mitigate leatherback bycatch. A time-area closure in the mid 1990s (a large area referred to as the 'Pacific leatherback conservation area') dramatically reduced bycatch in the Northeastern Pacific gillnet fishery (Moore et al. 2009). However, a tagging study of leatherbacks in the North Atlantic found that relatively few animals utilized an area closed to U.S. pelagic longliners to protect turtles, and most of the tagged animals traveled much farther distances to other non-protected areas of high pelagic longline use (James et al. 2005). In addition, during a 4-year closure of the Hawaii longline swordfish fishery, leatherback bycatch was simply redistributed via other fisheries when imports from longline fleets (that replaced the Hawaii fleet) exhibited considerably higher ratios of leatherbacks to unit weight of swordfish. (Gilman et al. 2006a).

Black-footed albatross and vaquita porpoise

Time-area closures have generally not been employed for black-footed albatrosses, likely because gear modifications are more popular amongst fishers, easier to implement both economically and socio-politically, and more likely to be voluntary or "bottom-up". In one published example, the closing of high-seas squid and salmon driftnet fisheries reduced the number of black-footed albatross killed annually (Naughton et al. 2007).

Time-area closures have been used over the past two decades to reduce vaquita bycatch. In 1993 the first biosphere reserve was established in the northern Gulf of California and Colorado River Delta (Rojas-Bracho et al. 2006), but populations declined 70% over the next 15 years (1993-2008) (Gerrodette and Rojas-Brancho 2011). These declines appear to have continued even after a time-area closure specifically designed for vaquita was established in 2005, with an estimated population decline of 25% from 2005-2008 (Gerrodette and Rojas-Brancho 2011). Although these closures have not produced measurable conservation outcomes, this appears to be a failure of implementation as the current spatial scale does not cover their entire range and enforcement has been inadequate (Gerrodette and Rojas-Brancho 2011).

Individual bycatch limits

Individual bycatch limits cap the number of marine megafauna that a given fishery can remove as bycatch via observers or electronic surveillance on fishing vessels. Bycatch limits are usually determined by potential biological removals (PBRs) and biological opinions, and impose costs on a fishery for exceeding the cap (Holland 2010). For example, the Hawaii longline swordfish fishery operates under annual bycatch limits for sea turtles, including turtles that are hooked, but released alive (Holland 2010). Take limits for leatherbacks in this fishery are established using PBR-like and quasi-population viability approaches (Snover 2008; Moore et al. 2009).

Leatherbacks turtle

Individual bycatch limits exist for leatherbacks in some US commercial fisheries based on extrapolation of observed takes. The Hawaii longline swordfish and tuna fishery have employed individual bycatch limits on the number of leatherbacks taken annually. From 2004 to 2010 leatherback interactions in the Hawaii shallow-set longline fishery were below the 16-leatherback limit. However, in November of 2011 the fishery reached the 16-leatherback limit and was immediately closed for the remainder of the year (NOAA 2012).

Black-footed albatross and vaquita porpoise

To our knowledge, individual bycatch limits have not been employed for black-footed albatrosses or vaquita porpoises. Bycatch limits have not been used for vaquita porpoises because an observer program would be difficult to implement in the small-scale northern Gulf of California fisheries. Additionally, bycatch likely needs to be eliminated in order to prevent their extinction (Jaramillo-Legorreta et al. 2007; Gerrodette and Rojas-Brancho 2011). Individual bycatch limits have not been employed for black-footed albatross because gear modifications are likely more popular with fishers and potentially more cost effective.

Gear modifications

Gear modifications for marine megafauna include fishing gear designs that are less attractive or act as deterrents to non-target species, and mechanisms that allow escape or quick release of bycatch species (Hall 1996; Wang et al. 2010). Gear modifications are usually popular with fishers because they seek to avoid potentially more economically and politically costly decisions, and in some cases fishers have advocated for them as a means to avoid fishery closures (Campbell and Cornwell 2008). By keeping fishers fishing in desired locations and reducing bycatch, gear modifications present a potential “win-win” scenario for fishers and fishery managers if adequately implemented (e.g. see Jenkins, 2007, 2010). Table 2.3 summarizes published data on gear modifications for the focal species.

Leatherback turtle

Gear modifications for leatherback turtles include circle hooks and bait/line modification for pelagic longline fisheries, Turtle Excluder Devices (TEDs) for trawl fisheries, and net modifications for mesh net fisheries (Gilman et al. 2006a; Gilman et al. 2010). Circle hooks and bait changes have decreased bycatch in pelagic longline fisheries by 75%, 83%, "significantly" (no percent reduction was given), 91%, and 67% (Watson et al. 2004; Gilman et al. 2007a; Garrison 2003; Santos et al. 2012; Pacheco et al. 2011), respectively. In all cases where circle hooks were combined with bait changes, reductions were observed when squid was replaced with mackerel or sardines (see Table 2.3). Observer data (Gilman et al. 2007a) and experiments (Watson et al. 2002) suggest that fewer leatherbacks were caught as bycatch on deeper branch lines. Similarly, lower profile nets in a gillnet fishery reduced leatherback bycatch by 32% and also increased catch rates of target species (Eckert et al. 2008). Regulations that increased the opening size of TEDs likely reduced annual leatherback mortality by 97% in US trawl fisheries (Epperly et al. 2002), and recent research suggests that gear modifications were largely responsible for reductions in leatherback bycatch and mortality between 1990 and 2007 (Finkbeiner et al. 2011). Two studies reported decreases in catch rates of some target species (Table 2.3).

Black-footed albatross

Gear modifications for reducing black-footed albatross in pelagic longline fisheries include tori lines (streamers that hang from a line attached at the stern of a fishing vessel), line-weighting, side setting (setting longline gear from the side versus the stern), bird curtains, night setting, setting in specific areas, and bait-dyeing (Hyrenbach and Dotson 2003; Gilman et al. 2007b). In three separate studies, blue-dyed bait reduced bycatch by 95%, 94%, and 63% (McNamara et al. 1999; Boggs 2001; Gilman et al. 2003b), respectively. Similarly, streamer lines reduced bycatch by 86% (McNamara et al. 1999) and contact rates with hooks by 76% (Boggs 2001). Night setting decreased bycatch by 97% (McNamara et al. 1999), 93% (Boggs 2001), 69% (Gilman et al. 2008), 98% (Boggs 2001), and 98% (100% when combined with blue-dyed bait) (Boggs 2003). Side setting eliminated bycatch in two studies (Gilman et al. 2003b, 2007a) and also eliminated the need to move bait and gear between two work stations, increased deck space, did not foul gear in the propeller, and carried no additional costs after the initial conversion (< $1000 US) (Gilman et al. 2007b). The use of a 9 m underwater setting chute and 6.5 m underwater setting chute decreased combined black-footed-Laysan albatross bycatch rates by 38% and 88%, respectively (Gilman et al. 2003b). Weighted lines decreased contact rates with hooks by 92% (Boggs 2001), and the use of a towed buoy and changes in offal discard practices mitigated bycatch by 86% and 88%, respectively (McNamara et al. 1999). In the Hawaii longline tuna fishery, multiple mandated gear modifications resulted in a 67% significant decrease in combined black-footed-Laysan albatross bycatch rates (Gilman et al. 2008). No studies reported decreases in catch rates or operational efficiency (Table 2.3).

Vaquita porpoise

Various gear modifications have been implemented under "switch-outs" (see buy-outs section) to reduce vaquita bycatch (Avila-Forcada et al. 2012). The RS-INP shrimp trawl (developed by Mexico's National Fisheries Institute; INAPESCA) and Scorpion and Box trawl (developed by Southeast Fisheries Science Center) have been tested over the past 20 years to reportedly eliminate vaquita (and sea turtle) bycatch (Aguilar-Ramírez et al. 2010; CIRVA Technical Report 2012). Field trials have shown that the industrial version of the RS-INP trawls reduced bycatch-to-shrimp ratios between 20 – 50%, significantly reduced fish bycatch, consumed less fuel, and caught more shrimp (CIRVA Technical Report 2012). Both the industrial and artisanal RS-INP design caught similar sizes of shrimp, with the artisanal version catching larger shrimp and proving more profitable than traditional trawls (CIRVA Technical Report 2012). The Mexican National Commission of Natural Protected Areas (CONANP) is currently encouraging and facilitating fishers to use hook and lines as well as fish traps instead of drift gillnets, while INAPESCA is testing the effectiveness of fish traps and trawls equipped with turtle excluder devices instead of gillnets (CIRVA Technical Report 2012; pers. comm. INAPESCA 2013). No studies reported decreases in catch rates or operational efficiency (Table 2.3).

Buy-outs

Leatherback turtle and black-footed albatross

To our knowledge, buy-outs have not been employed for black-footed albatross. Switch-outs have been employed to reduce leatherback (and loggerhead) bycatch in Ecuadorian surface longline fisheries. From 2004 to 2007, the World Wildlife Foundation, Inter-American Topical Tuna Commission, and NOAA developed and implemented a circle hook exchange program where 330,569 J hooks were exchanged for circle hooks on 169 boats (Mug et al. 2008). In the mahi-mahi fishery, circle hooks significantly reduced combined leatherback-loggerhead bycatch rates, but also significantly reduced target catch rates of mahi-mahi (Mug et al. 2008). In the tuna, billfish, and shark fishery, circle hooks significantly reduced leatherback-loggerhead bycatch rates, with no effect on target catch rates. However, Mizrahi (2008) suggests that the use of circle hooks in this fishery may result in increased shark catches.

Vaquita porpoise

In 2008, the Mexican government issued a buy-out program that included buy-outs, switch-outs, and rent-outs, and devoted almost $20 million US to its implementation (Morell 2008; Avila-Forcada et al. 2012). Fisher participation in the rent-out option was larger for fishers with savings and those who were members of cooperatives (Avila-Forcada et al. 2012). The switch-out option was chosen by fishers who owned their own boats, but participation decreased with the amount of profits per boat. True buy-outs attracted only older fishers who were planning to retire soon or fishers who possessed alternative skills, and became increasingly scarce as initial fishers set to retire were bought out (CIRVA Technical Report 2012). This is likely because fishers not set to retire wanted to continue fishing, and may even benefit from less competition when other fishers are bought out (Gerrodette and Rojas-Brancho 2011). The number of fishers entering the program has also changed since 2008, with 746, 324, and 683 fishers choosing one of the three options in 2008, 2009, and 2010, respectively (Avila-Forcada et al. 2012). The fishers that chose buy-outs and switch-outs (171 and 154) represent 8.2% and 7.4% of the estimated total fleet size in 2007, indicating that 15.6% of fishers have permanently switched to vaquita-safe fishing gear (Avila-Forcada et al. 2012). Furthermore, the buy-out has reportedly led to a 30% reduction in the number of gillnet vessels operating in the vaquita refuge in 2008 and 2009 (Gerrodette and Rojas-Brancho, 2011), although it is unknown if vaquita bycatch has decreased.

Lessons learned from focal species: when and where to implement a particular strategy?

Time-area closures appeared to be of limited effectiveness for the focal species. Two of the three examples for leatherbacks reported that time-area closures were either the wrong size or re-distributed bycatch (Table 2.2). In these cases, gear modifications or bycatch limits likely would have been more effective than closures (Table 2.4). Similarly, closures for vaquitas were consistently too small and inadequately enforced (Gerrodette and Rojas-Brancho 2011), suggesting that gear modifications may have been more effective if implemented in a top-down manner (see recommendations below; Table 2.4). Both black-footed albatrosses and leatherbacks were taken at high levels in Hawaiian longline fisheries. In areas with many fisheries or in fisheries with multiple bycatch species, time-area closures may be preferable (Game et al. 2009; Lewison et al. 2009; Table 2.4).

Time-area closures versus other strategies

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Individual bycatch limits versus other strategies

Individual bycatch limits were rarely used as a bycatch mitigation tool for the focal species, likely because they require observers on most vessels to implement this technique. This is particularly difficult to enforce in small-scale fisheries and in countries that cannot afford observer programs (Lewison et al. 2004a). Although it is difficult to draw conclusions based on the focal species, we postulate that bycatch limits may be favored by fishers in cases where gear modifications result in decreased target catches or when closures move fishers into areas with lower target catches because bycatch limits avoid spatial redistribution of effort (if they apply to all fisheries) (Table 2.4). Another potential advantage of bycatch limits is that they do not require extensive field-testing (assuming bycatch per vessel can be adequately estimated) (Table 2.4).

Gear modifications versus other strategies

In our literature review, gear modifications were consistently successful at reducing bycatch. However, in almost all cases a single fishery was responsible for high bycatch, suggesting that gear modifications may be more effective in cases where a single fishery results in high bycatch (Lewison et al. 2009; Table 2.4). Gear modifications have the added benefit of not redistributing bycatch; in cases where there is a high risk of bycatch being redistributed in other fisheries following closures, buy-outs, or closures resulting from bycatch limits being reached, gear modifications may be more effective over the other three strategies (Table 2.4). Additionally, in fisheries where target catches are not significantly reduced and fishers help develop the technology, gear modifications may have the added benefit of being favored by fishers (Table 2.4). Fishers may even be willing to accept a modest decrease in target catch if the modification allows them to fish in an area that would otherwise be closed (Read 2007).

Buy-Outs versus other strategies

True buy-outs were only used as a bycatch mitigation tool for our rarest species (i.e. vaquita). Although it is difficult to draw conclusions based on our focal species, we suggest that buy-outs are only an option in cases where immediate action is required and the socioeconomic consequences have been properly evaluated. In particular, they should only be considered over the other three options if a majority of fishers are willing to be bought out, if the buy-out will be adequately enforced, if fishers can find new jobs, and if the buy-out can produce measurable bycatch reductions.

Management applications: recommendations for improving strategies

Our focal species exhibited considerable differences in their response to each strategy, highlighting the need to evaluate measures in the context of species-fishery interactions, fishery dynamics, and socioeconomic conditions (Gilman et al. 2006b; Campbell and Cornwell 2008). All management approaches should ideally be developed and implemented in a bottom-up approach, as fishers are much more likely to comply with mitigation measures that work well from an economic and operational standpoint, regardless of whether these measures are mandated or voluntary (Cox et al. 2007). For example, fishers in the Hawaii longline tuna fishery voluntarily attached weights of 45 g or more within 1 m of the hook in 92% of sets at fishing grounds where seabird mitigation measures were not required (Gilman et al. 2008). Additionally, more studies should report on follow up implementations. Although a number of strategies we reviewed reduced bycatch, few studies reported on their long-term viability. Here, we outline recommendations for improving each strategy.

Bycatch limits can be improved by providing incentives for individual fishers to avoid bycatch since the limit is a common good shared by all fishers, which may actually create a disincentive for bycatch whereby fishers try to optimize catch without trying to reduce bycatch because other vessels will simply reach the limit (Ning et al. 2009). Consequently, auctioning bycatch limits, also referred to as bycatch shares, may be one possibility to providing an incentive for bycatch mitigation by allowing vessels to transfer takes so that individual vessels are rewarded for reducing bycatch (Ning et al. 2009). However, this will be difficult to achieve in fisheries where the number of individual animals that can be legally taken is far fewer than the number of vessels in the fishery (e.g. leatherback bycatch limits in Hawaii longline fisheries) (Holland 2010).

Gear modifications appear to be more effective when treatment methods are combined (e.g. hook/line and bait changes), although this is highly dependent on a number of factors. Further, although many gear modifications reduce bycatch in experimental trials, actual practice in fisheries is less effective (Cox et al. 2007; Campbell and Cornwell 2008). Thus, involving fishers in developing and testing gear modifications is critical for achieving fisher adoption of and compliance with gear modifications (Cox et al. 2007; Jenkins 2007, 2010; Lewison et al. 2011). For example, the most widely adopted gear modifications in the US have been those developed by fishers (Jenkins 2010). Gear modifications are also more likely to be adopted if they are developed locally, due in part to a “local inventor effect” where familiarity with the inventor or his reputation may influence adopters’ decision (Jenkins 2007, 2010).

Buy-outs can be improved by better understanding the socioeconomic consequences of the type of buyout chosen and how fishers will respond, the type of payment plan to be issued to fishers, and how to prevent new vessels from entering a fishery after a buy-out (Squires 2010). As demonstrated by our case study of vaquita, buyouts will only work if fishers are willing to accept them. Further, when integrating switch-outs with gear modifications, managers should consider compensating fisher’s on a year-to-year basis for revenue losses if target catch rates decrease.

Research priorities: integrating demographic and socioeconomic models

Demographic models have helped inform fishery management by monitoring population trends and determining which life stages are most sensitive (Caswell 2001). For example, Gerrodette and Rojas-Brancho (2011) and others (e.g. see Slooten 2007 and Slooten and Dawson 2009) have developed demographic models to assign different probabilities of population increases for various management schemes. In addition, bycatch assessment models that estimate reference points (i.e. sustainable impact levels) are being developed to address limited data and high uncertainty in population parameters (Moore et al. 2013). Future research should integrate demographic and bycatch assessment models with socioeconomic models, including fisher behavior, to develop predictive and decision-based models that assess potential outcomes of different management strategies (Fujitani et al. 2012; Hughes et al. 2011). All possible management techniques can be “tested” to determine their potential efficacy while accounting for both biological and socioeconomic factors as parameters. In particular, models should carefully balance fisher behavior (e.g. whether or not fishers are willing to accept a particular management plan) with biological factors. For example, Morzaria-Luna et al. (2012) demonstrated that the best management plan for vaquita also led to a loss of income in fisheries that could not be recovered, while Hughes et al. (2011) incorporated fishery demographics with tourism, fishing effort, and land use to examine the effects of different fishery management plans.

TABLE 2. 1. Status, life history characteristics, bycatch impacts, and current bycatch mitigation strategies of the three focal species; x indicates that the management strategy has been implemented or tested

Focal species	Current IUCN status	Distribution	Habitat use	Primary bycatch/ fishery	Bycatch limits	Gear modifications	Time-area closures	Buy-outs
Leatherback turtle	Critically endangered	Global	Pelagic; coastal during breeding season	Longline, mesh net/ industrial and small-scale	x	x	x	x*
Black-footed albatross	Vulnerable	North Pacific	Pelagic; coastal during breeding season	Longline/industrial-scale		x	x	
Vaquita porpoise	Critically endangered	Northern Gulf of California	Nearshore coastal	Mesh net, trawl/small-scale		x*	x	x

*Testing of gear modification using a “switch-out”, which is a type of buy-out program that compensates fishers that use modified fishing gear. See text for further details.

TABLE 2. 2. Synthesis of time-area closures for three focal marine megafauna species.

Focal species	Fishery	Known reduction in bycatch	Summary of management outcome	References
Leatherback turtle	California/Oregon drift-net fishery	Yes	Bycatch reduced from a mean of 14 turtles killed/year to zero.	Moore *et al.* (2009)
Leatherback turtle	Hawaii longline swordfish fishery	No	Four-year closure redistributed bycatch to other fisheries.	Gilman *et al.* (2006)
Leatherback turtle	North Atlantic pelagic longline fishery	No	Tagged animals traveled to non-protected areas.	James *et al.* (2005)
Black-footed albatross	High-seas squid and salmon driftnet fisheries	Yes	Significantly reduced number of animals killed each year.	Naughton *et al.* (2007)
Vaquita porpoise	Northern Gulf of California small-scale gillnet fishery	No	70% and 63% population decline following closure (from 1993-2005).	Gerrodette & Rojas-Brancho (2011); Morzaria-Luna *et al.* (2012)
Vaquita porpoise	Northern Gulf of California small-scale gillnet fishery	No	25% population decline (from 2005-2008) after additional refuge area.	Gerrodette & Rojas-Brancho (2011)
Vaquita porpoise	Northern Gulf of California small-scale gillnet fishery	No	Estimated 8% to 99% probability of population increase from 2008-2018 based on three potential sizes of closure after PACE-Vaquita.	(Gerrodette & Rojas-Brancho (2011); CIRVA Technical Report (2012)

TABLE 2. 3. Synthesis of gear modifications for three focal marine megafauna species.

Focal species	Fishery	Known reduction in bycatch or contact rates	Known reduction in target catch rates or operational efficiency	Summary of management outcome	References
Leatherback Turtle	Hawaii longline swordfish fishery	Yes	Target-species dependent	Circle hook and fish bait versus J hooks and squid bait significantly reduced bycatch rates by 83%, although success appears to depend on switching baits from squid to mackerel. Catch rates of some target species reduced.	Gilman *et al.* (2007a)
Leatherback Turtle	Hawaii longline fleet	Unknown	Unknown	Observer observations and line experiments showed more turtles hooked on shallowest branch lines.	Kleiber & Boggs (2000); Watson *et al.* (2002, 2005)
Leatherback Turtle	US Atlantic pelagic longline swordfish fishery	Yes	Target-species dependent	From 2002 and 2003 circle hooks baited with squid reduced bycatch rates by 75% compared to J hooks baited with squid, while circle hooks baited with mackerel reduced bycatch rates by 67% compared to J hooks baited with mackerel. Catch rates of some target species increased or reduced.	Watson *et al.* (2004)
Leatherback Turtle	Gulf of Mexico USA pelagic longline fishery	Yes	Unknown	Circle hooks baited with sardines during the day significantly reduced bycatch rates compared to J hooks baited with squid at night.	Garrison (2003)
Leatherback Turtle	Trinidad surface gillnet mackerel fishery	Yes	No	Lower profile nets significantly reduced bycatch rates by 32%. Target catch rates increased.	Eckert *et al.* (2008)
Leatherback Turtle	Gulf of Mexico and Southeast US shrimp trawl fisheries	Yes	Unknown	Increased opening size of TEDs estimated to reduce bycatch mortality by 97%.	Epperly *et al.* 2002
Leatherback Turtle	US fisheries	N/A	N/A	Gear modifications largely responsible for bycatch reductions from 1999 to 2007.	Finkbeiner *et al.* (2011)
Leatherback Turtle	Portuguese swordfish pelagic longline fishery	Yes	Unknown	Circle hooks baited with mackerel reduced bycatch rates by 91% compared to J hooks baited with squid.	Santos *et al.* (2012)
Leatherback Turtle	South Atlantic pelagic tuna longline fishery	No**	No	Circle hooks with the same bait significantly reduced bycatch composition by 67% compared to J hooks. Circle hooks significantly increased catch rates of primary target species (bigeye tuna).	Pacheco *et al.* (2011)
Black-Footed Albatross	US North Pacific swordfish and tuna pelagic longline fisheries	Unknown	Unknown	Weighted lines, line-setting, and blue-dyed bait likely reduced annual bycatch mortality.	Melvin *et al.* (2001)
Black-Footed Albatross	US North Pacific swordfish and tuna pelagic longline fishery	Yes	No	Blue-dyed bait, a towed buoy, offal discards, streamer lines, and night setting reduced bycatch rates by 95%, 88%, 86%, and 97%, respectively. Blue-dyed bait increased target catch rates, while the others had no apparent effect.	McNamara *et al.* (1999)

TABLE 2. 3. Synthesis of gear modifications for three focal marine megafauna species. Continued...

Focal species	Fishery	Known reduction in bycatch or contact rates	Known reduction in target catch rates or operational efficiency	Summary of management outcome	References
Black-Footed Albatross	Hawaii longline swordfish fishery	Yes***	Unknown	Blue-dyed bait, streamer lines, and 60 g swivel weights 3.7 m above the bait reduced contact rates by 95%, 75%, and 93%, respectively.	Boggs (2001)
Black-Footed Albatross	Hawaii longline tuna fishery	Yes***	No	A 9 m underwater setting chute reduced combined black-footed-Laysan albatross contact rates by 95%. Based on bait retention, vessels would experience a gain in efficiency between 14.7% and 29.6%.	Gilman *et al.* (2003a)
Black-Footed Albatross	Hawaii longline swordfish fishery	Yes	N/A	Night setting and night setting + blue-dyed squid bait significantly reduced bycatch by 98% and 100%, respectively.	Boggs (2003)
Black-Footed Albatross	Hawaii longline tuna fishery	Yes	No	A 9 m underwater setting chute, 6.5 m underwater setting chute, blue-dyed bait, and side-setting reduced combined black-footed-Laysan albatross bycatch by 38%, 88%, 63%, and 100%, respectively. Side setting and blue-dyed bait did not significantly reduce setting time.	Gilman *et al.* (2003b)
Black-Footed Albatross	Hawaii longline tuna and swordfish fisheries	Yes	No	Side-setting eliminated bycatch. Side setting eliminated the need to move gear and bait between two work stations, increasing available deck space.	Gilman *et al.* (2007b)
Black-Footed Albatross	Hawaii longline tuna fishery	Yes	No	Multiple mandated gear modifications resulted in a 67% significant decrease in black-footed-Laysan albatross bycatch rates. Weighted lines and side-setting presented several operational benefits.	Gilman *et al.* (2008)
*Vaquita porpoise	Northern Gulf of California gillnet fishery	Yes****	No	Modified trawl nets reportedly eliminated vaquita bycatch in trials. The industrial version reduced bycatch-to-shrimp ratios between 20 – 50%, significantly reduced fish bycatch, consumed less fuel, and caught more shrimp, while the artisanal version caught larger shrimp and was more profitable.	Aguilar-Ramírez *et al.* (2010); CIRVA Technical Report (2012)
*Vaquita porpoise	Northern Gulf of California gillnet fishery	N/A	N/A	The Mexican National Commission of Natural Protected Areas is promoting the use of hook and line and traps instead of drift gillnets, which do not catch vaquita.	CIRVA Technical Report (2012)
*Vaquita porpoise	Northern Gulf of California gillnet fishery	N/A	N/A	Mexico's National Fisheries Institute is testing the effectiveness of fish traps, which are believed to eliminate vaquita bycatch.	CIRVA Technical Report (2012)

*Gear modification implemented or currently being tested under a "switch-out", which is a type of buy-out program that pays fishers to use modified fishing gear. See text for further details.
**Significant reduction in number of turtles caught using circle hooks (12 vs. 4), but no significant difference was found in bycatch rates due to small sample size.
***Bycatch expressed as contact rates does not necessarily result in birds being hooked or killed.
****Eliminated bycatch in trials, but given the rarity of vaquita bycatch events, it was impossible to compare bycatch rates.

TABLE 2. 4. Potential comparative advantages of four bycatch mitigation strategies for vulnerable marine megafauna. Advantage of strategy in column 1 is compared against strategies in columns 2-5

Management Technique	Gear modifications	Time-area closures	Bycatch limits	Buy-outs
Gear modifications		Keeps fishers fishing May be more effective when bycatch events are dispersed May be more effective when a single fishery results in high bycatch "Bottom-up" approach may be more popular with fishers and easier to enforce Unlikely to redistribute bycatch	Will not result in closed fishery if limit exceeded Potentially more expensive in short-term, but may be less costly in long-term because there is no need to pay observers May avoid disincentives to reduce bycatch "Bottom-up" approach may be more popular with fishers and easier to enforce	〈 Keeps fishers fishing 〈 Avoids potentially costly socioeconomic impacts 〈 May be easier to implement 〈 "Bottom-up" approach may be more popular with fishers and easier to enforce 〈 Unlikely to redistribute bycatch
Time-area closures	May be more effective when bycatch events are clustered May be more effective where > one species are taken as bycatch May be more effective in areas with many high bycatch fisheries		May be easier to implement if observer effort is unrealistic May avoid disincentives to reduce bycatch	〈 Avoids potentially costly socioeconomic impacts 〈 May be easier to implement 〈 May be more popular with fishers 〈 May be easier to enforce, especially over long time-period
Bycatch limits	May be more popular with fishers in cases where gear modifications reduce target catch Requires no field testing, which can be time intensive	Keeps fishers fishing Unlikely to redistribute bycatch		〈 Keeps fishers fishing 〈 Avoids potentially costly socioeconomic impacts 〈 May be easier to implement 〈 May be more popular with fishers 〈 May be easier to enforce, especially over long time-periods
Buy-outs	May be better in cases where immediate action is required Fishers are compensated to varying degrees	May be better in cases where immediate action is required Fishers are compensated to varying degrees	Fishers are compensated to varying degrees, whereas this may not be the case if/when a bycatch limit results in a closed	

CHAPTER 3

Buoyless Nets Reduce Sea Turtle Bycatch In Coastal Net Fisheries

Introduction

As human populations continue to expand, fishing effort is increasing in coastal areas worldwide (Stewart et al. 2010). Coastal small-scale fisheries employ over 99% of the world's 51 million fishers and provide over half of the planet's wild-caught seafood products (Berkes et al. 2001; Chuenpagdee et al. 2006), underscoring their environmental and socioeconomic importance (Begossi 2006; Halpern et al. 2008). However, declining catches, inadequate resources and infrastructure, and overcapacity all highlight the challenges associated with managing small-scale fisheries (Sumaila et al. 2008; Madau et al. 2009; Stewart et al. 2010; Shester and Micheli 2011).

Entangling net fisheries are globally ubiquitous and have substantial socioeconomic and nutritional importance to coastal communities, especially in developing nations (FAO 2008). Nets have proliferated over the past 30 years because they are inexpensive and lucrative as well as easy to build, fish, and maintain. Notwithstanding, net fisheries have been identified as one of the leading sources of overfishing and bycatch worldwide (Chuenpagdee et al. 2003; FAO 2008). Their use in coastal small-scale fisheries has been linked to declines in commercially important fish populations (Sala et al. 2004), and their incidental capture (bycatch) can lead to high mortality in non-target species and alter ecosystem structure and function (Shester and Micheli 2011). Bycatch in nets is particularly problematic for vulnerable air breathing marine megafauna including sea turtles, marine mammals, sirenians, and seabirds (Heppell et al. 2005; Zydelis et al. 2009; Lewison et al. 2004, 2014), and has been known or believed to cause declines in a number of populations worldwide (D'Agrosa et al. 2000; Tasker et al. 2000; Read et al. 2006; Peckham et al. 2007, 2008; Crowder and Heppell 2011; Alfaro et al. 2011; Casale 2011; Wallace et al. 2013; Hamer et al. 2013).

Recent research suggests that bycatch of megafauna in small-scale coastal net fisheries might approach or even exceed bycatch in some industrial fisheries (Jaramillo-Legorreta et al. 2007; Peckham, et al. 2007, 2008; Alfaro et al. 2011; López-Barrera et al. 2012; Mancini et al. 2012). However, unlike industrial-scale fisheries, small-scale fisheries often lack adequate resources and infrastructure to assess and regulate their bycatch impacts (Shester and Micheli 2011). In certain high profile cases, governments have limited the use of nets in order to protect endangered megafauna populations including an international ban on the use of driftnets in the North Pacific (Wetherall et al. 1993), and restriction of net use in the Gulf of California to protect the vaquita porpoise (D'Agrosa et al. 2000). However, due to the great commercial and nutritional importance of coastal net fisheries, especially in developing nations, creative solutions that mitigate megafauna bycatch while maintaining fisheries are urgently needed.

Increased awareness of the importance of megafauna bycatch impacts over the past two decades (Dayton et al. 1995; Hall 1996; Lewison et al. 2004, 2014) has led to innovations in fishing gear and techniques that have resulted in reduced bycatch in a variety of fisheries (Hall et al. 2000; Gilman et al. 2005, 2006a,b, 2009; Werner et al. 2006; Senko et al. 2014a). However, mitigating net bycatch has proven challenging because nets are inherently non-selective, and changing net characteristics such as mesh size and techniques such as soak time often result in substantial reductions in target catch (Gilman et al 2009). Developing gear modifications for small-scale net fisheries is important because more selective fishing practices may be less profitable and flexible (i.e. the inherent non-selectivity of nets allows fishers to retain multiple target and sometimes non-target species). Net modifications have previously resulted in megafauna bycatch mitigation in certain fisheries without substantial reductions in target catch. Seabird bycatch was reduced with the use of high-visibility net in a coastal salmon gillnet fishery in Washington, USA (Melvin et al. 1999); porpoise bycatch was reduced in the New England gillnet fishery with the use of acoustic pingers (Kraus et al. 1997), and recent research suggests that sea turtle bycatch in bottom-set nets can be reduced at night through net illumination (Wang et al. 2010; 2013).

The overlap of intense bottom-set net fisheries with a highly productive foraging hotspot for loggerhead turtles (*Caretta caretta*) at Baja California Sur, Mexico (BCS) (Peckham et al. 2007; Wingfield et al. 2011) produces among the highest recorded megafauna bycatch rates worldwide (Peckham et al. 2007, 2008, 2013; INAPESCA 2013), primarily of large juveniles and sub-adults (Peckham et al. 2007) of high demographic importance (Crouse et al. 1987; Crowder et al. 1994). The resulting mortality is of international concern because loggerhead turtles are globally endangered (IUCN 2013), and the North Pacific population was recently uplisted to endangered under the U.S. Endangered Species Act (NOAA 2011) and identified as one of the world's most endangered sea turtle populations (Wallace et al. 2012).

To address the loggerhead bycatch problem at BCS, we have partnered directly with BCS net fishers since 2004, convening workshops and running experimental trials to design, test, and implement bycatch mitigation measures as part of a long-term fisher led community-based conservation program (Peckham and Maldonado-Diaz 2012). In 2007, at the recommendation of local master fishermen we together began investigating the viability of buoyless nets. Informal fisher interviews suggested that buoyless nets could be lucrative and reduce turtle bycatch. Thus, we took the simple but counterintuitive step of removing the buoys from float lines of conventional nets. To assess the effects of this net modification, we conducted controlled in-situ experiments in partnership with local fishermen at BCS to compare turtle bycatch rates with target catch rates, composition, and market value between traditional (control) and buoyless (buoys removed from float line) nets. Our study is unique in that we quantified the effects of a gear modification simultaneously on both target catch and bycatch rates in operating coastal net fisheries, yielding a comprehensive evaluation of the viability of this novel bycatch mitigation strategy.

Methods

Field trials

From 2007-2009 we conducted in-situ controlled experiments at Puerto López Mateos, BCS (see map of study site in Peckham et al. 2007) in local bottom-set net fisheries during the summer fishing seasons to examine the effects of buoyancy of the net float line on turtle bycatch rates and target fish catch rates, composition, and market value by pairing buoyless (buoys removed from float line) and conventional (control) nets. Buoyless nets were set adjacent to control nets (within 100 m) at approximately the same depths (15 - 56 m) within the loggerhead hotspot where high levels of turtle bycatch had previously been recorded (Peckham et al. 2007).

The west coast of BCS represents one of Mexico's most productive fishing grounds. Among myriad fisheries, grouper (*Mycteroperca* sp.), halibut (*Paralichthys californicus*), guitar-fish (*Rhinobatus* sp.), and other valuable groundfish are targeted by local small-scale fleets using bottom-set nets. In northwestern Mexico (and most of the world) nets are built with a monofilament mesh tied between two lines, a sink line rigged with lead weights and a float line rigged with buoys. To ensure that our trials were commercially valid in terms of target catch, all fishing was directed and conducted by local fishermen. Fishers selected fishing locations to maximize their target catch, and we substituted buoyless nets for a subset of their conventional nets. Buoyless nets were matched with control nets of the same dimensions and mesh size to form experimental pairs. Individual nets ranged in mesh size from 20.3 to 25.4 cm, in length from 111.12 to 120.38 m, and in height from 3.5 to 5.5 m. Control nets contained roughly 1 buoy every 1.7 m along the float line, for a total of 70 buoys per net. Experimental (buoyless) nets contained roughly 1 buoy every 8.5 m of float line, or 15 per net. As such, the experimental nets are not completely without buoys on the floatline, but they are called buoyless by fishermen because of their considerably reduced use.

In the summers of 2007 and 2008, we conducted 40 pairs of controlled opportunistic trials by substituting buoyless nets for a subset of participating fishermen's conventional nets. In exchange for fishing two buoyless-control net pairs and carrying an observer onboard we compensated fishermen US $50 per day-trip, and the fishermen retained the catch. Nets were checked daily between 0700 and 1000, resulting in soak times of 23 – 25 hrs. In the summer of 2009, we conducted 96 pairs of controlled experimental trials by hiring partner fishermen to fish experimental net pairs exclusively.

To avoid turtle mortality, nets were checked three times a day, between 0700-0900, 1600-1800, and 2300-0100, resulting in total soak times of 21-23hrs. All sea turtles caught were tagged with Inconel metal tags, measured, and released. The tagging and morphometric data were incorporated in the Grupo Tortuguero long-term monitoring database.

Data Analysis

The bycatch-per-unit-effort (BPUE) for each net was determined as: BPUE = the number of turtles captured/(net length/100 m) * (soak time of net/24 hours). The catch-per-unit-effort (CPUE) for each net was determined as: CPUE = kg of target species of fish/(net length/100 m) * (soak time of net/24 hours). Catch composition from each net was identified and categorized in partnership with host fishermen into four groups by market value per kg: group 1 (US$2.4 - 3.2), group 2 (US$ 1.6 - 2.4), group 3 (US$ 1.6 - 0.8), and group 4 (US$ 0.8 - 0). Market value of each species caught was determined by a market survey conducted by two master fishermen from Puerto López Mateos (each with over 20 years fishing experience) and converted from pesos to dollars (Table 3.1). Market value of each group per trip was calculated by multiplying the catch volume of each group by its market value. Market value of each trip was calculated by summing the market value of all four groups per trip. We used paired bootstrap resampling to test the null hypothesis that there would be no difference in BPUE, CPUE, and market value between buoyless and control nets. Data were resampled 10,000 times using SYSTAT 12.0. This approach measures the strength of evidence against a null hypothesis rather than showing significance at a certain probability level (Manly 2007).

Results

In 136 controlled sets of net pairs, 36 sea turtles were caught: 32 loggerheads, 3 green turtles (*Chelonia mydas*), and 1 olive ridley (*Lepidochelys olivacea*). Turtle BPUE rates were significantly lower in buoyless nets (0.06 ± 0.3 turtles 100 m net^{-1} $24hr^{-1}$; mean ± SE) than in control nets (0.19 ± 0.7; Fig. 1; N=136, p=0.002), with a 68% reduction in mean turtle bycatch rates and 67% fewer turtles caught in buoyless nets (9 turtles) than in control nets (27 turtles).

Catch of target fish was similar between the two net deigns, with 1456.6 and 1801.2 kg of fish landed in buoyless and control nets, respectively. Mean CPUE was 18% lower in buoyless (9.9 ± 1.4 kg 100m net^{-1} $24hr^{-1}$) than in control nets (12.0 ± 1.6; Fig. 2), but the overall difference was not significant (N=136, p=0.081). Catch composition by species remained consistent between both net treatments (Table 3.1). Total market value of target fish caught was 29% lower in buoyless ($2481) than in control nets ($3477). Market value was significantly lower in buoyless ($18±3) than in control nets ($25 ± 4; N=136; p=0.009; Fig. 3), with a 28% reduction in mean value compared to control nets.

Discussion

The selectivity of fishing nets can be increased by identifying and exploiting differences in the habitat use or perception capabilities of target versus non-target species (Gilman et al. 2009). Reducing the vertical profile of nets has been shown to lower sea turtle bycatch (Price and Van Salisbury 2007), while illuminating nets has been found to reduce catch rates of sea turtles at night (Wang et al 2010; 2013). Our results suggest that removing the buoys from net float lines can reduce turtle bycatch while maintaining target catch rates and composition, representing a bycatch mitigation solution with strong potential for commercial adoption.

Although buoyless nets yielded levels of catch volume similar to that of conventional nets, the market value of the catch of buoyless nets was marginally but significantly lower, an important factor for uptake by local fishers. However, this divergence likely resulted from unusually high landings of high value yellow snapper (*Lutianus Argentiventris*) by one crew in August 2009, in which 70 individuals of this species were caught during two weeks of buoyless net trials. No other individuals were caught in 2009, and in 2007 and 2008 combined, only one was captured by all crews.

Due to the deep working depth of our host fleet and poor underwater visibility we have not been able to observe how buoyless nets work relative to conventional nets. The float lines our partners used on their nets consisted of 8 mm nylon (universally used in the BCS region) so they have inherent buoyancy that we surmise keeps the nets partially open and elevated in the water column (as opposed to laying flat on the seafloor). We suspect that the buoyless float lines hang lower in the water column than those of conventional nets. As a result, it is likely that the vertical profile of the buoyless nets is reduced. This probably decreased sea turtle encounter rates as in other studies in which net profile was reduced (Price and Van Salisbury 2007). Despite the lower profile of buoyless nets, similarity in target catch may result from increased fish entanglement probability as a result of the slack net, similar in function to the enhanced catch of nets equipped with tie-downs (Gilman et al 2009). If turtles visually locate nets to forage out of them, it is also possible that removing the buoys removed a visual cue used to locate nets. We recommend future research with underwater cameras mounted on nets to better understand how buoyless nets function and interact with target and non-target species in relation to conventional nets.

There are minimal costs involved in adopting buoyless nets instead of conventional nets at BCS and elsewhere. Conventional nets can be converted by simply removing the buoys from the float line, requiring roughly 1-2 hrs work per net. Building new buoyless nets is less expensive than building conventional nets because the cost of buoys is saved (roughly 20% of total net cost). Furthermore, no training is required for fishermen to adopt buoyless gear because they are fished identically to conventional nets.

Although buoyless nets present no cost of adoption and are comparable in profitability to conventional nets under normal oceanographic conditions, there may be social barriers to adoption of the gear among fishermen. Their function is counterintuitive for fishermen who have spent decades designing and building nets to enhance fish encounter rates by maximizing net surface area. Despite some skepticism at the outset of our study, by the end of the trials more than 80% of the 20 participating fishermen reported that they would permanently switch to buoyless nets (E. Caballero-Aspe, unpub. data). The potential for uptake of the buoyless gear was probably enhanced by our participatory research program, an approach that has been documented to be effective in a variety of other studies (Jenkins 2007, 2010; Campbell and Cornwell 2008). We worked to both educate and empower local fishermen through a combination of outreach events, workshops, and leadership roles through which they developed and tested potential bycatch reduction solutions (Peckham and Maldonado-Diaz 2012).

Despite the promise of buoyless nets for reducing sea turtle bycatch, we are not recommending their adoption by the fleets that primarily impact loggerhead turtles at BCS. Given the endangered status of the North Pacific loggerhead population (NOAA 2011), its distinction as one of the world's most vulnerable sea turtle populations (Wallace et al. 2012), and their extraordinarily high mortality in local net fleet (Peckham et al. 2007, 2008), conservation action that effectively eliminates their bycatch is urgently needed. For example, in a parallel study local fishermen have demonstrated the profitability of replacing nets with hook and line gear of zero turtle bycatch (H. Peckham, unpub. data), and local fishers have also expressed interest in fish traps that would substantially reduce turtle bycatch. In addition to the increased selectivity of these fishing practices (Shester and Micheli 2011), fishers can generate greater profits by gaining access into premium markets by catching higher quality fish in better condition (alive). Finally, given the inherent difficulties associated with promoting and enforcing adoption of buoyless nets, we conclude that promoting hook and line and/or trap fishing is the better strategy in this extreme case.

Although we are not recommending their adoption by local net fleets at the loggerhead hotspot, buoyless nets could represent a comprehensive or partial solution for reducing turtle bycatch in other regions of the world where net fisheries overlap with less depleted sea turtle populations. For instance, bycatch of green turtles in some coastal areas (e.g. López-Barrera et al. 2012; Mancini et al. 2012; Senko et al. 2014b) could be mitigated with the use of buoyless nets. Because the buoyless design likely exhibits decreased vertical net profile, they may also result in lower bycatch of other vulnerable air-breathing megafauna including seabirds, cetaceans, pinnipeds, and sirenians. Site and species-specific testing is necessary to establish their utility in other fisheries and regions.

TABLE 3. 1. Target catch composition by price class in buoyless and control nets (species list grouped by price class showing N, % of catch during study, mean and SD of catch rate per trip, and 2009 market price).

	Control		**Buoyless**	
1st Class ($2.4-3.2)	**N**	**%**	**N**	**%**
Mycteroperca xenarcha, M. jordani	22	10.58	16	7.69
Epinephelus acanthistius	12	5.77	4	1.92
Mycteroperca prionura	1	0.48	4	1.92
Epinephelus niphobles	0	0	1	0.48
Epinephelus itajara	5	2.4	6	2.88
SUM	**40**	**19.23**	**31**	**14.9**
2nd Class ($1.6-2.4)				
Lutjanus peru	1	0.48	4	1.92
Paralichthys californicus	11	5.29	21	10.1
Atractoscion nobilis	22	10.58	19	9.13
Lutjanus argentiventris, L. colorado	41	19.71	30	14.42
SUM	**75**	**36.06**	**74**	**35.58**
3rd Class ($1.6-0.8),				
Sphyrna zygaena	2	0.96	0	0
Brotula clarkae	1	0.48	1	0.48
Seriola lalandi	2	0.96	3	1.44
Semicossyphus pulcher	4	1.92	3	1.44
Mustelus lunulatus, Mustelus califor	1	0.48	2	0.96
Paralichthys californicus	3	1.44	14	6.73
Cynoscion parvipinnis	0	0	1	0.48
Caulolatilus princeps	1	0.48	0	0
SUM	**14**	**6.73**	**24**	**11.54**
4th Class ($0.8-0.1)				
Raja binoculata, R. inornata	3	1.44	2	0.96
Gymnura marmorata	2	0.96	3	1.44
Myliobatis californicus	54	25.96	37	17.79
Balistes polylepis	1	0.48	0	0
Rhinobatus productus	13	6.25	32	15.38
Paralabrax clathratus	2	0.96	7	3.37
Rhinoptera steindachneri	2	0.96	0	0
Anisotremus interruptus	1	0.48	8	3.85
Diplectrum pacificum	1	0.48	7	3.37
SUM	**79**	**37.98**	**96**	**46.15**

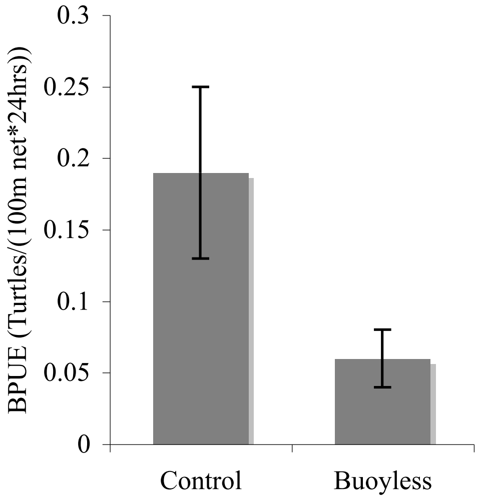

Figure 3. 1. Comparison of sea turtle BPUE using buoyless versus control nets. Buoyless nets resulted in a 68% reduction in the mean BPUE from the control nets, and analysis with paired bootstrap resampling indicated that the BPUE was significantly lower (n = 136, p = 0.002). Bars represent SE.

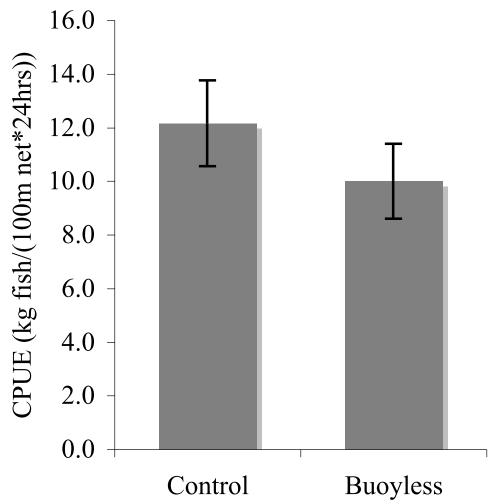

Figure 3. 2. Comparison of target fish CPUE using buoyless versus control nets. Mean CPUE in buoyless nets was 18% lower than in control nets, but analysis with paired bootstrap resampling indicated that the CPUE was not significantly different between net treatments (n = 136, p = 0.092). Bars represent SE.

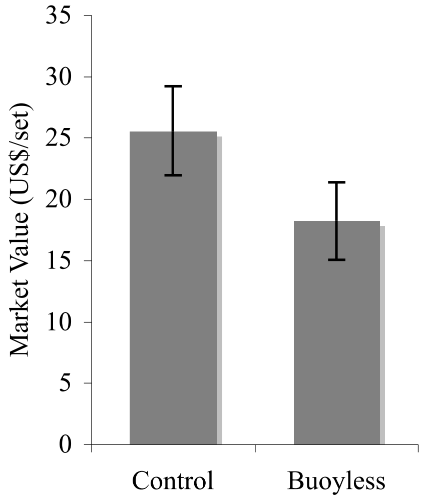

Figure 3. 3. Comparison of market value per paired set in buoyless versus control nets. The mean value of catch using buoyless nets was 29% lower than the catch value of control nets and analysis with paired bootstrap resampling indicated that market value was significantly lower (n = 136, p = 0.009). Bars represent SE.

CHAPTER 4

Effects Of Illuminated Nets on Sea Turtle and Overall Bycatch in a Coastal Net Fishery

Introduction

Small-scale fisheries employ over 99% of the world's 51 million fishers and generate over half of all wild-caught seafood (Berkes et al. 2001; Chuenpagdee et al. 2006) (Shester and Micheli 2011). Set nets are globally ubiquitous in coastal small-scale fisheries and play an important socioeconomic role in many coastal communities because they are inexpensive, easy to build, fish, and maintain, and can yield high landings of mixed species. However, despite their popularity and socioeconomic importance, bycatch in small-scale set net fisheries can lead to population declines in vulnerable megafauna such as sea turtles, marine mammals, and seabirds (D'Agrosa et al. 2000; Read et al. 2006; Peckham et al. 2007, 2008; Crowder and Heppell 2011; Alfaro et al. 2011; Casale 2011; Mancini et al. 2012; Wallace et al. 2013; Hamer et al. 2013; Senko et al. 2014). These declines, termed trophic downgrading, can lead to extensive cascading effects on lower trophic levels (Estes et al. 2011).

Recent research suggests that megafauna bycatch in small-scale fisheries may be comparable or even higher than bycatch in some industrial-scale fisheries (Jaramillo-Legorreta et al. 2007; Peckham, et al. 2007, 2008; Alfaro et al. 2011; López-Barrera et al. 2012; Mancini et al. 2012). However, unlike industrial-scale fisheries, small-scale fisheries often lack adequate resources to assess and regulate their bycatch (Shester and Micheli 2011). Given the socioeconomic importance of net fisheries in coastal communities worldwide, time-area restrictions are an impractical management strategy. In addition, closures are costly and difficult to enforce in small-scale fisheries, and may simply redistribute bycatch impacts to other areas or species (Campbell and Cornwell 2008; Lewison et al. 2009; Senko et al. 2014a). Thus, it is imperative to develop bottom-up management approaches in small-scale net fisheries, such as modified fishing gear or practices, which mitigate megafauna bycatch while sustaining fisher livelihoods.

Gear modifications have been successfully developed and implemented in high bycatch industrial-scale fisheries over the past decade (Hall et al. 2000; Gilman et al. 2005; Cox et al. 2007; Jenkins, 2007, 2010; Lewison et al. 2011), but comparatively few have been developed in small-scale net fisheries (Gilman et al. 2009). Gear modifications may be more popular with fishers because they allow fishers to continue to fish in their desired locations while avoiding potential economic losses from closures (Campbell and Cornwell, 2008; Senko et al. 2014a). Although gear modifications have reduced megafauna bycatch in experimental trials, actual practice in fisheries is less effective (Cox et al. 2007; Campbell & Cornwell, 2008). Involving fishers in developing gear modifications is important to achieve fisher adoption of and compliance (Cox et al. 2007; Jenkins, 2007, 2010; Lewison et al. 2011), and the most widely adopted gear modifications in U.S. commercial fisheries have been developed by or with input from local fishers (Jenkins 2007, 2010).

Gear modifications that use visual cues to alert or deter bycatch species to the presence of fishing gear can be developed by identifying differences in visual capabilities between target and non-target species and may represent a promising approach to mitigating bycatch while maintaining fisheries (Melvin et al. 1999; Gilman et al. 2005; Wang et al. 2010, 2013). Recent research revealed that illuminated nets significantly reduced sea turtle bycatch in a shallow-water nearshore estuary at night (Wang et al.

2010, 2013). The strong potential for bycatch mitigation generated from these two studies warrants testing illuminated nets in a high bycatch operational net fishery, in collaboration with local fishers and managers, as a necessary first step to assess the adoption potential of this promising gear modification.

Located off the Pacific coast of Baja California Sur, Mexico (BCS), the Gulf of Ulloa is a highly productive foraging hotspot for endangered loggerhead turtles (*Caretta caretta*) (Peckham et al. 2007; Wingfield et al. 2011). The overlap of small-scale bottom-set net fisheries with high concentrations of loggerheads in the hotspot causes among the highest recorded megafauna bycatch rates worldwide (Peckham et al. 2007, 2008, 2013; INAPESCA 2013), leading to high mortality of mostly large juveniles (Peckham et al. 2007) of high demographic importance (Crouse et al. 1987; Crowder et al. 1994). High bycatch mortality at BCS is of international concern because loggerhead turtles are globally endangered (IUCN 2013), and the North Pacific population was recently uplisted to endangered under the U.S. Endangered Species Act (NOAA 2011b) and identified as one of the world's most endangered marine turtle regional management units (Wallace et al. 2012).

The high bycatch of loggerhead turtles at the BCS hotspot provides a unique opportunity to test illuminated nets in an operational set net fishery with extremely high rates of megafauna bycatch (Peckham et al. 2007, 2008). Thus, I collaborated with local fishers and the National Fisheries Science Institute (INAPESCA) to: (1) determine if net illumination adversely affects target fish catch rates and market value in an operational set net fishery; (2) determine the effects of net illumination on sea turtle bycatch rates; and (3) determine if these effects vary between day and night periods. To our knowledge, this is the first study to assess illuminated nets as a megafauna bycatch reduction solution in an operational fishery across day and night periods, thus testing the strength of this visual cue.

Methods

Fishing trials and experimental design

We conducted controlled fishing trials in partnership with the Mexican National Fisheries Science Institute (INAPESCA) from 6 July to 9 July and 12 July to 15 July in 2012 in the loggerhead hotspot at the Gulf of Ulloa, BCS, to evaluate the effects of net illumination by pairing illuminated nets with control (conventional) nets (Figure 1). Intense small-scale net fisheries in the hotspot target California halibut (*Paralichthys californicus*), rockfish (*Mycteroperca* sp.), and other valuable demersal fish species. We used eight nets consisting of four pairs. Nets ranged in mesh size from 18 to 22 cm and in length from 153 to 199 m, all with a height of 6.1 m.

Nets were illuminated by clipping AA battery-powered green light-emitting diodes (LED) lights (Lindgren-Pittman) at 10 m intervals along the float line. We matched illuminated nets with control nets of the same approximate size using 100 m rope to form experimental net pairs. Nets were set over rock ledges and sandbars at depths ranging from 10.9 m to 43.9 m in well-known rockfish and halibut fishing grounds in the hotspot where we previously recorded high loggerhead bycatch rates (Peckham et al. 2007, 2008, 2011). Given that fishers soak their nets for 24 h in this fishery, we were able to assess how underwater light conditions (i.e. day vs. night soaks) mediated the strength of this visual cue. The experiment consisted of a fully crossed design partitioned into four treatments: day control, day illuminated, night control, and night illuminated, whereby we checked nets twice a day (at sunrise and sunset), resulting in soak times of 8-14 h for each net treatment. We used four replicates of each treatment at various locations throughout the study site to control for site effects and represent various fishing locations (e.g. depth, substrate, etc.) within the hotspot. The direction of control-illuminated net pairs was switched after each day-night soak, forming approximate 24 h deployments at each site to mimic the actual fishery.

Turtle, finfish, and overall bycatch

Captured sea turtles were recorded to species, tagged with Inconel metal tags, measured, and released. Morphometric and tagging data were incorporated into Grupo Tortuguero's long-term monitoring database. We determined turtle bycatch rates (BPUE) for day and night periods for each net as: turtle BPUE = number of turtles captured/([net length/100 m]) x ([net soak time/12 h]).

All bycatch were recorded and further partitioned into "finfish bycatch" (all fish which were considered bycatch) and "overall bycatch", the latter of which included finfish and also turtles, squid, and crabs. We determined finfish BPUE for day and night periods for each net as: finfish BPUE = kg of finfish bycatch /([net length/100 m]) x ([net soak time/12 h]). Similarly, overall bycatch for day and night periods for each net was defined as: overall BPUE = total kg of bycatch /([net length/100 m]) x ([net soak time/12 h]).

Target fish catch

Total target fish catches were recorded to species and weighed in aggregate for each net. We determined target fish catch rates (CPUE) for day and night periods for each net as: CPUE = kg of target catch/([net length/100 m]) x ([net soak time/12 h]). Market value of each species caught was determined by a local master gillnet fisher from the Gulf of Ulloa with over 20 years fishing experience using the current (2012) market price. We determined market value rates (MVPUE) for day and night periods for each net as: MVPUE = market value ($ US) of catch/([net length/100 m] x [net soak time/12 h]).

Data analysis

We removed all sets (i.e. illuminated-control net pairs) with no interactions (no turtles or target catch captured) from statistical analyses (but all sets were used to calculate mean bycatch rates) and tested for normality and homogeneity of variance. We compared turtle BPUE, CPUE, MVPUE, finfish BPUE, and overall BPUE between illuminated and control nets, day and night periods, and space (set) using a mixed effects model, which incorporated both random (space, i.e. set) and fixed (net treatment and time of day) effects. We log transformed turtle BPUE, CPUE, MVPUE, finfish BPUE, and overall BPUE to satisfy the assumption of normality. Analyses were performed in R 2.15.1. Results are presented as mean ± SD unless otherwise noted and statistical significance was inferred at a probability of 0.05 or less.

Results

Target fish catch rates

In 32 sets of net pairs during the day and 28 sets of net pairs during the night, target fish catch was similar between the two treatments, with 320.5 kg of fish taken in illuminated nets (N = 176.0 kg daytime; 144.5 kg nighttime) and 303.6 kg landed in control nets (N = 152.7 kg daytime; 133.0 kg nighttime). Location of sets (net pairs) significantly influenced CPUE ($F = 11.240$; $P = 0.001$) (Table 4.1). Target fish were captured at mean CPUE rates of 6.9±15.5 kg 100 m net-1 24hr-1 of illuminated net and 6.4±13.4 kg 100 m net-1 24hr-1 of control net across 24 h periods, 4.1±12.0 kg 100 m net-1 12hr-1 of illuminated net and 3.3±8.3 kg 100 m net-1 12hr-1 of control net during daytime, and 2.7±4.5 kg 100 m net-1 12hr-1 of illuminated net and 2.6±5.7 kg 100 m net-1 12hr-1 of control net during nighttime. Illuminated nets resulted in a 7% increase in mean CPUE over 24 h periods, an 18% increase in mean CPUE during daytime, and a 5% increase in mean CPUE at nighttime.

Market value

Market value of target fish catch was similar between the two treatments, with $898 worth of fish landed in illuminated nets (N = $527 daytime; $371 nighttime) and $714 worth of fish landed in control nets (N = $380 daytime; $334 nighttime). Location of sets (net pairs) significantly influenced MVPUE (F = 12.634; P = 0.001) (Table 4.2). Target fish were landed at mean MVPUE rates of $18±47 USD 100 m net-1 24hr-1 of illuminated net and $15±36 USD 100 m net-1 24hr-1 of control net across 24 h periods, $12±36 USD 100 m net-1 12hr-1 of illuminated net and $8±23 USD 100 m net-1 12hr-1 of control net during daytime, and $7±13 USD 100 m net-1 12hr-1 of illuminated net and $7±13 USD 100 m net-1 12hr-1 of control net during nighttime. Illuminated nets resulted in an 18% increase in mean MVPUE over 24 h periods, a 31% increase in mean MVPUE during daytime, and a 6% increase in mean MVPUE at nighttime.

Turtle, finfish, and overall bycatch

In 32 sets of net pairs during the day and 28 sets of net pairs at night, we captured 89 loggerhead turtles and one olive ridley turtle (*Lepidochelys olivacea*), 42 of which were captured in illuminated nets (N = 33 daytime; 9 nighttime) and 48 of which were capturing in control nets (N = 31 daytime; 17 nighttime). Significantly more turtles were captured during daytime (F = 9.570; P = 0.003) (Table 4.3). Turtles were captured at mean BPUE rates of 0.74±0.81 turtles 100 m net^{-1} 24hr^{-1} of illuminated net and 0.91±0.93 turtles 100 m net^{-1} 24hr^{-1} of control net across 24 h periods, 0.74±0.85 turtles 100 m net^{-1} 12hr^{-1} of illuminated net and 0.68±0.88 turtles 100 m net^{-1} 12hr^{-1} of control net during daytime, and 0.17±0.33 turtles 100 m net^{-1} 12hr^{-1} of illuminated net and 0.34±0.57 turtles 100 m net^{-1} 12hr^{-1} of control net during nighttime. Illuminated nets resulted in an 18% reduction in mean turtle BPUE over 24 h periods, an 8% increase in mean turtle BPUE during daytime, and a 50% reduction in mean turtle BPUE at nighttime. Of the 90 turtles captured, none (N = 0) showed any external signs of bycatch (i.e. marks or wounds from entanglement or fishing gear or fishing gear attached to the turtle). All turtles were captured at depths of < 40 m.

Finfish bycatch was captured at mean BPUE rates of 10.30±30.51 kg 100 m net^{-1} 24hr^{-1} of illuminated net and 16.50±24.13 kg 100 m net^{-1} 24hr^{-1} of control net across 24 h periods, 5.27±9.32 kg 100 m net^{-1} 12hr^{-1} of illuminated net and 7.52±12.40 kg 100 m net^{-1} 12hr^{-1} of control net during daytime, and 4.64±4.20 kg 100 m net^{-1} 12hr^{-1} of illuminated net and 8.91±13.80 kg 100 m net^{-1} 12hr^{-1} of control net during nighttime. Illuminated nets resulted in a 34% reduction in mean finfish BPUE over 24 h periods, a 30% reduction in mean finfish BPUE during daytime, and a 48% reduction in mean finfish BPUE at nighttime. Net illumination did not significantly reduce finfish BPUE, but the effect of time of day was significant (F = 4.39; P = 0.039; see table 4.4).

Total bycatch was captured at mean BPUE rates of 41.73±X41.58 kg 100 m net^{-1} 24hr^{-1} of illuminated net and 63.10±50.76 kg 100 m net^{-1} 24hr^{-1} of control net across 24 h periods, 31.58±35.53 kg 100 m net^{-1} 12hr^{-1} of illuminated net and 35.89±36.48 kg 100 m net^{-1} 12hr^{-1} of control net during daytime, and 12.25±12.73 kg 100 m net^{-1} 12hr^{-1} of illuminated net and 28.04±27.06 kg 100 m net^{-1} 12hr^{-1} of control net during nighttime. Illuminated nets resulted in a 34% reduction in mean total BPUE over 24 h periods, a 12% reduction in mean total BPUE during daytime, and a 56% reduction in mean total BPUE at nighttime. Illuminated nets significantly reduced total BPUE across day and night periods ($F = 4.1$; $P = 0.045$; see table 4.5).

Discussion

Our results indicate that net illumination is not an effective sea turtle bycatch mitigation solution in this fishery as there was no significant difference in turtle bycatch rates between control and illuminated nets, irrespective of day or night. However, illuminated nets reduced mean turtle bycatch rates by 50% at night and did not compromise target catch rates and market value, suggesting that: (1) LEDs may have been more visible against the contrast of darkness, although more testing is needed; and (2) illuminated nets may hold promise as a bycatch mitigation solution in other coastal net fisheries, particularly those that operate at night or in low light conditions.

Although illuminated nets did not significantly reduce finfish bycatch, they significantly reduced overall bycatch biomass by 34% across 24 h periods. The significant reduction in overall bycatch biomass was likely driven by the additional bycatch of squid, turtle, and crab. This significant decrease in overall bycatch has massive implications for reducing bycatch biomass in net fisheries at BCS and worldwide. Given maintained target fish catch rates and market value, we recommend continued testing of illuminated nets as a potential bycatch mitigation strategy for reducing overall bycatch biomass, including sea turtles and other vulnerable megafauna, in other high bycatch fisheries worldwide. However, political fallout from the recent unilateral identification of Mexico by the United States for loggerhead turtle bycatch under the Magnuson-Stevens Act precludes us from additional testing in this fishery.

Despite the lack of statistical significance, why was there an observed day-night dichotomy in mean bycatch reduction rates for illuminated nets versus control nets? Visual capacity, depth, and underwater light levels all influence aquatic animals' vision (Johnsen 2002), and visibility of illuminated nets likely varies based on underwater light conditions. LEDs may have been more visible against the contrast of darkness at night, which could have made it easier for turtles to see them. In addition, water turbidity is high at our study site, which may have reduced light penetration during the day, limiting the LEDs ability to illuminate the net. Evidence that increased illumination leads to decreased bycatch rates was provided by Wang et al. (2010), who found that chemical light-sticks placed every 5 m along a bottom set gillnet produced a greater decrease in mean green turtle bycatch rates (59%) than nets with LEDs placed every 10 m (40%). Given that green turtles can see wavelengths emitted from both light sources (Mathger et al. 2007), it was postulated that increased light was likely more effective than simply using light-sticks (Wang et al. 2010). Further testing, both in the laboratory and field, may determine if strengthening this visual cue results in decreased bycatch rates. It is unknown, however, if sea turtles simply avoid LED lights or if illumination of nets via LEDs provides a visual cue that allows sea turtles to avoid the net.

Two prior studies that evaluated LED net illumination as a potential sea turtle bycatch mitigation solution (i.e. Wang et al. 2010, 2013) both reported a significant 40% decrease in green turtle bycatch rates at night. Although our results were not significant and our sample size was smaller, the 50% reduction in sea turtle bycatch rates we observed at night is promising because our trials were conducted in an active fishery and environmental conditions at our study site are likely less favorable. In addition to higher turbidity, our trials took place in offshore waters that were deeper than the shallow, less turbid estuarine waters of Punta Abreojos, BCS, where Wang et al. (2010, 2013) conducted trials. While obtaining a larger sample size was logistically unfeasible for this study, the observed nighttime bycatch reduction points to the promise of LED net illumination in mitigating bycatch of loggerhead and other sea turtle species.

Costs and ease of use of LEDs are crucial components when assessing adoption potential. LEDs were easy to clip on the float line, remained lit throughout the trials, and ran on two AA batteries, which would probably only need to switched out once per season. Given that the nets are fished identically as control nets, no training is required for adoption. Although our study was conducted on a government research vessel, we relied on the expertise of veteran local gillnet fishers to run our trials. However, the current cost of illuminating nets is prohibitive. At $10/LED), illuminating the average amount of net used at the hotspot would be approximately $4,000 per boat per season (1 km of gillnet per 4 months). Thus, the cost of LEDs would likely need to be substantially reduced before they could be implemented, if appropriate, in other fisheries.

Given that target catch and market value remained consistent among all four net treatments, net illumination may be a promising sea turtle bycatch mitigation solution in other fisheries, particularly those that operate in fishing grounds with more favorable environmental conditions. Such testing may be possible at other sites along the BCS coast where net fishers operate at night and target similar fish species, such as nearshore coastal lagoons where fishers target halibut (*Paralichthys californicus*) and guitar-fish (*Rhinobatus* sp.). Some of these fisheries at BCS have high rates of green turtle bycatch (Mancini et al. 2012; Senko et al. 2014b) where fishers operate in close proximity to the shoreline (~ 100 m – 2 km), which allows them to soak their nets for shorter durations (Senko et al. 2014b). Additionally, although target fish catch was not compromised, future research is necessary to understand how varying wavelengths of net illumination affects different target fish species and subsequently target composition (Wang et al. 2013).

We are not recommending the adoption of illuminated nets or further testing of net illumination at the BCS hotspot because illuminated nets were largely ineffective over 24 h periods (a non-significant 18% reduction). However, given the apparent dichotomy in day-night bycatch rates, we recommend further testing, both in the field and laboratory, to elucidate the mechanisms by which sea turtles and other megafauna perceive the strength of varying visual and other behavioral cues. It is imperative to understand how sea turtle visual capabilities vary under different environmental conditions and in response to different cues, both from a behavioral and physiological standpoint, in order to develop better bycatch mitigation solutions. These studies can provide important impetus for further testing in the field (i.e. active fisheries). Future field testing could employ a number of different visual cues, such as flashing LEDs, varying wavelengths and placement of light sources, and luminescent net materials (see

Wang et al. 2010). For example, future research may place LEDs at closer intervals to provide a stronger visual cue, or test different intervals. Cameras can also be placed on nets in order to confirm or refute findings from the laboratory, which will better elucidate behavioral factors and shed light on how turtles interact with various visual cues associated with modified gear.

TABLE 4. 1. Summary of mixed effects model comparing log transformed target CPUE rates between control and illuminated nets across day and night periods (time of day) and space (set). Significant differences are indicated in bold.

	Df	SS	MS	*F*	*P*
Illumination	1	10.29	10.29	0.129	0.721
Time of Day	1	45.08	45.08	0.564	0.456
Set (location)	1	899.01	899.01	11.240	**0.001**
Illumination * Time of Day	1	4.30	4.30	0.054	0.817
Residual	72	5758.70	79.98		

TABLE 4. 2. Summary of mixed effects model comparing log transformed MVPUE rates between control and illuminated nets across day and night periods (time of day) and space (set). Significant differences are indicated in bold.

	Df	SS	MS	*F*	*P*
Illumination	1	215.2	215.2	0.327	0.570
Time of Day	1	487.6	487.6	0.742	0.392
Set (location)	1	8302.5	8302.5	12.634	**0.001**
Illumination * Time of Day	1	123.4	123.4	0.188	0.666
Residual	72	47317.0	657.2		

TABLE 4. 3. Summary of mixed effects model comparing log transformed turtle BPUE rates between control and illuminated nets across day and night periods (time of day) and space (set). Significant differences are indicated in bold.

	Df	SS	MS	*F*	*P*
Illumination	1	0.124	0.124	0.221	0.640
Time of Day	1	5.378	5.378	9.570	**0.003**
Set (location)	1	0.468	0.468	0.833	0.365
Illumination * Time of Day	1	0.771	0.771	1.372	0.246
Residual	64	35.969	0.562		

TABLE 4. 4. Summary of mixed effects model comparing log transformed finfish BPUE rates between control and illuminated nets across day and night periods (time of day) and space (set). Significant differences are indicated in bold.

	Df	SS	MS	*F*	*P*
Illumination	1	2.49	2.49	3.04	0.084
Time of Day	1	3.56	3.56	4.35	**0.039**
Set (location)	1	2.93	2.93	3.58	0.061
Illumination * Time of Day	1	0.15	0.15	0.18	0.671
Residual	114	93.24	0.82		

TABLE 4. 5. Summary of mixed effects model comparing log transformed overall BPUE rates (total bycatch biomass) between control and illuminated nets across day and night periods (time of day) and space (set). Significant differences are indicated in bold.

	Df	SS	MS	*F*	*P*
Illumination	1	7.53	7.53	4.1	**0.045**
Time of Day	1	2.26	2.26	1.23	0.27
Set (location)	1	3.57	3.57	1.94	0.166
Illumination * Time of Day	1	1.18	1.18	0.64	0.425
Residual	114	209.17	1.83		

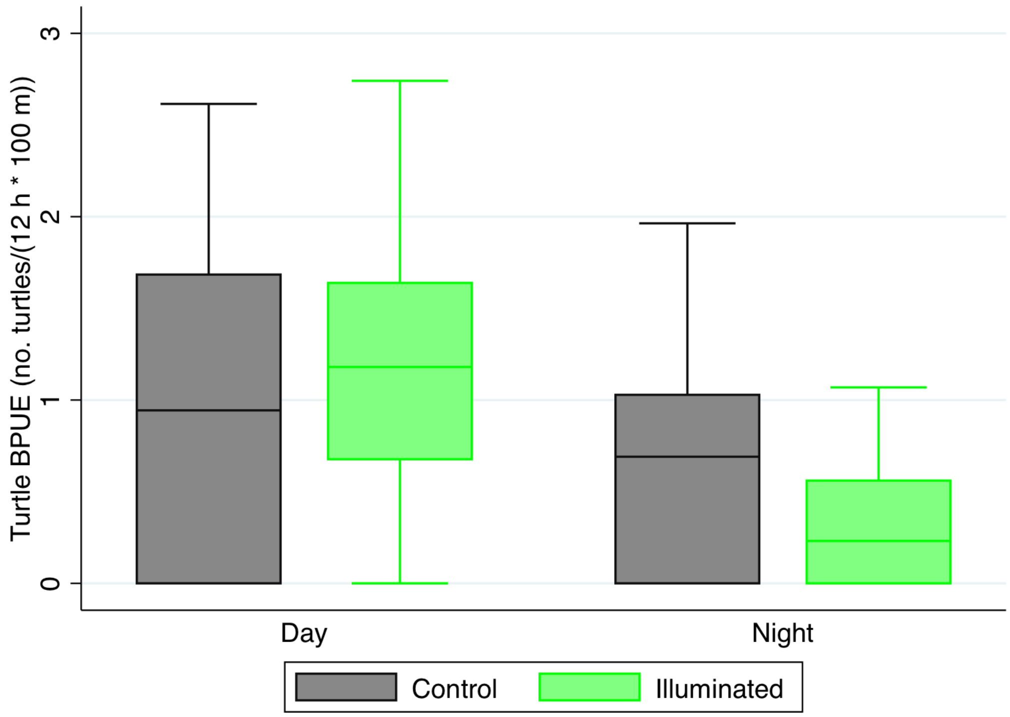

Figure 4. 1. Comparison of mean turtle BPUE in illuminated versus control nets. Illuminated nets resulted in an 18% reduction in mean turtle BPUE over 24 h periods, an 8% increase in mean turtle BPUE during daytime, and a 50% reduction in mean turtle BPUE at nighttime. The effect of time of day was significant ($F = 9.570$; $P = 0.003$; see table 4.3). Bars represent standard error of the mean.

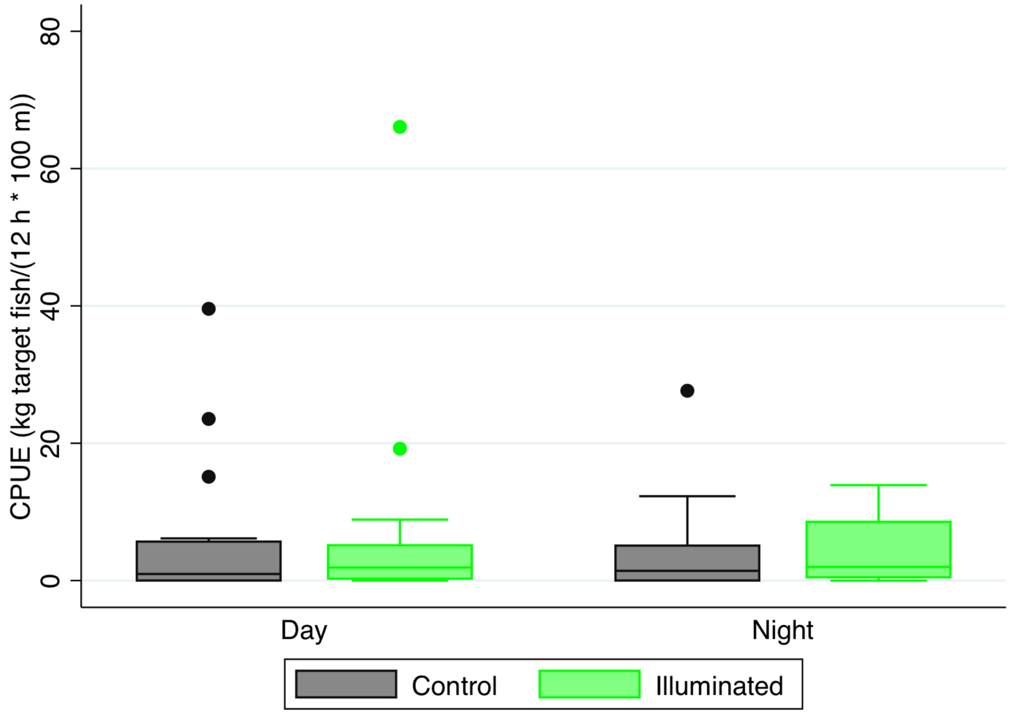

Figure 4. 2. Comparison of mean target fish CPUE in illuminated versus control nets. Illuminated nets resulted in an 7% increase in mean CPUE over 24 h periods, a 19% increase in mean CPUE during daytime, and a 22% increase in mean CPUE at nighttime. The effect of location (set) was significant (*F* = 11.24; *P* = 0.001; see table 4.1). Bars represent standard error of the mean.

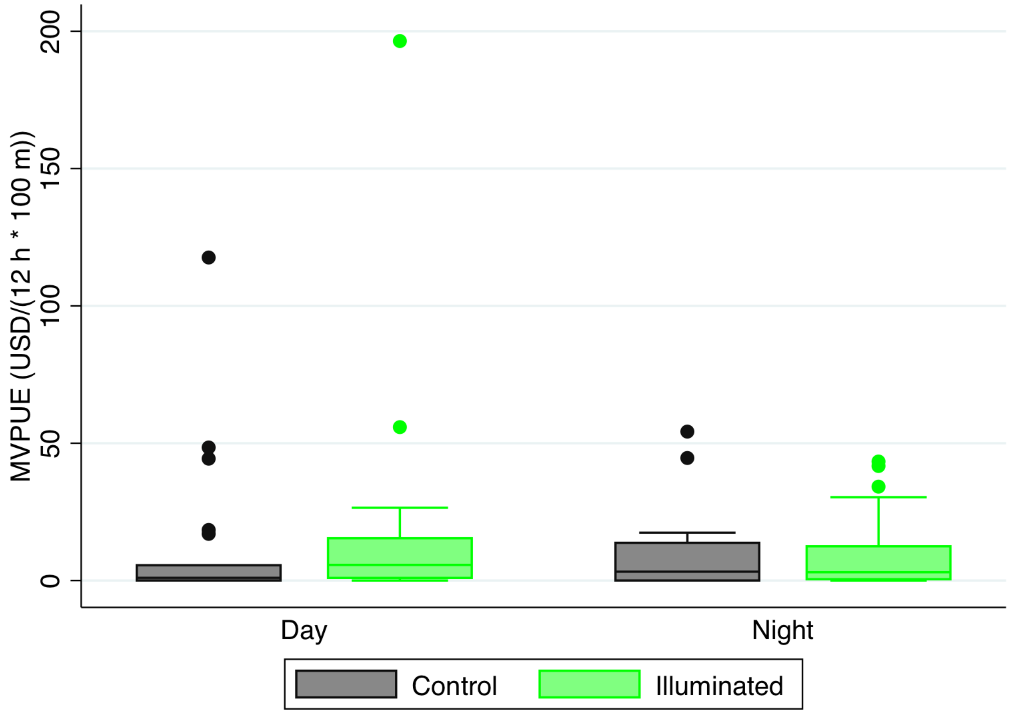

Figure 4. 3. Comparison of mean MVPUE in illuminated versus control nets. Illuminated nets resulted in an 18% increase in mean MVPUE over 24 h periods, a 31% increase in mean MVPUE during daytime, and a 6% increase in mean MVPUE at nighttime. The effect of location (set) was significant (F = 12.634; P = 0.001; see table 4.2). Bars represent standard error of the mean.

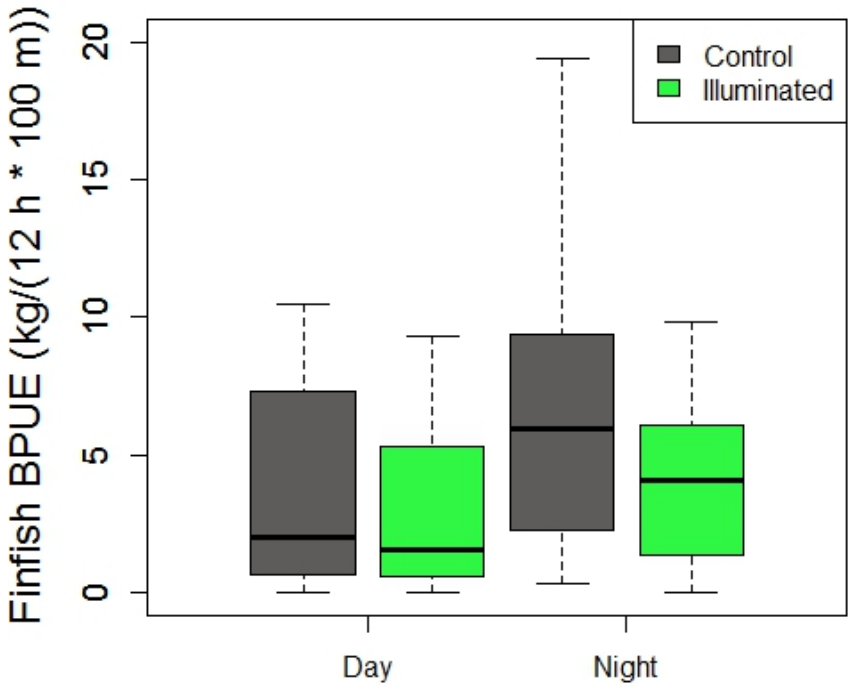

Figure 4. 4. Comparison of finfish BPUE in illuminated versus control nets. Illuminated nets resulted in a 38% reduction in mean finfish BPUE over 24 h periods, a 30% reduction in mean finfish BPUE during daytime, and a 48% reduction in mean finfish BPUE at nighttime. The effect of time of day was significant (F = 4.39; P = 0.039; see table 4.4).

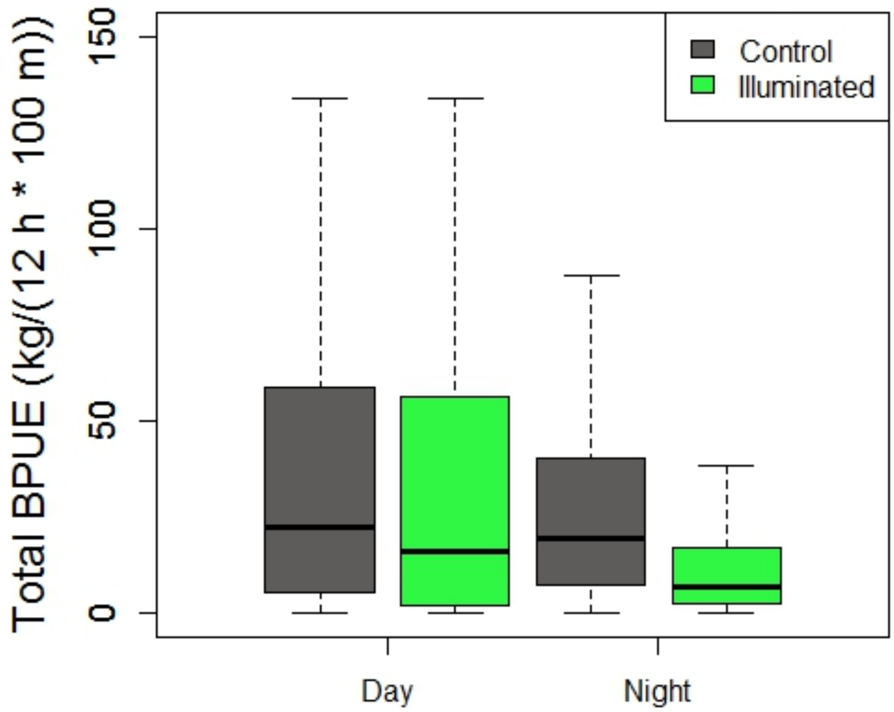

Figure 4. 5. Comparison of total BPUE in illuminated versus control nets. Illuminated nets resulted in a 34% reduction in mean total BPUE over 24 h periods, a 12% reduction in mean total BPUE during daytime, and a 56% reduction in total overall BPUE at nighttime. The effect of illumination was significant ($F = 4.1$; $P = 0.045$; see table 4.5).

CHAPTER 5

At Loggerheads Over International Bycatch: Initial Effects of a Unilaterally Imposed Bycatch Reduction Policy

Introduction

Fishing effort has increased globally over the past few decades (Swartz et al. 2010; Anticamara et al. 2011), with at least half of all fisheries either now fully exploited or overexploited (Worm et al. 2009; Branch et al. 2011; Ricard et al. 2011). In addition to overexploitation of many commercial stocks, the incidental capture of non-target organisms (bycatch) can lead to population declines in a range of vulnerable species, which in turn can alter ecosystem structure and function (Lewison et al. 2004; Shester & Micheli 2011). Bycatch can also damage gear, increase sorting time, and close fisheries or shift them into less profitable areas to protect non-target species (Benaka et al. 2012).

In United States federal waters, the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act (MSRA) is the primary law that codifies marine fisheries management. In an effort to improve international fisheries management, the U.S. Congress reformed the MSRA in 2006, amending the High Seas Driftnet Fishing Moratorium Protection Act (Moratorium Protection Act) with Section 610(a)(1) (hereafter 610), an international provision that directs the Secretary of Commerce to identify foreign nations engaged in bycatch of protected living marine resources (PLMRs) (NOAA 2011a; Benaka et al. 2012). Functionally, this responsibility is delegated to the National Marine Fisheries Service (NOAA Fisheries; Benaka et al. 2012). PLMRs consist predominantly of cetaceans, pinnipeds, sea turtles, and sharks

(NOAA Fisheries 2007). Listed species are either protected by U.S. law or international agreements and, with the exception of sharks, do not include species that are regulated under international fishery management organizations (NOAA 2011a).

Pursuant to the MSRA, the Moratorium Protection Act mandates the Secretary of Commerce to deliver a biennial report to Congress that identifies nations with vessels engaged in bycatch of PLMRs that lack a regulatory program that is comparable to that of the United States (NOAA 2011a; Benaka et al. 2012). Bycatch of PLMRs is defined as fishing from vessels of a nation, currently or within the calendar year preceding the biennial report to Congress, that results in bycatch of a PLMR that occurs on the high seas (i.e. in waters beyond any national jurisdiction) or bycatch of a PLMR shared with the United States but caught in waters beyond the exclusive economic zone of the United States (NOAA 2011a; Benaka et al. 2012).

Upon identification of a country for PLMR bycatch, NOAA Fisheries – acting through or in consultation with the U.S. State Department – is directed to initiate a bilateral consultation process with the identified nation that details the requirements of the Moratorium Protection Act, to offer help to mitigate bycatch, and to communicate what is required to receive a positive certification (NOAA 2011a; Benaka et al. 2012). Specifically, NOAA Fisheries is required to certify whether identified nations have: 1) adopted a bycatch regulatory program comparable to that of the United States (or implemented alternative management strategies that are analogous in effectiveness); and 2) established a management plan to assess stock status and enforce conservation efforts for the identified PLMR (NOAA 2011a). Following the consultation process, the Secretary of Commerce evaluates all information and gives the identified country a positive or negative certification in the following biennial report to Congress. A positive certification indicates that the bycatch issue has been adequately addressed, whereas a negative certification means that insufficient action has been taken. If a nation receives a negative certification, the Secretary of Commerce recommends to the President measures to be taken against the country, which may include trade sanctions including denial of access to U.S. ports and import restrictions on fish or fish products (NOAA 2011a).

Prior to 2013, no nation had ever been identified for PLMR bycatch because of the inherent challenges of collecting and analyzing bycatch data over the short timeframe of one year. However, in its 2013 biennial report to Congress, the United States identified Mexico under section 610 of the Moratorium Protection Act for bycatch of an internationally shared PLMR – the North Pacific loggerhead turtle (*Caretta caretta*) – in a gillnet fishery off the Pacific coast of Baja California Sur, Mexico (BCS) in 2012. In practical terms, as identified under the MSRA, Mexico had two years from January 2012 to present to demonstrate evidence of a U.S comparable loggerhead bycatch regulatory program and management plan to NOAA. If these were found to be insufficient, Mexico would likely face trade sanctions.

Drawing on the collective experience of my collaborators and myself working in this fishery and on section 610, I examine this unique case, evaluate the initial effects of the identification on community-based sea turtle conservation efforts and sea turtle management by Mexico, and make recommendations for improving the identification process of the law and its implementation. In addition to reviewing publicly available documents, I rely on direct on-the-ground observations in Mexico prior to and following the identification as well as information gathered from key stakeholder contacts including local fishers, government officials, scientists, and conservation practitioners.

North Pacific loggerhead turtles and Mexico's small-scale net fisheries

Located off the Pacific coast of BCS, the Gulf of Ulloa is a highly productive foraging hotspot for North Pacific loggerhead turtles (Peckham et al. 2007; Wingfield et al. 2011), most of which are large juveniles (Peckham et al. 2008) of high demographic importance (Crouse et al. 1987; Crowder et al. 1994). The overlap of local bottom-set gillnet and entangling net fisheries within this hotspot produces among the highest recorded sea turtle bycatch rates worldwide (Peckham et al. 2007, 2008; INAPESCA 2012; Koch et al. 2013). These fisheries result in high mortality because the nets are checked only once every 20 – 48 h, causing many entangled turtles to drown (Peckham et al. 2007). The resulting mortality is of international concern because loggerhead turtles are globally endangered (IUCN 2013), and the North Pacific population was recently uplisted to endangered under the U.S. Endangered Species Act (NOAA 2011b) as well as identified as one of the world's most endangered sea turtle populations (Wallace et al. 2012).

From 2007-2011 local fisher leaders progressively mitigated loggerhead bycatch in the Gulf of Ulloa by voluntarily switching to more turtle-friendly fishing gear and techniques in the loggerhead hotspot (Peckham & Maldonado-Diaz 2012). In November 2011, Mexico introduced an interagency protection plan to reduce loggerhead bycatch in gillnets in the Gulf of Ulloa, entitled "Monitoring Program for Protection of the Loggerhead Turtle." The plan was negotiated and signed by the Mexican Federal Attorney for Environmental Protection (PROFEPA), the National Commission of

Aquaculture and Fisheries (CONAPESCA), the National Commission of Natural Protected Areas (CONANP), the Fund for Protection of Marine Resources (FONMAR), the NGO Grupo Tortuguero de las Californias (GTC), and fishers from the Gulf of Ulloa (PROFEPA 2012).

During the summer of 2012, a collaborative, international research cruise led by INAPESCA (National Fisheries Science Institute, the federal agency that conducts fisheries research in Mexican waters) with partner investigators from U.S. academic institutions and U.S. and international NGOs documented unprecedented loggerhead bycatch rates. During July 2012, average bycatch rates were observed of 1.96 turtles caught per 100 m of gillnet per 24 h in conventional bottom-set gillnets fished during the research cruise within the loggerhead hotspot (INAPESCA 2012). Based on typical fishing effort of 400 – 800 m of net fished per day per boat, this translates to an estimated 8 –16 turtles captured per boat per day for those vessels fishing in the hotspot, exceeding previously published estimates by an order of magnitude, which as noted above were otherwise unprecedented globally (Peckham et al. 2008). Local fishers also reported higher than normal bycatch rates. In their report, INAPESCA stated "the available information on the incidental capture of sea turtles in the region known as the Gulf of Ulloa in the peninsula of Baja California Sur indicates that immediate action is necessary in the modification of fishing gear used by the artisanal fleet to avoid bycatch without affecting fisheries production" (INAPESCA 2012, *translated by authors*). Not surprisingly, strandings of presumably bycaught and discarded turtles concurrently increased dramatically at the shoreline adjacent to the loggerhead hotspot. Over the course of the summer more than 1,000 loggerhead carcasses stranded along a 43 km shoreline that borders the loggerhead hotspot (PROFEPA 2012; Miranda 2015).

Unilateral identification of Mexico for PLMR bycatch

Based on the INAPESCA study and PROFEPA stranding report, NOAA Fisheries contacted Mexico in December 2012 to request more information on the high level of mortality and to determine if Mexico had a regulatory program in place to manage bycatch of loggerhead turtles in their bottom-set gillnet fisheries (NOAA 2013). Mexico sent a detailed reply to NOAA Fisheries highlighting the activities of their federal agency that oversees fisheries management (i.e. CONAPESCA), but did not provide explicit information on regulatory measures to address this bycatch issue (NOAA 2013). Due to the high level of strandings and bycatch rates observed during the INAPESCA cruise, coupled with the absence of any harmful algal blooms or pollution events in this area at the time that could have caused increased sea turtle mortality, the United States identified Mexico for PLMR bycatch in its January 2013 biennial report to Congress (NOAA 2013) (Box 1). The United States notified Mexico of its identification decision through a diplomatic note from the State Department and a letter sent by NOAA Fisheries' (NOAA 2015). NOAA Fisheries noted in the 2013 biennial report to Congress that they did not believe Mexico had regulatory measures comparable in effectiveness to U.S. regulations for bycatch of the North Pacific loggerhead (NOAA 2013).

Mexico's response to the unilateral identification

Shortly following the identification, Mexican federal officials attributed the loggerhead mortality to alternative and seemingly unsupported causes including "bio-intoxication from macroalgae" (CONAPESCA 2013; Ibarra 2013; Rebolledo 2013;

Santoyo 2013; *Diaro Fuerza del Estado de México* 2014), rather than the fisheries bycatch in local fleets that their agencies had previously accepted and upon which they had made agreements to act (INAPESCA 2012; PROFEPA 2012). Given that the United States previously imposed a trade embargo against Mexico for bycatch of protected megafauna that was overruled by a GATT panel (see tuna-dolphin case; Parker 1999), Mexico's sudden denial of the previously accepted bycatch problem may have occurred because they did not deem the threat to be credible. The United States has employed unilateral environmental policies that impose trade sanctions irrespective of whether they fall within the letter or spirit of GATT obligations, so nations must assess the credibility of these threats (Gordon et al. 2001).

During 2013 and 2014, the Mexican government commissioned and funded a diverse array of investigators to evaluate alternative potential causes of loggerhead mortality in the region. This expensive, multidisciplinary undertaking concluded essentially that loggerhead mortality in the region could include disease and other natural causes in addition to fisheries bycatch (CONANP et al. 2014). However, as recently as January 2015, CONAPESCA publicly stated that the causes of mortality remained unknown.

Impacts of the Identification

We compare bycatch data, effort and quality of bycatch assessment, government bycatch management policy and practice, and fisher perceptions of bycatch to evaluate the initial effects of the identification (Table 5.1). Taking into account the qualitative nature of our assessment, in general terms we observed both positive and negative impacts of the identification of Mexico. Nevertheless, we contend that the identification of Mexico under section 610 was legally justified given the extraordinarily high level of strandings and bycatch rates observed on the index beach and during the INAPESCA cruise, respectively.

On the positive side, the identification and subsequent consultation process caused Mexico to eventually propose a fisheries refuge to protect loggerheads (Mexico 2015), including seasonal restrictions of high-bycatch gear to reduce bycatch as well as electronic monitoring of fishing and bycatch. Although these regulatory measures represent a promising advance in loggerhead protection and the development of a comprehensive bycatch management plan, NOAA Fisheries ultimately determined that they were not comparable in effectiveness to applicable U.S. regulations (NOAA 2015). Thus, the United States issued Mexico a negative preliminary certification (NOAA 2015).

On the negative side, the identification caused Mexico to deny the bycatch problem that its federal agencies had previously accepted and worked to address. This reaction hindered open dialogue and neutralized a decade's worth of social capital that included ongoing, community-based bycatch reduction programs. It also undermined Mexico's eventual attempts to mitigate the bycatch problem. During our decade-long community-based conservation work with loggerheads at the BCS hotspot, local fishers acknowledged their bycatch problem and were motivated to solve it primarily due to the high handling and gear-loss costs they incurred from turtles being entangled in their nets (Peckham and Maldonado 2012). The reversal in the official stance regarding bycatch, from actively working to mitigate it to publicly denying it, undermined and eroded fishers' development and adoption of bycatch solutions, representing considerable social capital and awareness among fishers that had taken a decade to construct. Many fishers reverted to fishing high-bycatch gear and practices, primarily because state and federal officials told them that official research indicated there was no bycatch problem, and conservation researchers and practitioners had actually fabricated the problem (see CONAPESCA 2013; Ibarra 2013; Rebolledo 2013; Santoyo 2013; *Diaro Fuerza del Estado de México* 2014). The tacit message was that the bycatch that befell fishers regularly was not the fishers' responsibility. Fishers involved in developing bycatch mitigation solutions were ostracized and harassed at port by other fishers and singled out in meetings by federal and state officials for being "traitors" to the fishing sector. Conservation practitioners were aggressively criticized, and in extreme cases physically assaulted and received death threats[1]. Consequently, the at-sea component of our loggerhead turtle community-based conservation work was suspended indefinitely. Shortly thereafter, INAPESCA canceled their ongoing research partnership with U.S. scientists, which included trials during the summer of 2013 to test additional turtle friendly gear in the hotspot, apparently due to political pressure from CONAPESCA.

This unforeseen shift in perspective and policy greatly jeopardized bycatch reduction programs that fisher leaders had voluntarily helped develop over the past decade. While these programs were inherently vulnerable to begin with due to the sensitive nature of switching gear and practices (Jenkins 2010), Mexico's reaction to the identification fostered a sense of mistrust, fear, and confusion among local fishers, which

[1]These observations are based on confidential conversations, direct on-the-ground observations, and focus group sessions with local fishers and community members. Given the extremely sensitive and charged nature of discourse, we hold these conversations in confidence and were unable to record individual responses or potentially identifying information. To help assure reliability of the information, we sought to corroborate information from multiple sources.

neutralized a decade's worth of social capital built in the community and hindered our capacity to continue community-based conservation work.

From a cultural standpoint, this dramatic shift possibly stems from a fundamental mistrust of researchers and NGOs from the United States intervening in Mexican environmental issues (e.g. see tuna-dolphin case; Parker 1999). Additionally, the suspension of the U.S.–INAPESCA collaboration with U.S. researchers was problematic for loggerhead conservation because it effectively halted Mexican government actors (gear technology experts from INAPESCA) that were generating official bycatch data while developing solutions. Thus, INAPESCA officials who were likely the best qualified to address the problem in Mexico, and who were also collaborating with U.S. fisheries scientists, sea turtle researchers, and gear technology experts, were removed from the situation, resulting in a tangible loss of capacity. Taken together, these negative effects clearly have reduced the quality of both bycatch assessment and management programs, and may have also contributed to higher bycatch mortality the summer following the identification (i.e. 2013) (Box 1).

Policy Recommendations

Based on the lessons learned from this case and one of our author's (LJ) experience helping to implement section 610, we offer the following policy recommendations to improve the identification process of section 610. These recommendations are broadly applicable to future identifications of other nations and can also help inform other unilaterally imposed conservation policies.

1. The identification process should provide NOAA Fisheries with more resources to better engage identified nations, including culturally appropriate liaising to engage national experts and officials in the development of solutions to help identified countries avoid the tendency towards denial and move straight into solutions. Mexico's defensive response to the identification begs the question – could the United States' communication of the identification and its repercussions have been more culturally appropriate? Drawing on the history of practice for the more frequently used and similar section 609 identification process for Illegal, Unreported, and Unregulated (IUU) fishing, NOAA Fisheries current process of discourse with identified nations is not individualized, meaning that communication of identification decisions is essentially the same between nations. The United States could have engaged CONAPESCA in creative ways and offered more resources to help.

One way of motivating change in official stances is by applying what is known as the "white glove" approach. For example, a sea turtle advocate in Northwestern Mexico swayed the opinion of an elected official from opposition to support of sea turtle conservation by publically praising him in a lengthy speech of thanks during a public festival. In essence, the advocate provided a tangible reward for the official in advance of behavioral change, reducing uncertainty and increasing the known benefit of a supportive stance. However, approaches like this are clearly context dependent. In order for NOAA Fisheries to craft culturally and socio-politically appropriate approaches to identification communications and strategies, they will need the expertise of relevant experts. Currently, this level of expert support and human resources exceeds what is allotted through NOAA Fisheries and the State Department for the identification process.

An example of a helpful resource would be an international policy expert and/or cultural ambassador that acts as a liaison to analyze the sociopolitical ramifications of a potential identification, including ways to circumvent possible problems, as well as explain the process better. NOAA Fisheries could either contract liaisons or employ existing ones if available; in the case of Mexico, NOAA Fisheries already had local liaisons working on loggerhead conservation in this particular fishery, but to our knowledge did not utilize them.

In Mexico, the identification affected a large number of families that depend on local fisheries, and such a process may have helped build trust, ease tension, and avoid confusion. Liaisons that are fluent in the language of the identified nation could go into the field and explain the process to state and federal officials and talk to local officials and fisher leaders and discuss ways to engage in the process, which would help bring legitimacy and also engage stakeholders early in the process. By having a liaison, it would afford NOAA Fisheries the opportunity to understand and evaluate potential on-the-ground repercussions and how best to circumvent them. This would help create a strategy that is more adaptive and affords increased flexibility and understanding of actions on the ground, particularly those that may be unanticipated.

2. Congress should consider re-evaluating the 12-month timeframe for which bycatch data can be considered in the identification process. A 2013 bill introduced before the 113th Congress (S.269) proposed to expand the identification timeframe from one to three years for section 610, but was never passed. The short timeframe of 12 months limits the capacity to identify nations to rare circumstances, such as in Mexico, where bycatch data unexpectedly becomes available. Extending the timeframe would make section 610 a policy that could be used more broadly given the ubiquitous nature of PLMR bycatch in coastal fisheries worldwide. In the United States, bycatch and discard data for protected stocks usually take at least 2 or 3 years before they are publically available due to the difficulty associated with collecting and analyzing these data, including the need to consolidate data from logbooks and observer reports (Benaka et al. 2012). In the case of Mexico it took a “perfect storm” to trigger an identification, as the high loggerhead mortality (Gardner & Nichols 2001; Nichols 2003; Koch et al. 2006) and extensive bycatch problem (Peckham et al. 2007, 2008) at BCS were well documented before 2012, but never fell within the 12-month window in which it could be used. In addition, extending the timeframe for which data can be considered may also mean that more and better data could be considered, and that these data could go through the various vetting and verification processes that many fisheries management agencies apply. This would also reduce the need to use preliminary or experimental data. Although the INAPESCA bycatch study used to identify Mexico was representative of the actual fishery (i.e. trials in the same location with the same gear and practices as local fisheries), other experimental trials may operate under different conditions from the identified fishery and use of such trials can potentially subject future identification decisions to criticism that hinders productive efforts to address PLMR bycatch.

3. The Secretary of Commerce should be mandated and funded to work through international fishery management organizations to continue establishing binding bycatch reporting requirements. Although the United States is mandated to work with identified nations to enter agreements through international organizations seeking international restrictions on the fishing practices that resulted in the PLMR bycatch (Benaka et al. 2012), the process is reactive and not proactive. Having a proactive mandate to work on international regulations prior to an identification may be helpful in situations where the United States has info that is credible but outside the timeframe for triggering an identification. The United States has long been a global leader in encouraging bycatch mitigation measures in international fisheries. However, inadequate funding and the lack of an explicit congressional mandate have limited this work. Establishing more reporting requirements for members of international fishery management organizations will provide more uniform data for identification consideration and would require more nations to collect bycatch data. The resulting increase in data would facilitate a fairer and more equitable consideration of bycatch (a ubiquitous problem) across nations. It would also help prevent the current situation in Mexico from occurring with other nations that are beginning to examine their bycatch problems through data collection and are vulnerable to a similar 610 identification as a result of these data, while other nations without bycatch data are not under the same scrutiny.

Conclusion and looking ahead

The unilateral identification of Mexico under section 610 has brought widespread domestic and international attention to the loggerhead bycatch problem and may ultimately catalyze a solution to reduce it. Unfortunately, the unintended outcomes produced by the identification eroded a decade’s worth of social capital and effectively precluded local conservation work. In particular, the denial of the problem by the

Mexican government after the identification led fishers to question the veracity of the bycatch problem and revert to using high-bycatch gear and practices that they had previously replaced, which fostered mistrust between fishers and conservation practitioners, jeopardizing a decade-long community-based conservation and fisher-led bycatch reduction program. Notwithstanding these effects, the United States was working with extremely limited resources and no prior implementation experience, and the identification was clearly justified. Congress, NOAA Fisheries, and the wider stakeholder community must all work together to improve the international bycatch provision. Further consideration and research will be needed to determine how this case may have affected other countries' willingness to collect and make data available that could be used in future identifications.

TABLE 5. 1. Comparison of bycatch data, quality of bycatch assessment, bycatch management, and fisher perception of bycatch prior to and following the unilateral identification of Mexico for bycatch of the North Pacific loggerhead turtle under section 610 of the Moratorium Protection Act. *Encompasses the consultation process.

	Before ID		*After ID		
	Pre–2012	2012	2013	2014	2015
Observed bycatch	Highest reported globally (Peckham et al. 2008)	Even higher (INAPESCA 2012)	Unknown (CONANP et al. 2014)	No known assessment	No known assessment
Quality of bycatch assessment	Independent, peer reviewed research	International collaboration between gear / turtle experts, academics, and federal fisheries scientists yields government report by fisheries science agency INAPESCA	Unpublished research funded by fisheries management agency CONAPESCA	No known assessment	No known assessment
Bycatch management programs	NGO coordinated fishers to develop bycatch solutions: results included gear / area switches	NGOs, scientists, academics, and INAPESCA partner to test bycatch reduction solutions, promising joint bottom-up and top-down solutions	Collaboration canceled	Unknown	Fisheries refuge to protect loggerhead turtles proposed by CONAPESCA
Perception of bycatch mortality by fishers	A problem they were causing that they wanted to solve to increase fishing profitability	A problem they wanted to continue to mitigate to increase fishing profitability	Bycatch does not exist and existing mortality is due to spurious causes	Bycatch does not exist and existing mortality is due to spurious causes	Bycatch does not exist and existing mortality is due to spurious causes

CHAPTER 6

Bycatch and Directed Harvest Drive High Green Turtle Mortality at Baja California Sur, Mexico

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 seagrass 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 (~ 70,000 eggs per night at Colola, Michoacan), green turtle populations began to plummet during the 1970s (Cliffton et al. 1982; Alvarado 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 2009; Senko et al. 2010a,b; Lopez-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, I 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.

Materials and Methods

Study site

I conducted monthly and bimonthly mortality surveys at 9 index sites along the Pacific and Gulf of California coasts of BCS between March 2006 and September 2008. 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 beaches and dumps at: Guerrero Negro (Isla Arena) (GNO), Punta Abreojos (PAO), Laguna San Ignacio (LSI), San Juanico (SJU), Bahia Magdalena (BMA), La Paz (LAP), Loreto (LOR), Mulege (MUL), and Santa Rosalia (SRO) (Figure 6.1).

Mortality surveys

I conducted beach surveys monthly and bimonthly at the study sites from February 2006 to September 2008 (Figure 6.1). I surveyed a total of 205 km of shoreline (see supplementary material A), representing 9.4% of the total BCS coastline. I also surveyed 9 town dumps bimonthly, representing ~ 6% of all coastal BCS communities (INEGI 2013). For each carcass found at beaches and dumps, I identified species, recorded gender (if possible), took digital photographs, and marked all carcasses with spray paint and/or cable binders to avoid recounts. I 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 (Bolten 1999). I recorded location of each carcass using a handheld GPS device.

Based on available external evidence, I 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). I 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).

Data analysis

I 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 Lopez-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 Lopez-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 types (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.

Results

Total mortality

From 2006 to 2008 we encountered a total of 778 carcasses at beaches and dumps (Table 6.1, Figure 6.2), of which 697 could be measured (see supplementary material B). Immature turtles 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 types (Figure 6.2). 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 6.1). Three sites along the Pacific coast (LSI, GNO, and BMA) accounted for 77% of all mortality (Table 6.1). Human consumption accounted for 48% of all mortality, followed by unknown mortality (32%), and bycatch (20%) (Table 6.1). 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.

Beach mortality

From 2006 to 2008 we encountered 439 carcasses at eight beaches (Table 6.1). We recorded 69% (N = 305) of carcasses at beaches during the summer months (May – October) (Table 6.1). 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 6.1). The Pacific coast accounted for almost all carcasses encountered at beaches (94%) (Table 6.1). Mean stranding rates of carcasses found at beaches ranged from 0.05 carcasses km–1 year–1 to 9.20 carcasses km–1 year–1 (Table 6.1).

Dumpsite mortality

From 2006 to 2008 we encountered 339 carcasses at nine dumpsites (Table 6.1). We recorded 57% (N = 193) of carcasses at dumps during the summer months (May – October) (Table 6.1). 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 6.1) 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 6.1).

Trends in overall mortality

Mortality attributed to bycatch was only identified in June and July (Figure 6.3), although one site (LSI) accounted for 99% of bycatch mortality. Unknown mortality also peaked in June (Figure 6.3). Human consumption at beach and dumpsites both peaked in October, although dumpsite consumption saw large annual variations (Figure 6.3). We found a significant difference amongst carcass size between sites within regions (i.e. Pacific and Gulf) ($F = 2.65$; df = 2.23×10^{-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. We found significant differences between the three mortality types ($F = 10.811$; 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.

Discussion

The 778 carcasses reported here likely represent only a small percentage of actual green turtle mortality at BCS because: (1) 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 hours, 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 (Figure 6.3). Mancini et al. (2012) 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 September. 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).

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. Overall, carcasses were larger in the Pacific, but this appears to be driven by the disparity between carcass size at LAP and BMA. This is likely because 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; Lopez-Castro et al. 2010).

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 (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

1,500 - 2,000 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 of 1.96 turtles 100 m net 24 hr–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 morality 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).

TABLE 6. 1.Cause of mortality and number of green turtle carcasses found at beaches and dumpsites along the Pacific and Gulf coast of Baja California Sur, Mexico from 2006 – 2008. See figure 6.1 for site abbreviations.

	Pacific						Gulf of California					Grand Total
	LSI	**GNO**	**PAO**	**SJU**	**BMA**	**Total**	**LAP**	**LOR**	**MUL**	**SRO**	**Total**	
Bycatch												
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
Human consumption												
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
Unknown												
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
Total beach mortality	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	9.2	0.81	0.13	0.31	0.63	1.36	0.06	0.05	0.61	N/A	0.14	0.81
Total dump mortality	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	121.2	17.19	7.91	17.95	23.3	50.9	159.86
Total overall mortality	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.

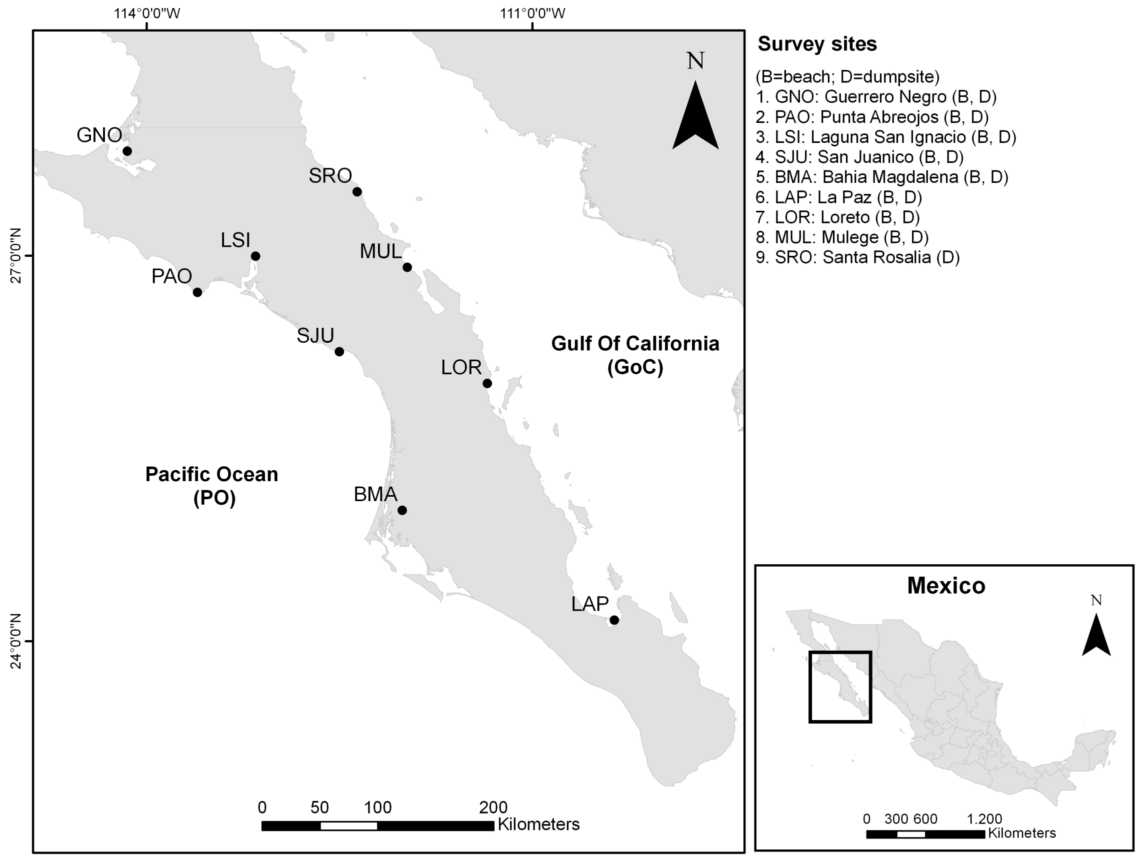

Figure 6. 1. Map of the study area where we conducted green turtle mortality surveys. Beaches (B) and/or dumpsites (D) were surveyed at each index site (marked with black circles). These sites are part of a long-term sea turtle monitoring program at northwestern Mexico by the conservation NGO Grupo Tortuguero and reflect areas of historical abundance and exploitation.

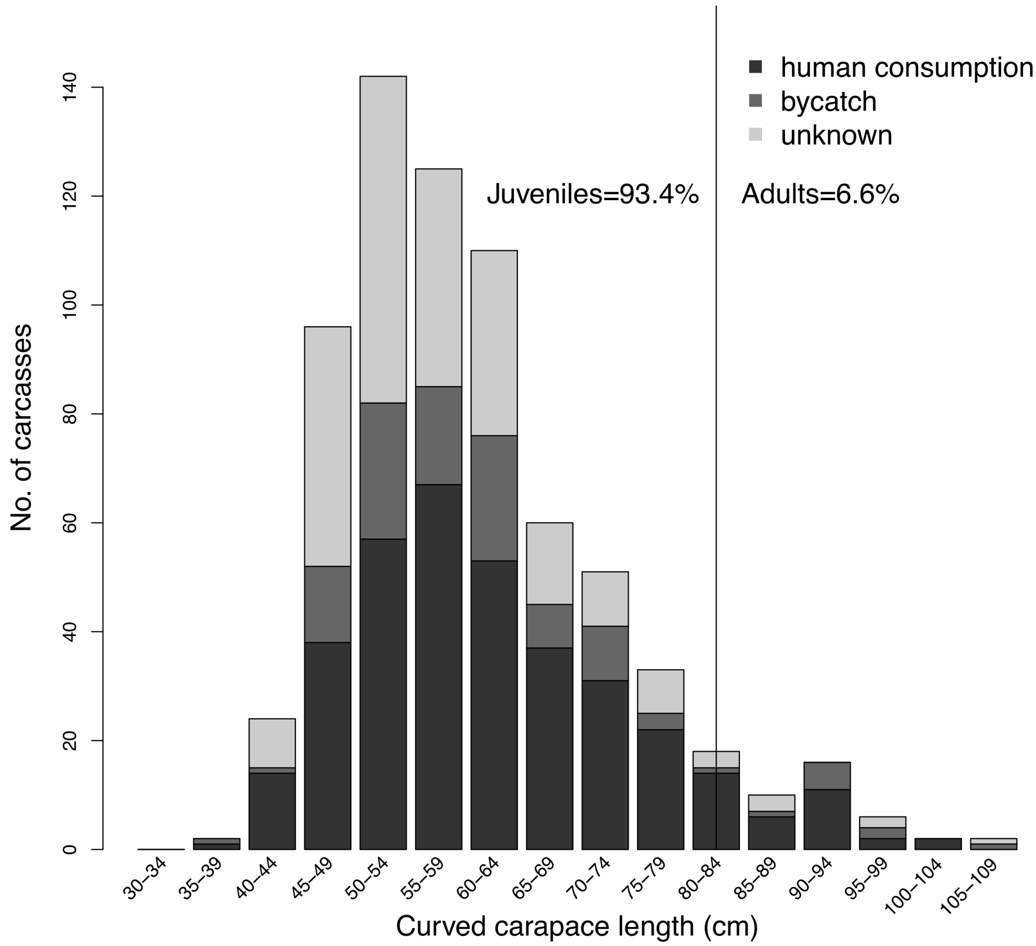

Figure 6. 2. Size distribution of green turtle carcasses encountered at beaches and dumpsites along the Pacific and Gulf coast of Baja California Sur, Mexico from 2006 to 2008 by mortality type (N = 778).

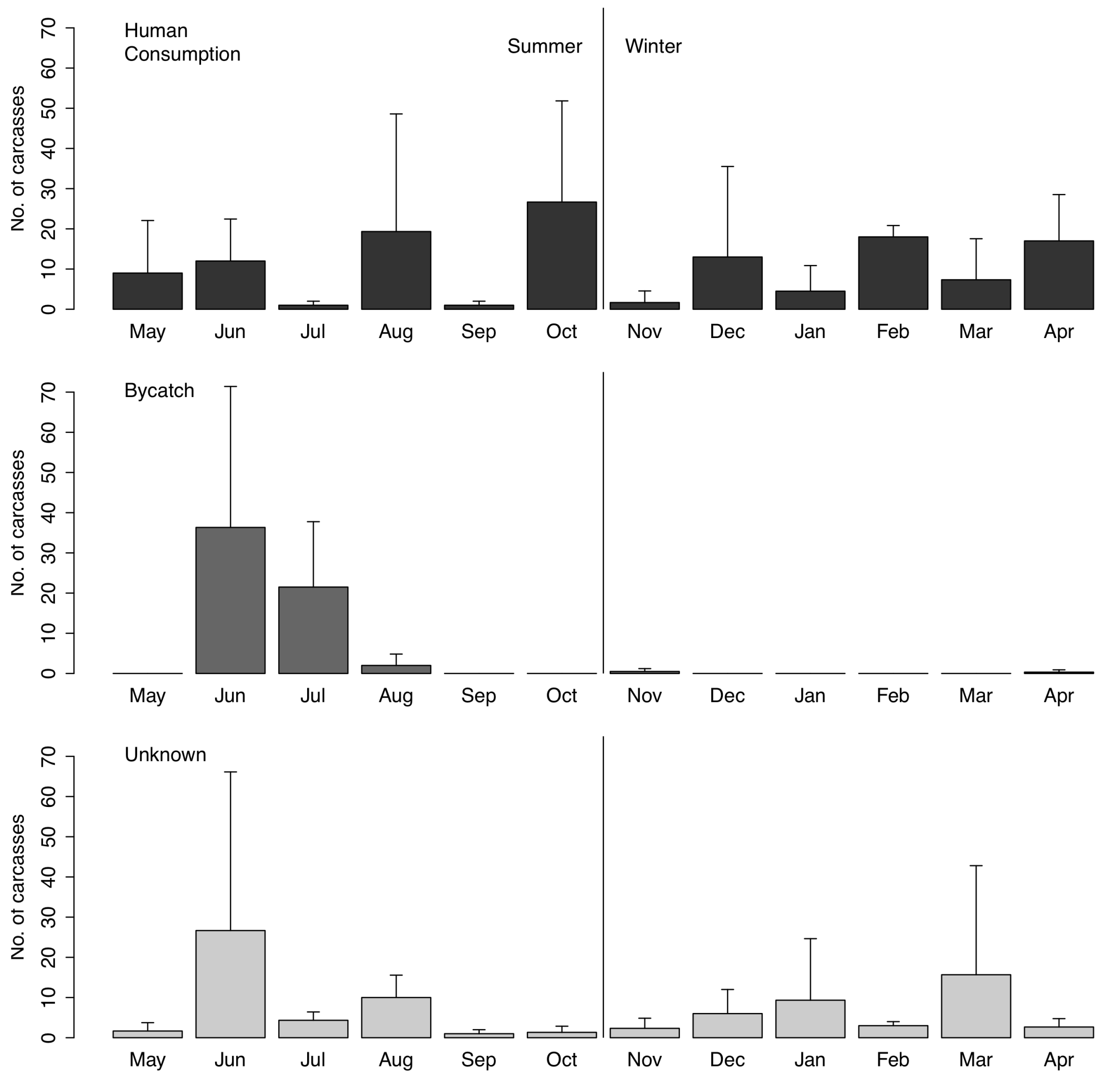

Figure 6. 3. Monthly and seasonal distribution of green turtle carcasses from each mortality type encountered at beaches and dumpsites at 9 index sites along the coast of Baja California Sur, Mexico from 2006 to 2008 (N = 778). Bars represent SD within months.

CHAPTER 7

Conclusions and Looking Ahead

Although globally ubiquitous in coastal waters, small-scale fisheries may produce levels of bycatch of marine megafauna that approach or even exceed bycatch in industrial fleets (Jaramillo-Legorreta et al. 2007; Peckham, et al. 2007, 2008; Alfaro et al. 2011; López-Barrera et al. 2012; Mancini et al. 2012). However, unlike industrial fisheries, small-scale fisheries often lack adequate resources to regulate their bycatch impacts (Shester and Micheli 2011). This is clearly the case at BCS, where I observed loggerhead turtle bycatch rates as high as 1 turtle captured in every 100 m of net (INAPESCA 2012; see chapter 5). These levels of bycatch translate to an estimated 4 – 10 turtles captured per boat, per day, or – alarmingly – 250 "turtle years" removed per boat, per day. These levels of bycatch are unprecedented and threaten the persistence of the North Pacific loggerhead, a population that was recently listed as one of the most vulnerable sea turtle populations in the world (Wallace et al. 2011).

Unlike loggerheads, I found that green turtles at BCS continue to be illegally hunted for their meat and shells despite over two decades of compete federal protection, local conservation efforts, and improvements in infrastructure and market conditions that provide easy access to other protein sources. In addition to directed harvest, green turtles also are killed as bycatch in small-scale fisheries, although the levels of bycatch mortality appear to be substantially lower than that of loggerheads.

Upon documenting the extraordinarily high rates of loggerhead bycatch at BCS, I conducted a literature review to compare the effectiveness of three commonly used bycatch reduction strategies. My review determined that gear modifications were generally more successful at mitigating bycatch of vulnerable megafauna than time-area closures, take limits, and buy-outs. Not surprisingly, gear modifications also tend to be more popular with fishers because they allow fishers to keep fishing in their desired locations and their desired times. Nevertheless, gear modifications are rare in net fisheries, and particularly when compared to other fisheries with high bycatch such as longlines or trawls. Consequently, in an effort to reduce loggerhead bycatch at BCS while also improving overall fisheries sustainability and maintaining fisher livelihoods, I collaborated with partner academic institutions, NGOs, and managers to test and developed two gear modifications – buoyless and illuminated nets. I found that buoyless nets reduced bycatch of loggerhead turtles without affecting target catch rates. By contrast, illuminated nets did not significantly reduce loggerhead bycatch rates (although there was a 50% reduction at night), but significantly reduced overall bycatch biomass without affecting both target catch rates and market value.

Despite the clear adoption potential of both gear modifications in the net fisheries at BCS, their broad implementation will be difficult due to several factors. These include, but are not necessarily limited to, a fundamental mistrust of "outsiders" and government intervening in fisheries, the inherent difficulty of switching gears, and especially the recent unilateral identification of Mexico for loggerhead bycatch under section 610 of the Magnuson-Stevens Act (MSA), which occurred while we were conducting our field trials and outreach work. Following the MSA policy intervention, Mexico denied the bycatch problem that their federal agencies had previously accepted and were working to address. This denial of the problem resulted in fishers losing trust with conservation practitioners and researchers because the government was officially denying the bycatch problem and using scientific explanations to justify the denial. These unintended outcomes halted loggerhead conservation work in the BCS region, including future research to test fish traps and other turtle-friendly gear in the hotpot. Nevertheless, the long-term effects of the identification, particularly on loggerhead bycatch reduction, will need to be carefully evaluated over the next several years.

Conservation action, coupled with more research, is urgently needed to solve the loggerhead bycatch problem at BCS. Mexico must immediately implement a bycatch management program that includes effective assessment and mitigation measures. A first step must include efforts to limit access (i.e. the number of fishers fishing with nets), which currently does not appear to be the case. Assessment of bycatch and fishing can be achieved by electronic monitoring devices on those vessels operating in the hotspot. Bycatch mitigation can be achieved by using spatial and temporal restrictions on fishing, gear modifications, gear switches, take limits, or by using a combination of measures. Given the logistical challenges of enforcing time-area closures and their unpopularity with fishers, gear modifications or gear switches are more likely to be effective in the long-term.

Although our suggested gear modifications showed strong adoption potential, neither is ready for implementation in the net fisheries at BCS. For example, illuminated nets had virtually no difference on loggerhead bycatch over 24 h periods, the time during which fishers soak their nets at BCS. Further testing of illuminated nets should be encouraged for its potential to reduce loggerhead bycatch at night and its extraordinary promise to reduce overall bycatch biomass over 24 h periods. The significant reduction in overall bycatch biomass has the added benefit of increasing operational efficiency by saving fishers time from removing bycatch organisms from nets. By contrast, while buoyless nets significantly reduced loggerhead bycatch without affecting target catch rates, market value was significantly lower. Thus, despite their strong potential, both gear modifications need further testing and modifications before they can be implemented.

The bycatch of large juvenile loggerheads in coastal mesh net fisheries at BCS gravely threatens their persistence and needs to effectively be eliminated. Although my research demonstrates that gear modifications have strong potential, gear switches will ultimately be needed as a means to remove entangling nets from the water altogether. In particular, fish traps and other turtle-friendly gears should be tested and encouraged, and include direct input of local fishers. At a nearby fishing cooperative (Punta Abreojos), fish traps were found to be more profitable than set gillnets with significantly lower bycatch rates (Shester and Micheli 2011). Future research should test the efficacy (e.g. target catch value, overall bycatch rates, bycatch composition, and operational and economic efficiency) of fish traps and fish trawls equipped with Turtle Excluder Devices (TEDs) as an alternative to bottom-set gillnets.

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APPENDIX A

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APPENDIX B

GREEN TURTLE MORTALITY SURVEY EFFORT

Distribution of survey effort at beaches surveyed from 2006 – 2008 along Pacific and Gulf coasts of Baja California Sur, Mexico. See figure 6.1 for site locations.

Index site	Total shoreline surveyed (km)	% of total BCS shoreline
Guerrero Negro	26.0	1.17
Punta Abreojos	38.2	1.72
Laguna San Ignacio	13.5	0.61
San Juanico	16.7	0.75
Bahia Magdalena	19.7	0.89
Mulege	19.0	0.86
Loreto	26.1	1.17
La Paz	46.1	2.08

APPENDIX C

LENGTH MEASUREMENTS OF GREEN TURTLE CACASSES

Curved carapace length measurements of green turtle carcasses found between beaches and dumpsites along the Pacific and Gulf coast of Baja California Sur, Mexico from 2006 to 2008. Only carcasses with measurements are included. See figure 6.1 for site abbreviations.

	Pacific						Gulf of California					
	LSI	**GNO**	**PAO**	**SJU**	**BMA**	**Total**	**LAP**	**LOR**	**MUL**	**SRO**	**Total**	**Grand total**
Beach – Bycatch												
N	111	1	0	0	0	112	0	1	0	N/A	1	113
Mean	61.26	63	-	-	-	61.26	-	48	-	-	48	61.2
SD	12.49	-	-	-	-	12.49	-	-	-	-	N/A	12.45
Range	39.7-105.4	-	-	-	-	39.7-105.4	-	-	-	-	N/A	39.7-105.4
Beach – Human consumption												
N	5	0	2	0	6	13	0	0	15	N/A	15	28
Mean	53.94	-	59.5	-	53.3	54.5	-	-	58.47	-	58.47	62.2
SD	5.61	-	18.38	-	12.95	10.66	-	-	8.03	-	8.03	12.58
Range	46.0-59.0	-	46.5-72.5	-	42.0-75.9	42.0-75.9	-	-	44.0-76.0	-	44.0-76.0	42.0-76.0
Beach – Unknown												
N	127	48	8	12	23	219	6	1	4	N/A	11	229
Mean	56.86	59.49	53.63	55.96	54.33	57.01	70.08	60	56.5	-	64.22	57.4
SD	11.17	9.53	7.68	6.83	10.2	10.45	9.61	-	8.54	-	10.69	10.6
Range	40.0-105.0	45.6-88.0	47.0-71.0	47.0-69.0	40.0-76.6	40.0-105.0	59.0-85.0	-	51.0-69.0	-	51.0-85.0	40.0-105.0
Dumpsite – Human consumption												
N	5	121	48	1	71	245	35	8	12	26	81	327
Mean	58.1	64.3	60.5	52	61.3	62.5	61.6	61.7	62.8	62.3	62	62.4
SD	13.4	11.9	13	-	16.42	13.6	8	6	10.3	10.2	8.8	12.6
Range	44.5-74.0	42.5-92.5	40.0-96.0	-	38.5-101.0	38.5-101.0	45.0-75.0	54.7-71.5	50.0-86.0	47.5-87.0	45.0-87.0	38.5-101.0

N/A, not applicable