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Cumulative estimates of sea turtle bycatch and mortality in USA fisheries between 1990 and 2007

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ABSTRACT

Sea turtles interact with a variety of fishing gears across their broad geographic distributions and ontogenetic habitat shifts. Cumulative assessments of multi-gear bycatch impacts on sea turtle populations are critical for coherent fisheries bycatch management, but such estimates are difficult to achieve, due to low fisheries observer effort, and a single-species, single-fishery management focus. We compiled the first cumulative estimates of sea turtle bycatch across fisheries of the United States between 1990 and 2007, before and after implementation of fisheries-specific bycatch mitigation measures. An annual mean of 346,500 turtle interactions was estimated to result in 71,000 annual deaths prior to establishment of bycatch mitigation measures in US fisheries. Current bycatch estimates (since implementation of mitigation measures) are ~60% lower (137,800 interactions) and mortality estimates are ~94% lower (4600 deaths) than pre-regulation estimates. The Southeast/Gulf of Mexico Shrimp Trawl fishery accounts for the overwhelming majority of sea turtle bycatch (up to 98%) in US fisheries, but estimates of bycatch in this fishery are fraught with high uncertainty due to lack of observer coverage. Our estimates represent *minimum* annual interactions and mortality because our methods were conservative and we could not analyze unobserved fisheries potentially interacting with sea turtles. Although considerable progress has been made in reducing sea turtle bycatch in US fisheries, management still needs improvement. We suggest that sea turtle bycatch limits be set across US fisheries, using an approach similar to the Potential Biological Removal algorithm mandated by the Marine Mammal Protection Act.

1. Introduction

Fisheries bycatch, or the incidental capture of non-target species during fisheries operations, is a global issue for management of marine resources, as it occurs in virtually all fishing fleets (Hall et al., 2000) and can be a driver of marine megafauna population declines (Lewison et al., 2004a, 2005; Read et al., 2006; Soykan et al., 2008; Wallace et al., 2008). Sea turtle bycatch occurs in large-scale as well as small-scale fishing fleets, in gear types such as trawls, longlines, and gillnets, pound nets, dredges and to a lesser extent, pots and traps (Chuenpagdee et al., 2003; Lewison et al., 2004b; Zollett, 2009; Moore et al., 2009; Casale, 2010; Wallace et al., 2010a). Understanding impacts of individual fishing gears on sea turtles is important, but comprehensive analyses across multiple fisheries are necessary to adequately assess cumulative impacts of fisheries bycatch on sea turtle populations (Bolten et al., 2010; Wallace et al., 2010a).

Despite the need for cumulative assessments, several factors have made them difficult to conduct for sea turtles. In the United States, inadequate levels of observer coverage and biased spatiotemporal representations of fisheries activities produce uncertain estimates of sea turtle bycatch, while policies designed to address fisheries bycatch do not sufficiently integrate management practices across several fisheries to ensure sea turtle population persistence and viability (Lewison et al., 2004a; Sims et al., 2008; Moore et al., 2009; Wallace et al., 2010a). For example, sea turtle conservation guided by the US Endangered Species Act (ESA) has generally been translated by NOAA (National Oceanographic and

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Atmospheric Administration) into sea turtle bycatch assessments and regulations on a fishery-by-fishery basis; this constrains evaluation and mitigation of cumulative bycatch impacts (Griffin et al., 2006). Such an approach is problematic because a given population of sea turtle may interact with more than one fishery (domestically or internationally), and a given fishery or gear type may interact with more than one sea turtle population (Moore et al., 2009).

The guiding framework for assessing fisheries impacts on sea turtles in the US differs sharply from the potential biological removal (PBR) framework defined under the US Marine Mammal Protection Act (MMPA) for evaluating impacts of direct human caused mortality and serious injury to marine mammals. Briefly, PBR is a precautionary estimate of additive mortality that would permit an affected population to remain above defined management targets. The PBR estimate is calculated from population abundance and potential population growth rate estimates, and is robust to various forms of parameter uncertainty (Wade, 1998; Taylor et al., 2000). Under the MMPA, all fisheries (state and federal) interacting with marine mammals are subject to observer coverage from which cumulative estimates of lethal takes are calculated. If cumulative lethal take across all fisheries exceeds the designated PBR, then a Take Reduction Plan (TRP) is assembled to reduce lethal take in the most problematic fisheries (for review of bycatch management policies in US fisheries, see Moore et al., 2009). In contrast to the MMPA framework, the absence of clearly defined statutory guidelines for assessing cumulative impacts of bycatch on sea turtles populations has led to shortcomings in how such impacts are evaluated. This can have undue consequences for sea turtle protection, fisheries viability, or both.

Sea turtle bycatch in US fisheries provides a good case study to examine cumulative impacts of fisheries. The United States Exclusive Economic Zone (EEZ), including territorial waters, is the world's largest (11 million km^2), and it hosts a diverse array of fisheries (Moore et al., 2009; Table 1). In addition, six species of sea turtles (green turtles – *Chelonia mydas,* loggerheads – *Caretta caretta,* leatherbacks – *Dermochelys coriacea*, olive ridleys – *Lepidochelys olivacea,* hawksbills – *Eretmochelys imbricata*, and Kemp's ridleys – *Lepidochelys kempii*), all of which are listed as Threatened or Endangered by the US. Endangered Species Act and Endangered or Critically Endangered by the IUCN Red List of Threatened Species (www.iucnredlist.org), occur within the US EEZ. The southeast United States and Gulf of Mexico provides important nesting habitat to loggerheads, leatherbacks, greens and Kemp's ridleys. While several of these species typically spend juvenile years in Atlantic oceanic gyres (i.e. Musick and Limpus, 1997; Bolten et al., 1998), Atlantic near-shore waters provide important foraging, mating and inter-nesting habitat (i.e. Musick and Limpus, 1997; Hopkins-Murphy et al., 2003). Pacific US waters provide important foraging habitat for migratory loggerhead, leatherback, and olive ridley populations (i.e. Polovina et al., 2004; Benson et al., 2007; Dutton et al., 2008), while the Northwestern Hawaiian Islands hosts an important endemic rookery of green sea turtles (i.e. Balazs and Chaloupka, 2006; Dutton et al., 2008). Research on sea turtle bycatch in United States fisheries has helped to elucidate important spatial and temporal patterns in sea turtle distribution and bycatch (Polovina et al., 2003; Kot et al., 2010), and in finding specific gear configurations and fishing practices that help in the reduction of bycatch and mortality events (Watson et al., 2005; Sasso and Epperly, 2006; Swimmer et al., 2006). With the help of this empirical knowledge, the USA has demonstrated a commitment to the reduction of bycatch over the past decade by passing a number of pertinent regulations and by instituting extensive on-board observer programs for several fisheries (Moore et al., 2009; Table 1), but has neglected to assess cumulative impacts relative to population status thus far. Along these lines, Bolten et al. (2010) point to the importance of quantifying relative impacts of various threats to sea turtle populations to prioritize conservation resources and to evaluate the efficacy of recovery plans.

In this study, we compiled existing fleet-wide estimates of sea turtle bycatch and mortality events in the United States over the last two decades, and assessed these estimates for individual fisheries and species. Although cumulative bycatch estimates do not

Table 1
Overview of US fishery resgulations pertinent to sea turtle conservation. Pre- and post-regulatory strata were identified for each fishery based on the first year a sea turtle bycatch mitigation strategy was mandated, except for the SE and Gulf of Mexico Shrimp Trawl fishery. In this case, pre- and post-regulatory strata were distinguished by the 2003 ruling to enlarge escape openings in TEDs.

Fishery	Year regulations in place	Description of regulations	Final ruling citation
Atlantic Shark Bottom Longline	None		
Atlantic/GoM Pelagic Longline	2001; 2004	Spatial and temporal closures, circle hooks mandated	50CFR223.206; 69FR40734
CA Pelagic Longline	2004	Spatial, gear-specific closure	69FR11540
CA Set Net	None		
CA/OR Drift Gillnet	1997; 2001; 2006	TRP enacted, spatial and temporal closures for Dc and Cc	62FR51805; 66FR44549; 68FR69962
GoM Reef Fish	2006; 2009	Time area closures, effort reduction	71FR45428; 74FR20229; 74FR53389
GoM/Caribbean Hook and Line	None		
Hawaii Pelagic Longline	2000; 2004	Spatial and temporal closures, gear restrictions, 100% observer coverage	67FR40232; 69FR17329
Mid-Atlantic Bottom Trawl	1996	TEDs required for summer flounder targeted trawls	61FR1846
Mid-Atlantic Scallop Dredge	2004; 2006	Gear modifications, turtle chain mats required	NEFMC Atlantic Sea Scallop FMP; 71FR50361; 73FR18984
Mid-Atlantic Scallop Trawl	None		
NC Inshore/Mid-Atlantic Gillnet	2000; 2002; 2006	Spatial and temporal closures, gear restrictions (i.e.) large mesh gillnets	67FR71895; 67FR56931; 71FR24776
NC Pound Net	None		
SE/GoM Shrimp Trawl	(i.e.) 1987; 1994; 1996; 2003	TED requirements, inshore TEDS, hard TED requirements, TED size requirements, other TED modifications	52FR24244; 61FR18102;68FR8456; 69FR31035
SE Shark Driftnet	None		
SE Snapper/Grouper	None		
Virginia Pound Net	2002; 2004; 2006; 2008	Spatial and temporal closures, gear restrictions (i.e.) pound net leaders, mesh size, inspection program	67FR41196; 69FR24997; 71FR36024; 73FR68348

Table 2
Resources presenting fleet-wide bycatch estimates in gear types and individual fisheries used in this analysis. A complete list of references used in this analysis can be found in Supplemental Data I, along with a link to a search library containing many of the sources.

Fishery	# of resources available
Gillnets/Pound Nets	*24*
CA/OR Drift and Set Gillnet	6
North Carolina Inshore Gillnet	9
Mid-Atlantic Gillnet	1
Southeast Shark Driftnet	5
North Carolina Pound Net	2
Virginia Pound Net	1
Longlines and Vertical Lines	*24*
Gulf of Mexico Reef Fish	1
Atlantic Shark Bottom Longline	2
Atlantic/Gulf of Mexico Pelagic Longline	10
CA Pelagic Longline	1
Hawaii Pelagic Longline	8
South East Snapper/Grouper	1
Gulf of Mexico/Caribbean Handline	1
Trawls/Dredges	*9*
Mid-Atlantic Bottom Trawl	3
Mid-Atlantic Scallop Trawl/Dredge	3
Southeast/Gulf of Mexico Shrimp Trawl	3

translate directly into population impact estimates which require information about population abundance and dynamics (NRC, 2010), they enable evaluation of the relative importance of individual US fishing fleets in terms of their respective contributions to total mortality. In addition, a straightforward tally of cumulative takes provides insight into the effectiveness of bycatch reduction efforts by comparing cumulative takes and mortality before and after the promulgation of various bycatch reduction measures. All of these considerations may be useful in helping prioritize allocation of conservation resources.

2. Methods

2.1. General methods

We compiled available information on sea turtle bycatch in US fisheries from peer-reviewed publications, US National Marine Fisheries Service (NMFS) Biological Opinions, National Oceanic and Atmospheric Administration (NOAA) Technical Memoranda, and NMFS Fisheries Science Center Reports (see Supplemental Data I for complete reference list). We focused our literature review on studies that provided extrapolated, fleet-wide estimates of sea turtle bycatch and mortality between 1990 and 2007. From each study we recorded gear type, observed bycatch, observed mortality, estimated bycatch, estimated mortality, effort data and demographic data when available.

Table 3
Estimated annual sea turtle bycatch and mortality between 1990 and 2007. Estimates are rounded to the nearest hundred (when >100) or ten (when <100).

Bycatch		
Region	Pre-regulation (mean)	Post-regulation (mean)
Pacific	700	100
Atlantic	345,800	137,700
Total US	346,500	137,800
Mortality		
Region	Pre-regulation (mean)	Post-regulation (mean)
Pacific	300	60
Atlantic	70,700	4500
Total US	71,000	4600

Across all reports, a wide variety of extrapolation methodologies were used (e.g. Ratio Estimator, Generalized Additive Models, Generalized Linear Models), and many studies used stratified estimates based on temporal, spatial, environmental, physical, and biological variables. Each extrapolation and estimation method is associated with varying degrees and sources of error and uncertainty (for a

Table 4
Estimated Atlantic and Pacific mean annual sea turtle bycatch and mortality (sorted by individual fisheries) between 1990 and 2007. Ranges presented when more than one annual estimate per regulatory stratum is available. Estimates are rounded to the nearest hundred (when >100) or ten (when <100). In the case of shrimp trawls, pre-regulation and post-regulation refers to pre-2003 and post-2003 TED enlargements.

Fishery	Pre-regulation mean	Pre-regulation range	Post-regulation mean	Post-regulation range
Atlantic bycatch interactions				
SE/Gulf of Mexico Shrimp Trawl	340,500	NA	133,400	NA
Atlantic/Gulf of Mexico Pelagic Longline	1600	414–3553	1400	625–2143
Mid-Atlantic Bottom Trawl	1100	NA	600	NA
Virginia Pound Net	600	NA	600	NA
Gulf of Mexico Reef Fish	600	NA	600	NA
Mid-Atlantic Gillnet	400	43–1018	300	154–465
NC Pound Net[a]	200	129–355	200	194–269
SE Demersal Shark Longline	200	107–339	200	107–339
Mid-Atlantic Scallop Trawl	100	NA	100	NA
NC Inshore Gillnet[a]	100	28–275	100	28–275
SE Snapper/Grouper	100	NA	100	NA
Mid-Atlantic Scallop Dredge	300	74–749	90	0–180
Gulf of Mexico Hook and Line	10	NA	10	NA
SE Shark Drift Gillnet	<10	0–19	<10	0–19
Pacific bycatch interactions				
HI Pelagic Shallow & Deep Set Longline	700	601–849	100	3–558
CA Set Gillnet	10	0–43	10	0–43
CA/OR Drift Gillnet	30	6–102	<10	0–29
CA Pelagic Deep Set Longline	<10	NA	<10	NA
Atlantic mortality events				
SE/Gulf of Mexico Shrimp Trawl	69,300	NA	3700	NA
Mid-Atlantic Bottom Trawl	200	NA	300	NA
Gulf of Mexico Reef Fish	200	NA	200	NA
Mid-Atlantic Gillnet	200	17–407	100	62–186
Mid-Atlantic Scallop Dredge	600	NA	70	0–135
SE Demersal Shark Longline	50	15–97	50	15–97
SE Snapper/Gouper	40	NA	40	NA
NC Inshore Gillnet[a]	30	0–84	30	0–84
Atlantic/Gulf of Mexico Pelagic Longline	100	0–726	20	0–50
Virginia Pound Net	<10	NA	<10	NA
SE Shark Drift Gillnet	<10	0–3	<10	0–3
Gulf of Mexico Hook and Line	0	NA	0	NA
NC Pound Net[a]	0	NA	0	NA
Mid-Atlantic Scallop Trawl	0	NA	0	NA
Pacific mortality events				
HI Pelagic Shallow and Deep Set Longline	300	245–359	50	0–251
CA/OR Drift Gillnet	20	0–40	<10	0–19
CA Set Gillnet	<10	0–30	<10	0–30
CA Pelagic Deep Set Longline	<10	NA	<10	NA

[a] Indicates incomplete estimates.

Table 5
Estimated mean annual sea turtle bycatch and mortality (sorted by species) between 1990 and 2007. Estimates are rounded to the nearest hundred (when >100) or ten (when <100). *Note*: totals from Tables 4 and 5 do not match, as Table 4 accounts for interactions and mortality of *unknown* species while Table 5 does not.

Species	Bycatch		Mortality	
	Pre-regulation	Post-regulation	Pre-regulation	Post-regulation
Atlantic				
Lepidochelys kempii	156,000	98,300	4300	2700
Caretta caretta	166,900	26,500	63,500	1400
Chelonia mydas	18,900	11,400	500	300
Dermochelys coriacea	3800	1400	2300	40
Eretmochelys imbricata	20	<10	20	<10
Pacific				
Caretta caretta	400	50	200	20
Lepidochelys olivacea	100	30	70	20
Dermochelys coriacea	100	30	50	10
Chelonia mydas	40	10	20	10

complete discussion of uncertainty and error associated with these estimates see Supplemental Data II). We did not attempt to standardize across methodologies to generate cumulative estimates, but instead summed estimates across studies. To reflect the uncertainties in this method, we present totals rounded to the nearest hundred (when estimates are >100), or to the nearest ten (when estimates are <100). These approximate values were chosen based on the fact that annual estimates produced for each fishery generally vary within one order of magnitude (Table 4; Supplemental Data II). In cases where 100% observer coverage is mandated (e.g. Hawaii shallow-set Longline Fishery after 2004), observed bycatch values reported were used to represent a fleet-wide total. When bycatch and mortality estimates were reported in ranges, not point estimates, we used lower range values. For poorly documented fisheries for which fisheries-wide bycatch estimates were not provided, only target species-specific bycatch estimates, we used these existing estimates to represent entire fishery bycatch estimates. For example, pre-regulatory estimates of the Mid-Atlantic bottom trawl fishery are only available for the summer flounder portion of the fishery, even though the fishery also targets croaker, weakfish, squid and mixed groundfish (Murray, 2006). Therefore, bycatch and mortality estimates in these fisheries are likely to be negatively biased.

Pre- and post-regulatory strata were identified for each fishery based on the first year a sea turtle bycatch mitigation strategy was mandated (Table 1). Annual bycatch and mortality estimates were separated into pre- and post-regulatory strata, and we calculated mean, minimum, and maximum values for bycatch and mortality estimates within these strata (see Supplemental Data II for metadata and methods). For fisheries with no bycatch regulation measures in place, pre-regulation values were also used for post-regulation values if independent post-regulation estimates did not exist. Mean values were summed across fisheries to estimate cumulative sea turtle bycatch and mortality in the Atlantic, Pacific and total USA (Table 3). Bycatch and mortality estimates were also summed across species and sorted by fishery to evaluate relative individual fishery impacts (Table 4), and finally summed across fisheries and sorted by species to evaluate absolute mortality for individual species (Table 5).

2.2. Southeast and Gulf of Mexico Shrimp Trawl fishery-specific methods

Several factors posed problems in our estimations of total interactions and mortality events for the Southeast (SE) and Gulf of Mexico shrimp fishery. These problems include the error and uncertainty associated with data, a shrimp fishery effort reduction over the last two decades, and concerns about efficacy in Turtle Excluder Devices (TEDs) before a 2003 enlargement mandate. For these reasons, and due to the sheer importance of this fishery in contributing to overall sea turtle human-induced mortality, we handled shrimp trawl bycatch estimates slightly differently than estimates from other fisheries.

For shrimp bottom trawls in the SE and Gulf of Mexico, Epperly et al. (2002) and NMFS (2002), and an unpublished 2008 NMFS Memorandum provide the only estimates of total bycatch and mortality for the fishery. Epperly et al. (2002) provide bycatch and mortality estimates of loggerheads, leatherbacks, greens and Kemp's ridleys before, and projections after, the 2003 TED enlargement mandate using CPUE data from 1997 to 1998 adjusted for aerial surveys. However, Epperly et al. (2002) strongly cautioned against the use of green and Kemp's ridley aerial survey adjusted estimates due to error arising from species misidentification. NMFS (2002) Biological Opinion confirmed this assertion and deemed that while 1997–1998 CPUE data adjusted for aerial surveys is the best estimation method for leatherbacks and loggerheads, 1997–1998 CPUE data without aerial survey adjustment are most appropriate for greens and Kemp's ridleys. Thus, we derived estimates of pre-regulatory bycatch and mortality for leatherbacks and loggerheads from Epperly et al. (2002), but we used estimates of pre-regulatory bycatch and mortality for greens and Kemp's from NMFS (2002) Biological Opinion.

Further constraining data validity, both these reports calculated estimates from past effort data without the knowledge that Gulf of Mexico shrimp effort would drop ~74% by 2007 (Nance, 2010). Accordingly, in an unpublished Memorandum, NMFS recalculated bycatch and mortality estimates post 2003 TED enlargements, using 2007 effort data from the Gulf of Mexico but not elsewhere in the Southeast (Ponwith, 2008). Therefore, we derived our post-regulation estimates (after 2003 TED enlargements) from the 2008 Memorandum of updated bycatch and mortality estimates. We acknowledge that reduction in sea turtle bycatch since 2003 is not due solely to TED regulations but in large part to the reduction of fleet effort. Nonetheless, it was more appropriate to use updated bycatch estimates based on true effort (Ponwith, 2008) rather than projected effort (Epperly et al., 2002) for our post-regulatory estimate.

Although pre- and post-regulatory strata were identified for each fishery based on the first year a sea turtle bycatch mitigation strategy was mandated, the SE and Gulf of Mexico Shrimp Trawl fishery regulatory strata were established using other criteria. TEDs were first used in 1987, but an analysis by Epperly and Teas (2002) revealed that the minimum openings of TEDs were too small to exclude larger sizes of individual leatherbacks, loggerheads and greens, although effective at excluding Kemp's ridleys and juvenile loggerheads. Therefore, NMFS ruled in 2003 that TED openings should be large enough to exclude all sea turtles, including the large individuals in shrimp trawl fisheries (68 FR 8456). We established 2003 as the beginning of effective reduction of sea turtle bycatch for this fishery, based on this ruling, and on the fact that available reports provide estimates for specifically before and after TED enlargements in 2003 (for further details see Methods in Supplemental Data II). We acknowledge that although 2003 may provide an appropriate baseline for the beginning of adequate bycatch measures for larger species (e.g. loggerheads, leatherbacks), TED regulations that were already in place were likely effective for reducing fishery-induced mortality of smaller species (e.g. Kemp's ridleys). A lack of monitoring and compliance in SE and Gulf of Mexico Shrimp Trawl fisheries has further reduced post-implementation efficacy of TEDs complicating the use of 2003 as the inception of adequate sea turtle bycatch reduction measures (Cox et al., 2007). Thus, we refer to shrimp fishery strata separately as pre-2003 and post-2003, distinct from the pre-regulation and post-regulation strata designated to all other fisheries.

3. Results

3.1. Cumulative estimates

We used a total of 57 sources including peer-reviewed publications (8), NOAA technical memoranda (14), Fisheries Science Center reports (15), Biological Opinions (3), and other forms of government documents (17) in our analysis (Table 2; Supplemental Data I). Longline and gillnet studies each comprised 24 of the total reports used, and trawls and dredges together totaled nine reports (Table 2).

Summing mean values of minimum bycatch estimates for each fleet resulted in an estimate of at least 346,500 turtle interactions annually across all US fisheries prior to establishment of regulations to reduce sea turtle bycatch. These interactions resulted in at least 71,000 deaths annually (Table 3). The pre-regulation bycatch estimate is more than twice the post-regulatory estimate, in which 137,800 turtle bycatch events were estimated, resulting in 4600 estimated deaths (Table 3). Unless otherwise indicated, post-regulatory bycatch estimates and mortality events are presented in the remainder of this section.

In the Atlantic Ocean a mean estimate of 137,700 bycatch interactions occurred annually (Table 3). Kemp's ridleys interacted with Atlantic fisheries most frequently, followed by loggerheads and green sea turtles. Of the total interactions, 4500 were estimated to have resulted in mortality on an annual basis (Table 3).

In the Pacific Ocean a mean estimate of 100 bycatch interactions occurred annually (Table 3). Loggerheads were estimated to interact with Pacific fisheries most frequently, followed by olive ridleys and leatherbacks. Of these 100 interactions, 60 were estimated to result in mortality on an annual basis (Table 3).

3.2. Fisheries-specific estimates

When considering all US fisheries with known sea turtle bycatch, the SE/Gulf of Mexico Trawl fishery was responsible for the vast majority (up to 98%) of all sea turtle interactions and for more than 80% of all mortality between 1990 and 2007 (Table 4). The shrimp trawl fishery alone was estimated to account for around 69,300 lethal takes annually before TED enlargement requirements in 2003, and approximately 3700 following the implementation of the TED regulation and the effort reduction in the Gulf of Mexico (Table 4). The Gulf of Mexico portion of the fishery comprised a large percentage of total interactions (73%) and mortality (96%) (Supplemental Data II). Following shrimp trawls, the Atlantic/Gulf of Mexico Pelagic Longline, Mid-Atlantic Bottom Trawl, Virginia Pound Net, and Gulf of Mexico Reef Fish Longline fisheries, have been responsible for the greatest annual sea turtle interactions in the Atlantic, respectively (Table 4). Second to shrimp trawls, the highest annual mortality in the Atlantic Ocean occurred in the Mid-Atlantic Bottom Trawl, Gulf of Mexico Reef Fish Longline, Mid-Atlantic Gillnet, and Mid-Atlantic Scallop Dredge fisheries, respectively (Table 4). In the Pacific Ocean, the Hawaii Pelagic Longline fleet, including bottom-set and shallow-set effort, was responsible for approximately 100 annual turtle interactions, resulting in an estimated 50 deaths, followed by the California Set Gillnet fishery responsible for an estimated 10 interactions and deaths.

3.3. Species-specific estimates

Largely due to shrimp trawling in the SE and Gulf of Mexico, an estimated 2700 Kemp's ridleys (juveniles and adults) died annually from fisheries interactions even after mitigation efforts (Table 5). According to this estimate, the Kemp's ridley was the species that suffered the highest absolute mortality from fisheries bycatch in the USA.

An estimated 1400 North Atlantic loggerheads died annually from fisheries interactions (Table 5). Furthermore, loggerheads interacted with more fisheries than any other sea turtle species (seventeen out of the eighteen fisheries analyzed in this study). Following the SE/Gulf of Mexico Shrimp Trawl fishery (responsible for 23,300 annual interactions), the Mid-Atlantic Bottom trawl, Gulf of Mexico Reef Fish Longline, Atlantic Pelagic Longline and Virginia Pound Net fisheries were *each* responsible for between 500 and 600 loggerhead interactions on an annual basis (Supplemental Data II). Although the Mid-Atlantic Scallop Dredge fishery accounted for fewer overall loggerhead interactions (90) relative to other fisheries, it exhibited the fifth highest mean annual loggerhead mortality and serious injuries (68) among fisheries in the Atlantic (Supplemental Data II).

Annual mortality of Atlantic greens and leatherbacks was estimated at 300 and 40, respectively (Table 5). Green turtles interacted primarily with the SE/Gulf of Mexico Shrimp Trawl fishery (11,300 bycatch events), followed by the North Carolina Inshore Gillnet fishery (70) and North Carolina Pound Net fishery (37) in the Atlantic Ocean (Supplemental Data II). With respect to leatherback turtles, the Atlantic/Gulf of Mexico Pelagic Longline fishery was responsible for the most interactions (900) and mortality events (17) in the Atlantic Ocean, followed by the SE/Gulf of Mexico Shrimp Trawl fishery (Supplemental Data II). Hawksbill turtles interacted with several Atlantic fisheries before regulations were implemented, accounting for around 20 deaths annually, including the Atlantic Pelagic Longline fishery and Mid-Atlantic Bottom Trawl fishery. Currently there are scant data on hawksbill bycatch, accounting for only a few annual mortality events (Table 5; Supplemental Data II).

In the Pacific, around 20 olive ridleys and loggerheads, and 10 greens and leatherbacks, died annually from interactions in US fisheries (Table 5). Olive ridley, loggerhead, green and leatherback interactions were confined primarily to the Hawaii Pelagic Longline fishery (26, 46, 11 and 23 interactions, respectively) (Supplemental Data II).

4. Discussion

4.1. Cumulative estimates

Our study provides the first cumulative bycatch estimates for sea turtles across US fisheries. We conservatively estimate that 137,800 takes, 4600 of which were lethal, occurred annually in fishing gear since the requirement of mitigation measures throughout most fisheries, and following vast reductions in SE/Gulf of Mexico Shrimp Trawl effort, representing a greater than 60% reduction in interactions, and more than 90% reduction in mortality. Although we urge caution in the interpretation of these estimates due to sampling discrepancies, our results demonstrate that significant progress has been made in reducing sea turtle bycatch in US fisheries. To build on this progress, a coherent framework for addressing cumulative bycatch impacts on sea turtle population dynamics across fisheries is needed to ensure successful management of sea turtle populations. Furthermore, such a management framework can allow for prioritization of limited conservation resources to address bycatch in fisheries that have the largest cumulative impacts on sea turtle population dynamics (Moore et al., 2009; Bolten et al., 2010; NRC, 2010).

4.2. Fisheries-specific estimates

Shrimp trawling in the SE and Gulf of Mexico has the largest bycatch of sea turtles of all US fisheries, accounting for up to 98% of annual interactions and >80% of deaths, most of which occur in the Gulf of Mexico fleet (Supplemental Data II). Furthermore, estimates produced for the shrimp fishery are likely underestimates of actual bycatch and mortality events due to the zero-inflated nature of the observer data and because the observed effort is not likely a true representation of actual fleet effort (Epperly et al., 2002). Because annual estimates of bycatch and mortality in shrimp trawls are one to two orders of magnitude higher than those in other fisheries, our cumulative bycatch estimate is essentially a function of bycatch in shrimp trawls. This is particularly problematic considering the very low observer coverage of the shrimp trawl fleet at the time of the study (<1%) (Table 6) and high associated error and uncertainty. Furthermore, post-regulatory estimates for the SE/Gulf of Mexico Shrimp Trawl fishery are based on CPUE projections for a proposed gear change, not on direct observation. Finally, Gulf of Mexico Shrimp Trawl effort is not recorded directly, but estimated from landings and interview data, causing negative bias in nearshore and offshore bycatch rates, and positive bias in midshelf bycatch rates (Gallaway et al., 2003). Therefore, these projections should be interpreted with caution in light of the high variability in the estimates.

Compounding high uncertainties surrounding estimates of trawl bycatch is the fact that shrimping effort in the Gulf of Mexico fishery has declined by 74% in the last decade. A recalculation of bycatch estimates by Ponwith (2008) using 2007 effort data poses several problems. First, only effort data were updated, not CPUE data, and second, effort data were only updated for the Gulf of Mexico and not elsewhere in the southeastern Atlantic. This approach assumes that a reduction in effort is directly proportional to a reduction in bycatch and mortality, and does not consider other factors possibly influencing bycatch rates, like changes in sea turtle distribution and fishing effort (Sims et al., 2008). New estimates were thus only produced for the Gulf of Mexico portion of the shrimp fishery (previously accounting for 74% of interactions and 96% of mortality of entire shrimp fishery). Thus, we are negatively-biasing our post-2003 estimates for the shrimp fishery. Furthermore, the recent *BP*-Deepwater Horizon oil spill in the Gulf of Mexico will have an unknown effect on shrimp trawl effort, and resulting impacts on sea turtle populations in the region are largely undetermined. This produces major implications for turtle-fisheries interactions and mortality, as the Gulf of Mexico fleet accounted for an overwhelming majority of total deaths generated by shrimp fishery interactions (Supplemental Data II), and will further complicate our ability to make inferences about impacts of shrimp trawling on sea turtle populations in the Gulf of Mexico. These factors underscore the need to have better fishing effort and observer bycatch data for trawl fisheries.

Table 6
Percent observer coverage and NMFS onboard observer program classification system (based on 2004 data) in U.S. fisheries. Classification system built on the following criteria (NMFS 2004): Baseline: 0.5–1% coverage of total effort. Pilot: 1–2% coverage of total effort across time/gear/area/vessel strata. Developing: Established stratification design implemented, strategy for precision goal developed. Mature: Optimal sampling allocation scheme implemented, precision goal (CV = 20–30%) met.

Fishery	NMFS Classification	% Observer Coverage
GoM Reef Fish	Baseline	1.5–2.1%
Virginia Pound Net	Baseline	0.5–1%
SE Snapper/Grouper[a]	Baseline	20% (logbook reporting)
CA Pelagic Longline	Pilot	
NC Inshore Gillnet	Pilot	4.5–11.9%
SA/GoM Shrimp Trawl[b]	Pilot	<1%
Mid-Atlantic Gillnet	Developing	1–5%
Atlantic/GoM Pelagic Longline	Developing	4–14%
Hawaii Pelagic Longline[c]	Developing	4–100%
Mid-Atlantic Bottom Trawl	Developing	1–5%
Scallop Dredge	Developing	3–11%
CA/OR Drift Gillnet	Mature	4–23%
SE Shark Driftnet	Mature	12–34%
Atlantic Shark Bottom Longline	Not specified	3–4%
CA Set Net	Not specified	2–20%
Scallop Trawl	Not specified	3%

[a] % coverage is not from onboard observers, but% logbooks turned in.
[b] No observer program in place for skimmer trawls or butterfly nets.
[c] 100% coverage pertains only to shallow-set, not deep-set longline effort.

Other fisheries are also deficient in terms of information required to assess their true bycatch impacts (Table 6). For example, the Mid-Atlantic Bottom Trawl, Virginia Pound Net, Gulf of Mexico Reef Fish, and Mid-Atlantic Gillnet fisheries account for the third through sixth highest numbers of interactions in U.S. waters, but all have less than 5% observer coverage (NMFS, 2004; Table 6). Low sampling effort, combined with the complex issues raised in modeling rare events, can compromise the accuracy of bycatch estimates (McCracken, 2004; Supplemental Data II). Such relatively low levels of observer coverage can be sufficient if the coverage is unbiased and management can deal with the resulting precision in bycatch estimates (Sims et al., 2008). However, as bycatch data are not independent (bycatch data within a trip are more closely related than across trips), CPUE extrapolations across large areas can undermine efforts of unbiased coverage (Epperly et al., 2002; McCracken, 2004; Supplemental Data II). In the case of sea turtle bycatch management, consideration of adequate levels of precision in bycatch estimates to inform observer coverage is lacking, whereas this issue is accounted for explicitly in the PBR approach (Taylor et al., 2000). Therefore, enhanced observer coverage in these fisheries would improve understanding of their impacts on sea turtle populations.

The paucity of data on sea turtle bycatch and low observer coverage is a result of fisheries management structure during the timeframe of this study (see Moore et al. (2009) for review). Data deficiencies might also be attributed to the difficulty of observing sea turtle interactions and mortality, specifically in trawl and dredge fisheries. After the mandate of TEDs, it is difficult to observe actual numbers of sea turtle interactions because most turtles can escape before nets are hauled in. Likewise, chain mats placed in front of scallop dredges intended to reduce sea turtle mortality, can effectively deter turtles from being caught in dredge gear, but may also cause unobserved injury or mortality (NMFS-NERO, 2009).

Management efforts have begun to address sea turtle bycatch conservation priorities in the US (Moore et al., 2009). Specifically, a recently promulgated regulation has required all fishing vessels subject to US jurisdiction to take observers upon request in territorial waters, the EEZ and high seas, and therefore in all state, federal and recreational fisheries (72 FR 43176). A complementary NMFS program, the Strategy for Sea Turtle Conservation and Recovery (Strategy), intends to evaluate sea turtle bycatch across jurisdictional boundaries and fishing sectors on a per gear basis (http://www.nmfs.noaa.gov/pr/species/turtles/strategy.htm). As such, NMFS has identified reducing sea turtle bycatch in trawls as a priority, and has proposed to require TEDs for several trawl fisheries and increased TED openings in the summer flounder trawl fishery (72 FR 7382).

4.3. Species-specific estimates

The most commonly available metric for monitoring sea turtle abundance and trends is the number of nesting females (or their nesting activities; e.g. tracks or nests). This segment represents a very small portion of a sea turtle population, so quantifying population-level impacts of fisheries bycatch, which affects juveniles and adult males as well as adult females, is extremely challenging (NRC, 2010). In the absence of complete population information, sea turtle body size allows for calculation of reproductive values based on size-age relationships. This reproductive value is then used to create a relative index of population-level impacts (Wallace et al., 2008). For example, studies of Atlantic loggerhead population dynamics demonstrate the importance of size differences as indicators of ontogenetic habitat variations, whereby turtles nearer to reproductive age are distributed along the continental shelf, while juveniles typically occupy oceanic waters of the North Atlantic Gyre (Bolten et al., 1998). However, recent findings suggest that for some loggerheads there is no abrupt shift from oceanic to neritic lifestages, but rather flexible movements between habitats (Witzell, 2002; Hawkes et al., 2006; McClellan and Read, 2007; Casale et al., 2008; Mansfield et al., 2009). As such, reproductively valuable loggerheads may be caught in near-shore and high-seas fisheries. Unfortunately, most of the reports used in this analysis did not include body size information, precluding quantification of population-level impacts. Clearly, enhanced reporting of demographic information of turtles taken as bycatch would improve assessments of relative impacts of multiple fisheries on sea turtle populations (NRC, 2010).

Our analysis suggests that approximately 2700 Kemp's ridleys are killed annually from shrimp trawl interactions (including adult males and females as well as juveniles), comprising a substantial fraction of the number of annual nesting females from the Northwest Atlantic and Gulf of Mexico rookeries combined (Burchfield, 2009; Supplemental Data II). However, because the National Research Council in 1990 estimated that 5000 Kemp's were killed annually before the implementation of TEDs in shrimp trawls (Magnuson et al., 1990), the current mortality estimate represents a substantial reduction in Kemp's ridley annual mortality. In fact, following long-term declines, Kemp's nesting populations have increased steadily since the 1990s (Shaver et al., 2004; Burchfield, 2009), probably due in large part to TED regulations implemented in 1987 (Heppell et al., 2005).

Atlantic loggerheads present a more disconcerting situation. The Florida nesting population, constituting 90% of total US loggerhead nesting in the Atlantic Ocean, exhibited a 43% decline from 1998 to 2006 (Witherington et al., 2009). Florida loggerhead inter-nesting and breeding habitat is used extensively by the shrimp trawl fleet throughout the Gulf and Southeast USA (Lewison et al., 2003). In fact, even after the enlargement of TED openings, an estimated 650 loggerheads (adults and juveniles) died annually in Atlantic shrimp trawl fisheries (Supplemental Data II), and many of these individuals are likely to be of high reproductive value as assumed by their proximity to nesting beaches and neritic habitats (Wallace et al., 2008). Due to their large nesting assemblages in Florida and throughout southeast and Gulf states, and their annual migrations to higher latitudes (Plotkin and Spotila, 2002), loggerheads interact with more fisheries than any other sea turtle species in the USA resulting in 1400 annual deaths (Table 5). Furthermore, loggerheads of southeastern United States origin have been documented as bycatch in drift longline fleets of the eastern and western Mediterranean during their juvenile stage (Laurent et al., 1998), and their offshore distribution make them susceptible to bycatch in Canadian pelagic longlines as well (Brazner and McMillan, 2008). Because geographic distributions of sea turtles generally span across international borders (Wallace et al., 2010b), further studies need to address the cumulative impacts of US and foreign fleets on sea turtle populations. In light of these reasons, it is not surprising that the recently completed NMFS and USFWS North Atlantic Loggerhead Recovery Plan concluded that fisheries bycatch was the most important threat to this population (Bolten et al., 2010).

Although Pacific fisheries interact with fewer turtles and are responsible for fewer deaths than Atlantic fisheries, Pacific turtle populations are smaller in size than those in the Atlantic, and thus bycatch can still impact populations. For example, Pacific loggerheads have annual nesting assemblages of less than 1500 females (Kamezaki et al., in press), and pre- and post-regulatory mortality events were estimated at 200 and 20, respectively. Taken together with small-scale artisanal fisheries bycatch in their foraging range (Peckham et al., 2007) and high seas longline bycatch in their migratory corridors (Polovina et al., 2000), bycatch in the Pacific is certainly a threat to the persistence of loggerhead populations. However, several initiatives and mitigation efforts are underway to reduce loggerhead bycatch in these areas (Peckham et al., 2007; Howell et al., 2008). For example, bycatch in the Hawaii-based longline fishery has decreased substantially since the implementation of an integrated bycatch reduction scheme that relies on agency-industry cooperation, 100% observer coverage, gear modifications, bycatch quotas, and innovative technologies (Howell et al., 2008). However, a recent NMFS rule increasing Hawaii shallow-set longline swordfish effort and total allowable sea turtle take could potentially allow bycatch and mortality to increase again, albeit moderately and with continued 100% observer coverage (74 FR 65460). Finally, although fisheries management in the last 15 years has reduced bycatch, the latent effects of pre-regulation mortality might still be impacting populations. Sea turtles are long-lived and slow to reproduce, so it could take decades for the next generations to replace individuals killed over a decade ago. This is true especially for species such as loggerheads, which reach reproductive maturity around 20–35 years of age (Parham and Zug, 1997; Snover et al., 2010). We conclude that bycatch reduction strategies must be implemented consistently and continuously in the long-term to ensure population recovery.

4.4. Looking ahead

Despite our efforts to conduct a comprehensive assessment of sea turtle bycatch in United States waters, our analysis is not exhaustive. In addition to new estimates of sea turtle bycatch that have been published since our analysis was completed, NMFS has recently turned its attention to a handful of new fisheries with possible sea turtle bycatch not considered in this study.

Most new estimates of sea turtle bycatch in fisheries are not substantively different from the values presented in our study. For example, NMFS has published new estimates for the vertical line component and bottom longline portion of the Gulf of Mexico reef fish fishery between 2006 and 2008 (NMFS-SEFSC, 2009a,b) summarized in the recent Biological Opinion (NMFS, 2009). The vertical line component is responsible for several dozen loggerhead interactions annually resulting in fewer than ten deaths, and fewer than ten Kemp's ridley, green, leatherback and hawksbill mortality events (NMFS, 2009). New estimates in the bottom longline portion of the reef fish fishery suggest 500 loggerheads are taken annually resulting in *ca*. 300 deaths. These results do not deviate substantially from our assessment of the Gulf of Mexico reef fish fishery of 500 annual loggerhead takes resulting in *ca*. 200 deaths. Likewise, Garrison et al. (2009) report leatherback and loggerhead interactions in the Atlantic Pelagic Longline fleet in 2008 to be around 380 and 770, respectively, but these numbers do not differ substantially from estimates used in our analysis (Supplemental Data II).

However, new bycatch estimates available for the SE/Gulf of Mexico Shrimp Trawl fishery, updated from 2009 effort data, suggest 61,300 loggerheads interactions occur annually (46% in the Gulf of Mexico and 54% in the Southeast Atlantic), resulting in 1450 deaths (54% in the Gulf of Mexico and 46% in the Southeast Atlantic) (Ponwith, 2011; Supplemental Data II). This is a marked increase with respect to bycatch interactions and deaths projected by 2007 effort data from the Gulf of Mexico (23,336 interactions resulting in 647 deaths) used in this analysis. As the percentage of mortality events occurring in the Southeast Atlantic portion of the fishery has increased from 3% to 46% after 2003 TED regulations, our post-regulatory estimates for Atlantic loggerhead sea turtles are negatively biased (Supplemental Data II). These new data demonstrate the importance of improved observation and data reporting in understanding and managing protected species bycatch in fisheries.

NMFS has recently directed attention to a number of new fisheries with potential sea turtle bycatch not covered in this analysis. Through its Annual Determination, NMFS has identified numerous fisheries potentially interacting with sea turtles to carry observers upon NMFS request for the next five years (75 FR 27657). Additionally, NMFS mandated observer coverage for the skimmer trawl portion of the SE / Gulf of Mexico Shrimp Trawl fishery (75 FR 27657).

5. Conclusions

In addition to recognizing successful efforts to reduce sea turtle bycatch discussed above, our analysis has identified a number of critical management needs in monitoring and mitigating sea turtle bycatch. First, cumulative take limits across fisheries should be estimated to identify whether population recovery goals under the ESA would be impeded by fishery-related mortality in the US. Evaluation of fishery-specific takes under the ESA (e.g. in preparing Biological Opinions) should be conducted within the context of such limits as a reference frame. Estimating appropriate take limits should incorporate information about population size and trends, conservation status, and other vital rates, and should be robust to plausible forms of uncertainty in these parameters. Second, enhanced observer coverage is needed in fisheries with scant or nonexistent bycatch data. Budget constraints make this a difficult challenge to overcome, but limited resources should be prioritized to monitor fisheries most likely to have significant impacts on sea turtle populations, like the SE/Gulf of Mexico Shrimp Trawl fishery. Third, there should be increased reporting of demographic data (e.g. turtle body sizes) to improve our understanding of population impacts. Fourth, integrated management approaches should be considered, similar to the Hawaii pelagic longline fishery, including gear modification, strict observer coverage (Table 6), and adaptive spatial–temporal closures (Howell et al., 2008). Finally, fisheries impacts in the US EEZ should be considered in conjunction with those from neighboring nations, high-seas fleets, and different resource-use sectors to provide a more cumulative and realistic picture of ocean-wide anthropogenic threats to sea turtles.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biocon.2011.07.033.

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