REVIEW

Global patterns of marine turtle bycatch

Bryan P. Wallace[1,2], Rebecca L. Lewison[3], Sara L. McDonald[2], Richard K. McDonald[2,4], Connie Y. Kot[2,5], Shaleyla Kelez[2], Rhema K. Bjorkland[2], Elena M. Finkbeiner[2], S'rai Helmbrecht[2], & Larry B. Crowder[2]

[1] Global Marine Division, Conservation International, Arlington, VA 22202, USA
[2] Center for Marine Conservation, Duke University Marine Laboratory, Beaufort, NC 28516, USA
[3] Department of Biology, San Diego State University, San Diego, CA 92182, USA
[4] University of Richmond, Richmond, VA 23173, USA
[5] Marine Geospatial Ecology Lab, Duke University, Durham, NC 27708, USA

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Correspondence
Bryan P. Wallace, Global Marine Division, Conservation International, 2011 Crystal Drive, Arlington, VA 22202, USA. Tel: +703-341-2663; fax: +703-979-2873. E-mail: b.wallace@conservation.org

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Abstract

Fisheries bycatch is a primary driver of population declines in several species of marine megafauna (e.g., elasmobranchs, mammals, seabirds, turtles). Characterizing the global bycatch seascape using data on bycatch rates across fisheries is essential for highlighting conservation priorities. We compiled a comprehensive database of reported data on marine turtle bycatch in gillnet, longline, and trawl fisheries worldwide from 1990 to 2008. The total reported global marine turtle bycatch was ∼85,000 turtles, but due to the small percentage of fishing effort observed and reported (typically <1% of total fleets), and to a global lack of bycatch information from small-scale fisheries, this likely underestimates the true total by at least two orders of magnitude. Our synthesis also highlights an apparently universal pattern across fishing gears and regions where high bycatch rates were associated with low observed effort, which emphasizes the need for strategic bycatch data collection and reporting. This study provides the first global perspective of fisheries bycatch for marine turtles and highlights region–gear combinations that warrant urgent conservation action (e.g., gillnets, longlines, and trawls in the Mediterranean Sea and eastern Pacific Ocean) and region–gear combinations in need of enhanced observation and reporting efforts (e.g., eastern Indian Ocean gillnets, West African trawls).

Introduction

Human impacts on the world's oceans are extensive and varied, warranting urgent and comprehensive management of marine resources in many places (Halpern *et al.* 2008). Marine fisheries, a primary source of protein for billions of people globally (FAO 2009), are the major anthropogenic influence on marine systems worldwide, affecting marine animal populations and ecosystem function (Jackson *et al.* 2001; Pauly *et al.* 2005). A central issue for marine fisheries is bycatch, or the unintended capture of nontarget organisms during fisheries operations (Hall *et al.* 2000; Soykan *et al.* 2008). Although the type and amount of bycatch varies greatly between small- and large-scale fisheries, and among the diversity of gear types employed, total fisheries bycatch amounts to several million tonnes globally each year (Kelleher 2005; Davies *et al.* 2009).

Fisheries bycatch has been identified as a primary driver of population declines in several species of marine megafauna (e.g., elasmobranchs, mammals, seabirds, turtles; Lewison *et al.* 2004a). Marine megafauna species interact with various types of fishing gear because they occupy broad geographic ranges spanning geopolitical boundaries and oceanographic regions that support many different fisheries. The frequency of interactions (defined as accidental encounters with fishing gear that can result in injury and possibly death) depends on spatiotemporal overlap between critical habitat for a given species and fishing activities, encompassing a wide range of fishing methods and gear characteristics (Wallace *et al.* 2008).

Research on marine megafauna bycatch has increased exponentially, but the disparate nature of bycatch data has precluded comprehensive analyses of bycatch rates and their impacts across ocean basins, gear types, and species (Soykan *et al.* 2008). Gear- or taxa-specific estimates of global marine megafauna bycatch (e.g., Lewison *et al.* 2004b, 2005; Read *et al.* 2006) have underscored the magnitude of bycatch impacts and highlighted the need for bycatch reduction strategies to recover depleted populations (Gilman *et al.* 2006; Cox *et al.* 2007; Howell *et al.* 2008). Similarly, research on spatial patterns of bycatch events within and across taxa has illustrated the need for effective management strategies (Sims *et al.* 2008; Lewison *et al.* 2009). The majority of bycatch studies focus on a particular region and/or fishing gear, which limits their generality. Single-species or single-gear studies belie one of the central challenges to understanding the magnitude and extent of fisheries bycatch: characterizing the global bycatch seascape across fishing gears, ocean regions, and species.

Information on bycatch rates, the amounts of fishing effort on which these rates were based, and the status of the affected population(s) is crucial to characterizing bycatch patterns and to predicting the potential impact of bycatch (Lewison *et al.* 2004b; Soykan *et al.* 2008). Because marine megafauna bycatch events are rare relative to overall fleet fishing effort, bycatch analyses must account for an abundance of zeros in bycatch data sets (Sims *et al.* 2008). The amount of effort observed, analogous to survey effort, can affect observed bycatch rates. For example, Sims *et al.* (2008) found that high or low bycatch rates of marine turtles and seabirds in gillnets in the northwest Atlantic Ocean tended to occur where relatively low fishing effort were observed, illustrating potential biases in bycatch rates based on relatively low levels of observed fishing effort.

Six of the seven marine turtle species are categorized as Vulnerable, Endangered, or Critically Endangered globally by the IUCN Red List (www.iucnredlist.org; accessed 11 December 2009), and fisheries bycatch is recognized as a major threat to all species. We compiled a comprehensive database of all reported data on marine turtle bycatch in gillnet, longline, and trawl fisheries worldwide from 1990 to 2008. Our goals were to (1) summarize and evaluate relationships among reported bycatch rates, observed fishing effort, and bycatch research coverage across regions and fishing gears; (2) describe the probable impacts of bycatch on marine turtle populations among region-gear combinations based on inferred reproductive value of bycaught turtles; and (3) identify region–gear combinations as priorities for conservation action and/or enhanced monitoring and research. Our evaluation of patterns in reported bycatch across fisheries and geographic regions is designed to facilitate identification of particular gear types and/or regions that merit conservation intervention and mitigation. This synthesis provides the first global, multi-gear perspective of fisheries bycatch for marine turtles.

Methods

Data compilation, standardizations, and conversions

We compiled a database of reported marine turtle bycatch globally from peer-reviewed publications, agency and technical reports, and symposia proceedings published between 1990 and 2008 (complete reference list in Appendix S1). Reported bycatch data represent bycatch information from direct observation, termed observer data, as well as from interviews with fishers (∼10% of all records). Because much of the bycatch literature exists outside standard literature databases, we also directly contacted agencies around the world in charge of collecting and collating bycatch information to ensure our database was comprehensive. We did not, however, include logbook data because such data have been found to underrepresent observed bycatch of marine megafauna (Baum *et al.* 2003). It was not possible to calculate the proportion of global fishing effort represented, nor to describe temporal or spatial trends in marine turtle bycatch, as the available information was restricted spatially and temporally, and thus only represented "snapshots" of fishing activities and bycatch that occurred during the past 20 years.

Bycatch data were grouped in three general fishing gear categories: gillnets, longlines, and trawls. These three categories, which include several different gear types within each gear category (e.g., bottom trawls and midwater trawls within "trawls"), are recognized by the FAO as major fishing gears (described as "gillnets and entangling nets," "hooks and lines," and "trawl nets": http://www.fao.org/fishery/topic/1617/en). Despite the broad nature of these gear categories, this classification scheme allowed us to draw general conclusions over two decades, hundreds of studies, and multiple spatial scales, balancing relevant variation and details with a "common denominator" approach. Moreover, further delineation among gear types would have precluded comparisons of marine turtle bycatch rates across regions due to limited data points; e.g., mid-water trawls in one region but not in another, but "trawls" in both.

Our database reflects incidence of interactions between marine turtles and fishing gear. For each study, we recorded information on the time period when and geographic region where reported bycatch occurred (based

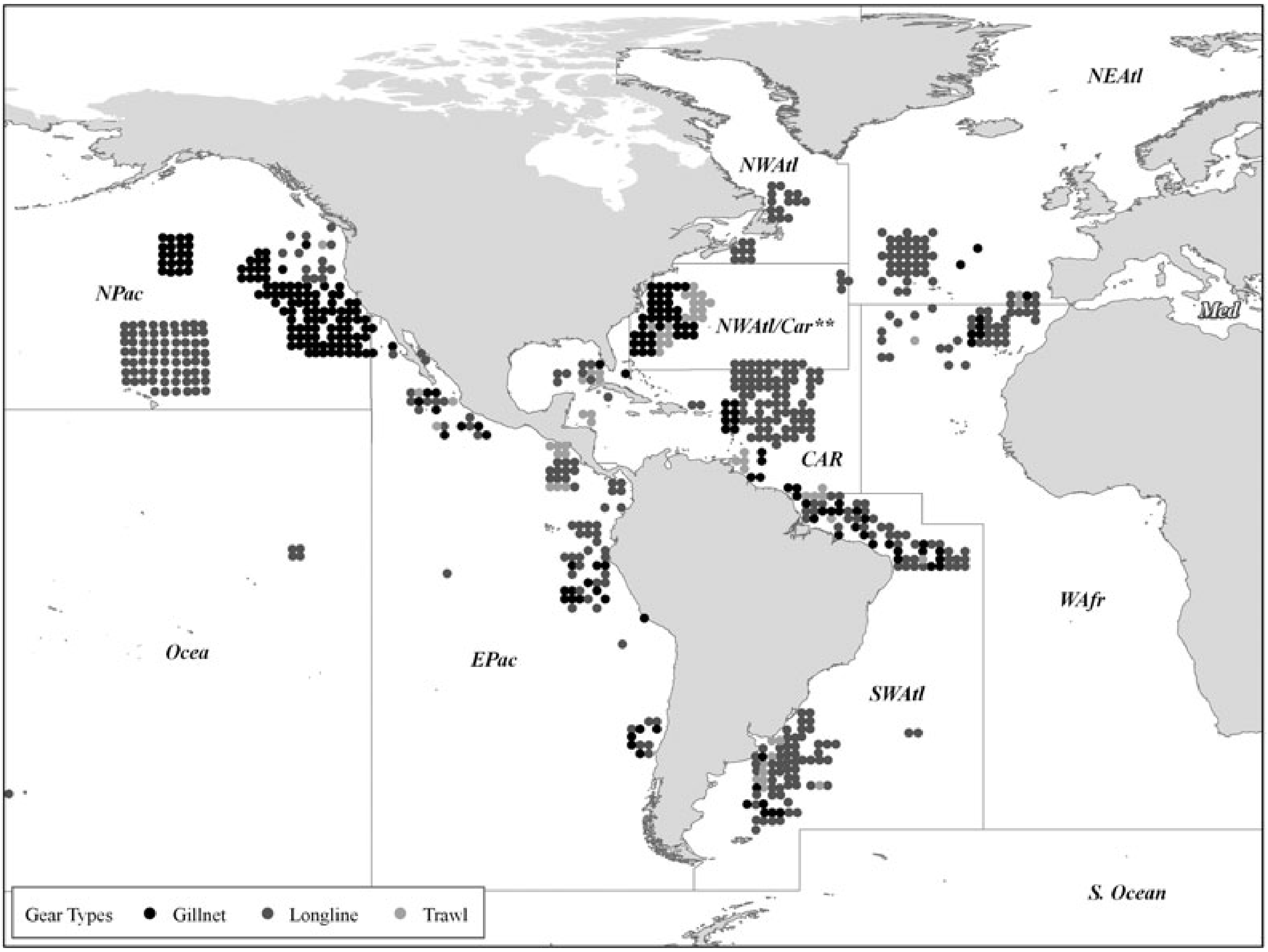
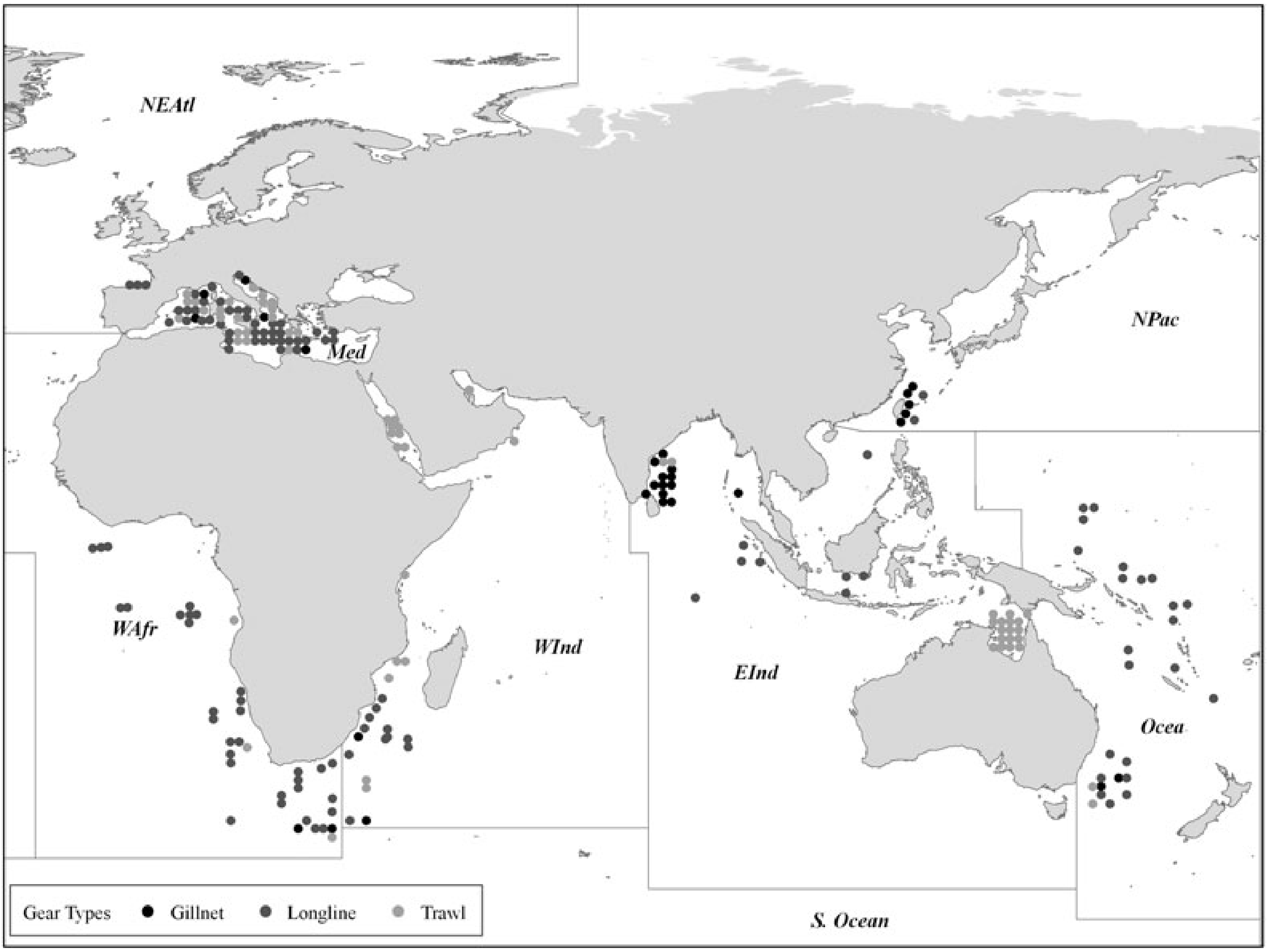


Figure 1 Geographic delineation of regions and putative distribution of marine turtle bycatch records for gillnets (green), longlines (blue), and trawls (red). Points represent all records we compiled in our database (n = 993), including those we used in analyses (n = 700). Regions were roughly based on FAO fishing regions (http://www.fao.org/geonetwork/srv/en/main.home?uuid=ac02a460-da52-11dc-9d70-0017f293bd28). Locations were plotted according to reported geographic coordinates, or when coordinates were not available, based on region-specific descriptions of each fishing gear. Map was split into two panels to facilitate visual assessment of distribution of bycatch studies. Although some regions appear in both panels, data are only displayed once. NPac: North Pacific Ocean; EPac: eastern Pacific Ocean; Ocea: Oceania; NWAtl: Northwest Atlantic Ocean; Car: Caribbean; **NWAtl/Car: area of overlap between those two regions for longlines only (some bycatch records originated could not be assigned to one region); NEAtl: northeast Atlantic Ocean; WAfr: West Africa; Med: Mediterranean; WInd: western Indian Ocean; EInd: eastern Indian Ocean.

roughly on FAO fisheries statistics regions, FAO 2008; Figure 1), species reported as bycatch, bycatch rate (bycatch per unit effort; BPUE), the metric in which BPUE was reported, observed fishing effort, and the metric in which observed fishing effort was reported. To account for the fact that a single study could report multiple bycatch rates (i.e., for each species taken as bycatch, for each year bycatch was observed), we entered each as a separate record. Thus, we present the number of records, rather than number of studies, to describe the amount of reported bycatch information. We summarized only observed, reported information; we did not calculate our own estimates or extrapolations, nor did we include reported estimates or extrapolations from reviewed studies. Furthermore, we do not present summaries of mortality rates among fishing gears because such values were reported inconsistently across regions and gears. Our database included a total of 192 studies that yielded 993 records of marine turtle bycatch between 1990 and 2008 (Table 1; Figure 1).



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We found a diversity of units used for reported effort and BPUE across bycatch records (Table 1; Appendix S2); between 10 and 21 different metrics for fishing effort and BPUEs were reported across the three gear categories. Although there were similarities among reported metrics within fishing gears, the high variability in terminology and definitions of metrics reflected the overall lack of standardized reporting methods across fisheries and

Table 1 Summary of reported bycatch records (i.e., bycatch rates and fishing effort) and total number of unique fishing effort and bycatch rate metrics reported in published literature. A record was entered in the database if it contained bycatch rate data, observed fishing effort data, and/or number of turtles taken.

Gear type	Total no. records	Total no. Effort records	No. unique effort metrics reported	Total no. BPUE records	No. unique BPUE metrics reported
Gillnets	251	185	17	156	21
Longlines	554	492	10	482	16
Trawls	128	83	10	91	14
Total	933	760	37	729	51

BPUE = bycatch per unit effort.

Table 2 Summary of reported sea turtle bycatch and fishing effort in gillnets, longlines, and trawls worldwide. All data shown are based on reported data, not estimates or extrapolations. "Weighted median BPUE" was calculated by accounting for the proportion of total effort observed per record to derive a bycatch rate per unit effort (BPUE); BPUEs with no reported effort were not included in calculation of the weighted median BPUEs, and no weighted median BPUE was calculated for region–gear combinations with only one record (see text for details on calculations). "Weighted median BPUEs" and "median observed fishing effort" values presented with minimum and maximum values in parentheses. Effort units reflect converted values to standardized "sets" relative to gear type and region (see text for details on methodology). "No. of records" represents the number of records used to calculate the weighted median BPUEs (i.e., those reporting both a BPUE and fishing effort); the total number of records of bycatch, including those reporting number of turtles taken, for that region–gear stratum in parentheses. "Total observed effort" is the sum of all observed fishing effort reported for each region–gear stratum.

Region	No. turtles taken	Weighted median BPUE	No. of records	Median observed effort	Total observed effort
Gillnets (effort expressed in number of sets)					
Caribbean	5,971	0.0119 (0.0000–0.1700)	28 (35)	82 (52–68,355)	105,724
Eastern Indian	5,251	0.1904 (0.0313–0.3496)	2 (3)	13,760	13,760
Eastern Pacific	353	0.0392 (0.0032–0.2212)	5 (5)	312 (90–312)	458
Mediterranean	177	0.0772 (0.0000–2.2169)	9 (9)	54 (27–369)	912
Northeast Atlantic	6	0.0135 (0.0080–0.0190)	2 (2)	193 (125–261)	386
North Pacific	475	0.0000 (0.0000–0.0157)	51 (51)	587 (178–2,695)	17,859
Northwest Atlantic	18	0.0000 (0.0000–0.0506)	18 (18)	111 (99–291)	1,002
Oceania	300	NA	0 (2)	NA	NA
Southwest Atlantic	394	0.1315 (0.0153–1.3700)	13 (13)	27 (1–523)	1,024
West Indian	78	NA	0 (1)	NA	NA
GN Total	13,023		129 (139)		141,125
Longlines (effort expressed per 1,000 hooks)					
Caribbean	1,384	0.0042 (0.0004–0.1657)	14 (14)	90 (2–3,139)	4,427
Eastern Indian	26	0.0190 (0.0000–0.3200)	8 (8)	221 (14–539)	994
Eastern Pacific	2,040	0.2138 (0.0005–19.3000)	47 (47)	51 (1–10,604)	14,870
Mediterranean	28,071	0.2740 (0.0000–7.1411)	69 (75)	291 (12 – 22,594)	85,741
Northeast Atlantic	1,366	0.0367 (0.0070–4.5450)	37 (37)	32 (16–427)	1,878
North Pacific	624	0.0134 (0.0000–2.5000)	18 (35)	95 (33–1,329)	4,347
Northwest Atlantic	6,719	0.5954 (0.0100–4.6000)	29 (29)	283 (14–11,604)	73,040
Northwest Atlantic/Caribbean	4,546	0.0050 (0.0000–0.5207)	70 (70)	422 (181 – 4,450)	11,006
Oceania	466	0.0014 (0.0000–0.2000)	18 (20)	1,272 (16 – 68,000)	107,032
Southwest Atlantic	9,916	0.2240 (0.0000–11.6129)	96 (96)	79 (8–20,263)	24,499
West Africa	397	0.0356 (0.0000–0.5140)	21 (27)	272 (33–520)	2,362

Continued

Table 2 Continued.

Region	No. turtles taken	Weighted median BPUE	No. of records	Median observed effort	Total observed effort
Western Indian	409	0.0080 (0.0112–0.1000)	9 (11)	1,380 (44–6,725)	15,306
LL total	55,964		436 (469)		345,502
Trawls (effort expressed in number of hauls)					
Caribbean	135	0.0035 (0.0004–0.2130)	14 (14)	1,133 (95–13,600)	15,481
Eastern Indian	1,057	0.0044 (0.0019–0.0333)	6 (6)	3,092	3,092
Eastern Pacific	419	0.0890 (0.0000–0.3311)	7 (8)	173 (57–661)	953
Mediterranean	2,323	0.0843 (0.0000–0.2393)	19 (19)	1,024 (100–14,142)	53,766
Northeast Atlantic	3	0.0144 (0.0064–0.0095)	2 (2)	209 (105–313)	418
Northwest Atlantic	430	0.0049 (0.0000–0.3140)	17 (17)	1,058 (641–5,282)	18,992
Oceania	895	0.0032 (0.0020–0.6100)	6 (6)	810 (84–8,652)	13,552
Southwest Atlantic	194	NA (0.6000–7.2000)	1 (4)	5	5
West Africa	100	0.0079 (0.0000–0.0135)	4 (4)	192 (30–922)	1,335
Western Indian	10,485	0.0027 (0.0001–0.2278)	12 (12)	33,420 (177–219,324)	365,714
Trawl total	16,041		88 (92)		473,307
Overall total	85,028		653 (700)		

regions (Appendix S2). To compare bycatch rates within and among regions, we addressed this nonuniformity in reported metrics by converting all fishing effort metrics into standardized "sets" within each of the three main gear categories and within regions. We chose the "set" because it was the most commonly reported unit of observed effort across the three gear types and thus was the appropriate unit to permit straightforward evaluation of the amount of marine turtle bycatch per "typical" operation; i.e., when gear goes into and then is removed from the water. We defined "set" as a net deployment for gillnets, 1,000 hooks for longlines, and a trawl haul for trawls. Despite the high variation in fishing gear characteristics within major fishing gears, this standardization allowed us to compare bycatch rates and relative amounts of gear observed and to explore patterns in bycatch across regions and gears. A case-by-case record of the conversions can be found in Appendix S3. Many records were eliminated as not applicable (i.e., no BPUEs or effort reported, unable to convert units), leaving a total of 700 records for analyses (Table 2).

We computed summary statistics for BPUEs and observed effort for each region-gear–species combination using the standardized BPUE values and reported fishing effort values (species-specific data not shown). To limit potential bias from BPUEs reported from low observed effort (see Sims *et al.* 2008), we also calculated a "weighed median BPUE" for each region–gear–species combination, and then across species within each region–gear combination. We computed the weighted median BPUEs by (1) calculating the proportion of effort observed in each record relative to the total amount of effort observed for that region–gear–species combination; (2) then multiplying the standardized BPUE value (i.e., individual turtles per "set") by this proportion of effort to obtain a weighted BPUE (i.e., the BPUE weighted by the relative amount of effort associated with it); and (3) dividing the median of these weighted BPUEs by the median of the effort proportion values. Thus, weighted median BPUEs accounted for the relative effort observed in each record, as well as the overall effort observed for each region–gear–species combination.

Relationships among bycatch rates, observed fishing effort, and research coverage

To evaluate the relationships among marine turtle bycatch rates, fishing effort, and bycatch research coverage, we performed two different, but complementary analyses. First, for all records within each gear type, we plotted standardized BPUEs and associated fishing effort across species and regions to test the hypothesis the highest bycatch rates were associated with the lowest amounts of gear observed (sensu Sims *et al.* 2008). Second, we ranked weighted median BPUEs and total fishing effort for each gear–region combination for all marine turtle species. We then performed a semiquantitative categorization of the relative ranks of these variables to identify region–gear combinations with: high bycatch-high fishing effort, high bycatch-low fishing effort, low bycatch-high fishing effort, low bycatch-low fishing effort. Regions with fewer than two records for a particular gear were not included in this analysis. To facilitate interpretation of the "confidence" in these relative ranks, we tallied the number of records reported for each gear–region combination.

Relative impact of bycatch on marine turtles

Assessments of population-level effects of bycatch should take into account the magnitude of interactions, specifically mortalities, as well as the "reproductive value" (i.e., the relative contribution of individuals within an age-class to current and future reproduction) of the individuals taken (Wallace *et al.* 2008). Reproductive values tend to increase from minimum values for small, young turtles to maximum values at the onset of sexual maturity (Crouse *et al.* 1987; Heppell *et al.* 2005; Wallace *et al.* 2008). Although there was insufficient information available to incorporate mortality rates from all reported bycatch, we were able to infer reproductive values of bycaught marine turtles by compiling reported body sizes of marine turtles taken as bycatch and assigned each record to either a "small" (juvenile) or "large" (subadult or adult) category. Records where bycatch of both small and large turtles was reported were categorized as "mixed." We based our categorization scheme on the average sizes of turtles reported in each record relative to species-specific size-at-maturity data from the literature. The division between "small" and "large" categories roughly coincided with the separations between small juvenile and large juvenile/subadult size classes reported for different sea turtle species (see Appendix S4 for definitions of size categories). However, only ∼15% of records ($n = 152$) presented information on body sizes or demographic classes of turtles taken as bycatch; body sizes, and thus inferred reproductive values of turtles taken as bycatch were not available for the majority of region–gear combinations.

Identification of conservation and monitoring needs

To identify conservation and monitoring priorities across region–gear combinations, we compared the relative rankings of bycatch rates and observed fishing effort, as well as the number of bycatch records and turtle size information. Regions with high bycatch rates and high levels of observed effort, especially those taking large turtles, were identified as requiring urgent conservation actions to reduce bycatch (i.e., mitigation measures). Regions were identified as monitoring and research priorities if they had high bycatch rates but low levels of observed effort, and/or no available turtle size data.

Results and discussion

This study represents the first global synthesis of reported bycatch rates and observed fishing effort across major gear types for marine turtles. There was high interregional variation in bycatch rates, effort observed, and research coverage within all gear types (Table 2). While BPUE values of zero were commonly reported, maximum BPUEs were 2.2 turtles per set for gillnets (Mediterranean Sea), 19.3 turtles per 1,000 hooks for longlines (eastern Pacific Ocean), and 7.2 turtles per haul for trawls (southwest Atlantic Ocean).

Based on all records we compiled, just over 85,000 marine turtles were taken as bycatch in gillnets, longlines, and trawls globally from 1990 through 2008 (Table 2). However, this reported total is likely an underestimate for several reasons. First, the reported bycatch rates from our database were based primarily on on-board observer programs that typically cover small proportions of the total fishing effort within a fleet (<1%–5%; e.g., Epperly *et al.* 2002; Garrison 2007). Thus, assuming reported bycatch from observed effort is, in general, representative of bycatch from unobserved effort, the reported tally reflects only 1%–5% of total marine turtle bycatch over this time period. Finally, bycatch data underrepresent small-scale fishing activities, which have been documented to have large cumulative bycatch impacts (Peckham *et al.* 2007; Moore *et al.* 2010). Given these data limitations, it is reasonable to surmise that true total marine turtle bycatch was at least two orders of magnitude higher than the reported total.

Relationships among bycatch rates, observed fishing effort, and research coverage

Beyond calculating a general estimate of the numbers of marine turtles taken as bycatch, our synthesis revealed important crossregional, crossgear patterns among reported bycatch rates, observed fishing effort, and degree of research coverage. For all fishing gears, the relationship between BPUEs and amounts of gear observed is nearly universal: high bycatch rates typically were based on low observed effort, and the higher the observed effort in a given region, the narrower the range of BPUEs reported (Figure 2). This phenomenon reflects both the relative rarity of bycatch events (Sims *et al.* 2008) and the disproportionately high frequency of bycatch events where fishing activities overlap with high turtle densities, particularly in small-scale, near-shore fisheries (Lee Lum 2006; Peckham *et al.* 2007). Along these lines, it is also possible that high bycatch rates determined from relatively little observed effort reflect a publication bias in which researchers are more motivated to publish high bycatch rates to justify conservation action than to publish low bycatch rates. For all of these reasons, caution is needed in interpretation of high bycatch rates when they are based on low observed effort. Because our findings are based on relative measures that do not characterize bycatch at subregional spatial scales, we cannot identify the lower limit for observed effort, i.e., how much effort must be observed to ensure BPUEs are representative. Rather, this analysis underscores the importance of comprehensive and stratified observer coverage and the continued need for synthesis across bycatch studies.

The results of the ranking exercise (Figure 3) provided regionally nuanced explanations to substantiate this BPUE-fishing effort pattern. For example, "high bycatch-low effort" ranks might reveal overlap of areas of high turtle density and intense, but relatively low fishing effort, particularly in small-scale fisheries (Lee Lum 2006; Peckham *et al.* 2007). Indeed, the highest overall BPUE but second-lowest total effort observed for trawls occurred in the eastern Pacific, which is consistent with the high density of olive ridley turtles (*Lepidochelys olivacea*) and small-scale trawl fisheries in that region (Arauz *et al.* 1998). In contrast, Oceania was classified as a "low bycatch-high effort" region for longlines, which reflects consistent observer monitoring and the prevalence of industrial tuna longline fisheries in open-ocean areas (Beverly & Chapman 2007) (Figure 1) that are infrequently occupied by the generally neritic marine turtle species in that region (e.g., green turtles *Chelonia mydas*; Limpus 2008). In other regions, our findings justify confidence in high reported bycatch rates; e.g., high BPUEs in longlines

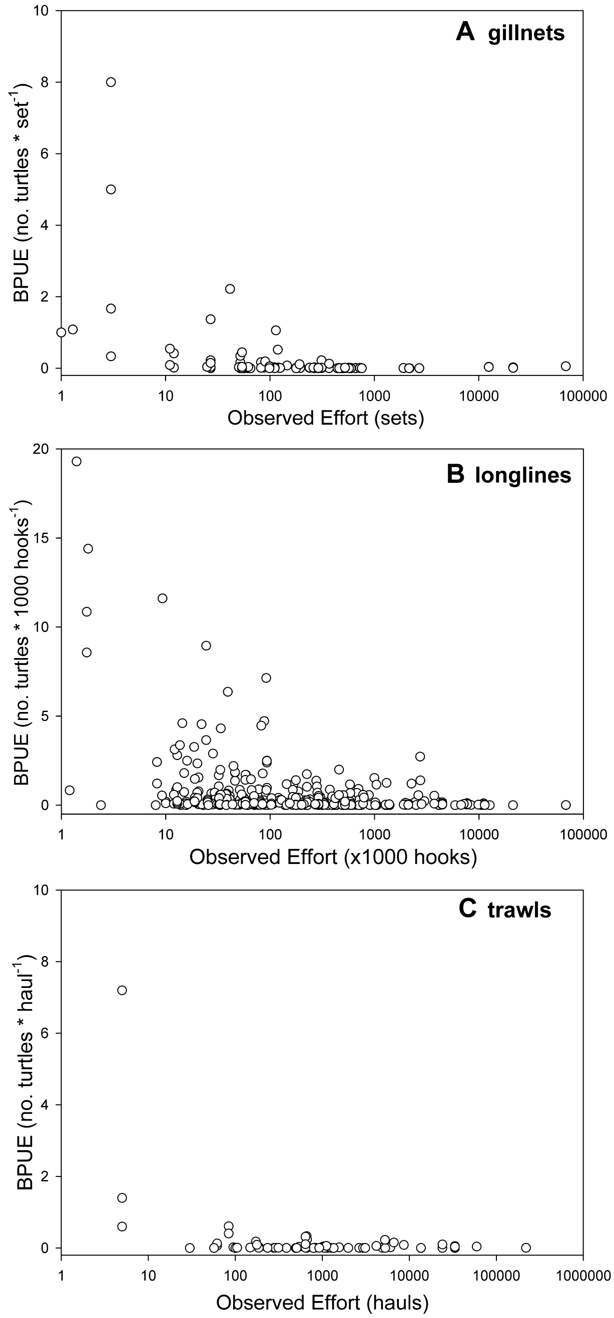

Figure 2 Standardized bycatch per unit effort (BPUEs) of marine turtles and observed effort per record (i.e., the total effort observed per record from which the associated BPUE was derived) in (a) gillnets, (b) longlines, and (c) trawls. All data points from all region-gear-species combinations are shown together.

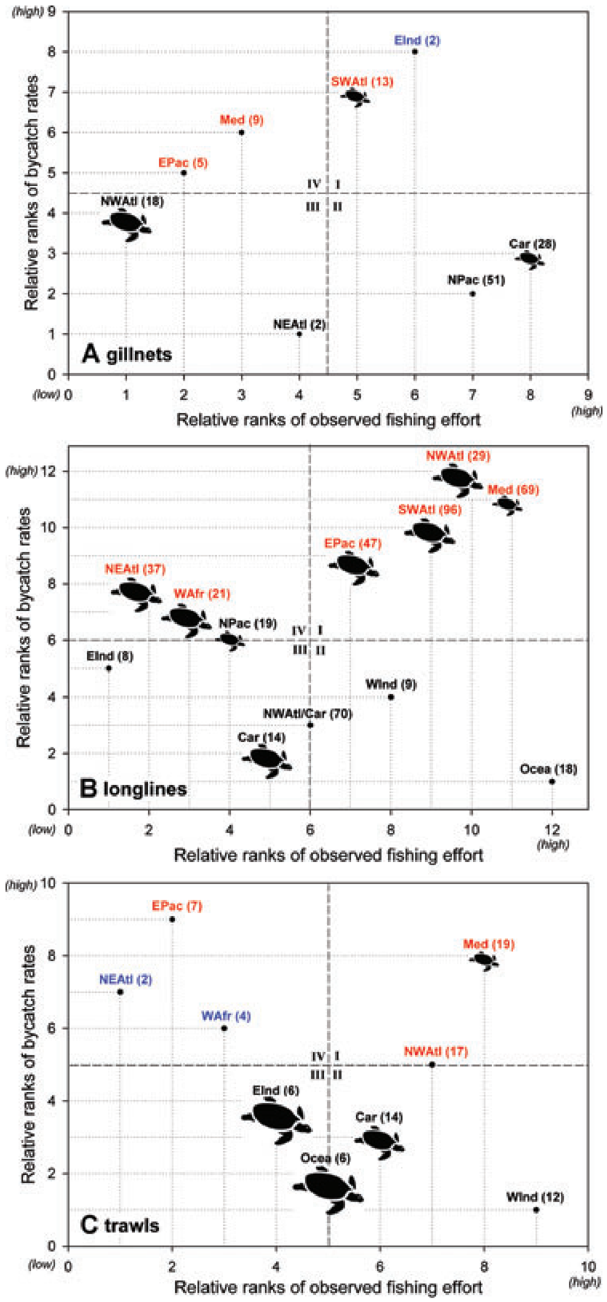

Figure 3 Regional comparison of bycatch rates of marine turtles and the total amount of fishing effort observed for (a) gillnets, (b) longlines, and (c) trawls. Each region was ranked based on weighted median bycatch rates (see text for description) and total amount of fishing effort observed. Values are listed on an increasing scale, based on the number of regions with available data per gear type, with 1 representing the lowest relative bycatch or effort. The four quadrants represent regions with (I) High bycatch-High observed effort; (II) Low bycatch-High observed effort; (III) Low bycatch-Low observed effort; (IV) High bycatch-Low observed effort. Body sizes of turtles taken as bycatch were categorized as "large," "small," or "mixed" (see text for description) and are represented by differentially sized turtle icons. Regions without a turtle icon had no available body size data. Using these relative ranks, we identified region–gear combinations as conservation priorities (in red) if they had high ranks for bycatch rates (quandrants I and IV) with high research coverage (i.e., ≥5 records), and large turtles taken as bycatch. We identified region–gear combinations as monitoring priorities (in blue) if they had high bycatch-low effort ranks (quadrant IV) combined with low research coverage (i.e., ≤4 records). Values in parentheses represent the number of bycatch records on which the rank was assigned. Regions with < 2 records for a particular gear were not plotted.

and trawls were associated with high observed effort in the Mediterranean (Figure 3).

Relative impact of bycatch on marine turtles

We combined available information about body sizes of bycaught turtles with BPUEs and fishing effort patterns to investigate regional variation in probable population impacts of bycatch. Although insufficient data exist on mortality rates associated with this bycatch, our results highlight trends in magnitude of bycatch and potential population impacts. For example, large turtles were frequently reported as bycatch in longlines and gillnets in the northwest Atlantic (Figure 3; Appendix S4). In this region, longline BPUEs and observed effort ranks for longlines were among the highest in the world, whereas these ranks for gillnets were among the lowest. These findings suggest that longlines are likely to have a larger impact than gillnets on marine turtle populations in the northwest Atlantic. Distribution of gillnet operations in the northwest Atlantic tend to overlap more with distributions of marine mammals, particularly small cetaceans, than with marine turtles, whereas longlines in that region tend to overlap with offshore habitats of abundant marine turtle populations (Moore *et al.* 2009). Longlines in the southwest Atlantic and eastern Pacific also exhibited high effort-high bycatch of large (and small) turtles (Figure 3). However, these results might also reflect the greater research attention and emphasis on longlines as compared to other fishing gears (Lewison & Crowder 2007); our study revealed that reports of longline bycatch are two-fold more common than reports of bycatch in either trawls or gillnets (Table 1).

High bycatch rates of smaller turtles, despite their lower reproductive values, also can have significant population impacts depending on the magnitude of total effort. For example, although small turtles (i.e., "less valuable" individuals to overall population dynamics; Crouse *et al.* 1987; Heppell *et al.* 2005) dominated the reported marine turtle bycatch in the Mediterranean, BPUEs and observed effort for trawls and longlines in that region were among the highest in the world (Figure 3). In this case, the combination of high frequency of bycatch events and high fishing effort means that the cumulative impact of bycatch on Mediterranean marine turtle populations—despite a preponderance of "small" turtles—warrants conservation attention (Casale 2008; Alessandro & Antonello 2009).

Data gaps and caveats

Our approach of relying strictly on reported bycatch information and standardizing fishing effort metrics produced noteworthy gaps in our results, particularly with regard to fisheries of conservation concern that were not identified by our analyses. For example, due to a lack of available data, our results did not include the total bycatch and demographic classes of turtles taken in northwest Atlantic or eastern Indian trawls. Other types of information (e.g., strandings data, estimates of trawl bycatch) show that the magnitude and relative impact of trawls might dwarf that of any other fishing gear in those regions (Epperly *et al.* 2002; Shanker & Choudhury 2006; Moore *et al.* 2009). In addition, there is a lack of bycatch reports from small-scale fisheries around the world, particularly in areas of overlap between high densities of marine turtles and artisanal fishing activities (e.g., eastern Pacific, Peckham *et al.* 2007; southeast Asia, Chaloupka *et al.* 2004; East and West Africa, Moore *et al.* 2010). Marine turtle bycatch in small-scale fisheries is a critical data gap that requires vastly improved assessment.

Aggregating gear types within three major gear categories facilitated broad comparisons across bycatch studies, but detailed characterization of variation in fishing gear configurations and methods is necessary to improve understanding of marine turtle bycatch patterns (Watson *et al.* 2005; Gilman *et al.* 2009). Similarly, intraregion analyses would be useful to identify important bycatch trends on finer spatial scales. Finally, although we presented results aggregated across all marine turtle species, we recommend development of management prescriptions that are targeted toward particular region–gear–species combinations to address appropriate species- and population-specific conservation concerns within regions.

Implications for conservation and monitoring

By synthesizing available reported bycatch data for all marine turtle species from 1990 through 2008, our analyses among regions and gear types provided a robust description of bycatch patterns over the past two decades. In cases where high bycatch rates have been reported across many records and are based on high observed fishing effort, scientists and managers can have confidence that those rates accurately reflect true bycatch trends. Due to high ranks for both bycatch rates and observed fishing effort, all fishing gears in the Mediterranean and eastern Pacific were identified as urgent conservation priorities, as were gillnets and longlines in the southwest Atlantic (southwest Atlantic trawls could not be ranked), and longlines and trawls in the northwest Atlantic (Figure 3). Given the large amount of fishing gear observed in these regions, targeted action to reduce turtle–gear interactions is essential for population persistence, and is already underway for some fleets (Watson *et al.* 2005; Cox *et al.* 2007; Casale 2008; Gilman *et al.* 2009). Moreover, bycatch mitigation efforts should be focused toward high bycatch-high effort regions where large turtles are reported as bycatch (e.g., longlines in the eastern Pacific and southwest Atlantic; Figure 3) due to strong potential population-level effects of these scenarios.

In contrast, where few records of marine turtle bycatch have been reported and are associated with low observed effort, there should be far less confidence in associated bycatch rates (Table 2, Figure 3). In such cases, greater observer effort and reporting of turtle-fisheries interactions are needed. Region–gear combinations showing high bycatch rates but low research coverage require enhanced bycatch observation and reporting to improve characterization of turtle–gear interactions (Figure 3). These regions can also warrant conservation action due to the important consequences of high bycatch rates for vulnerable populations (e.g., eastern Indian Ocean gillnets, trawls in West Africa and northeast Atlantic; Jaramillo-Lagoretta *et al.* 2007; Peckham *et al.* 2007). Clearly, region–gear combinations with virtually no publicly available bycatch reports (i.e., those that were not ranked, such as gillnets in the western Indian Ocean and West Africa) represent urgent research priorities. Furthermore, body size measurements of turtles taken as bycatch, in addition to reported BPUE, fishing effort, and mortality rates, are needed to assess fully the potential impacts of bycatch on marine turtle populations (Wallace *et al.* 2008; Moore *et al.* 2009).

Despite continued challenges to effective management of marine resources (target and nontarget) involved with fisheries, successful recovery of fisheries stocks can occur under management regimes that involve well-designed time-area closures, catch shares or individual transferable quotas, and enhanced gear selectivity (Worm *et al.* 2009). We contend that similar management techniques have been successful in reducing marine turtle bycatch in various fisheries (Gilman *et al.* 2006; Cox *et al.* 2007; Howell *et al.* 2008; Moore *et al.* 2009), and reduction of total fishing effort to bolster viability of target fish stocks would also decrease pressure on megafauna populations due to bycatch. Because fishers, managers, and conservationists alike have incentives to reduce fisheries bycatch (Hall *et al.* 2000), informed, targeted management approaches that involve multiple stakeholders have the best chance at successfully ensuring healthy target stocks and healthy nontarget populations.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Complete reference list for database entries.

Appendix S2. List of unique metrics in which fishing effort and bycatch rates, or bycatch per unit effort (BPUE) values were reported.

Appendix S3. Marine turtle bycatch data conversions.

Appendix S4. Size-based demographic class designations of marine turtles reported as bycatch.

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