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Source: Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 2010(2010) : 263-276

Published By: American Fisheries Society

URL: https://doi.org/10.1577/C09-013.1

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Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 2:263–276, 2010
American Fisheries Society 2010
DOI: 10.1577/C09-013.1

[Article]

Using Observed Interactions between Sea Turtles and Commercial Bottom-Trawling Vessels to Evaluate the Conservation Value of Trawl Gear Modifications

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Abstract.—The bycatch of sea turtles (order Testudines) in bottom-trawl fisheries is an important conservation issue currently being addressed by the U.S. National Marine Fisheries Service and its stakeholders. The agency is considering the implementation of new sea turtle conservation regulations in several mid-Atlantic trawl fisheries, including the expanded use of turtle excluder devices (TEDs). The characteristics of observed sea turtle bycatch are used to calculate four conservation metrics. The lowest-level metric is simple to calculate but not informative of population impacts because it does not adequately incorporate the magnitude and demographics of the affected population. The highest-level metric incorporates both magnitude and demographics and is therefore more difficult to calculate but also more informative. Five size categories of turtles were evaluated with respect to the protection afforded by various TED configurations, and the conservation value of 12 bycatch mitigation alternatives was estimated using each of the four conservation metrics. The most informative metric was adult-equivalent bycatch mortality. A TED with a large escape opening had the highest estimated conservation value for loggerheads *Caretta caretta*. Up to 66 more adult-equivalent loggerheads were estimated to be protected by the large opening than by the standard opening. A similar number could be protected by extending TED use north of 37°N. The number of adult-equivalent loggerheads estimated to be protected by standard and wide-bar spacing is nearly the same. The percentage of encountered turtles caught in trawls is not an adequate proxy for the number of adult-equivalent mortalities caused by the fishery. Evaluating sea turtle bycatch using adult-equivalent mortalities facilitates comparisons across disparate bycatch mitigation alternatives and provides a meaningful way to assess the efficacy of bycatch mitigation alternatives for the recovery of sea turtle populations.

The bycatch of sea turtles (order Testudines) in commercial fisheries is an important conservation issue (Epperly et al. 2002; Santora 2003; Murray 2004; Lewison and Crowder 2007) currently being addressed by the U.S. National Marine Fisheries Service (NMFS) and its stakeholders. Bycatch refers to the incidental capture of nontarget species, which may be unharmed, injured, or dead (Lewison et al. 2004). Hundreds of sea turtles are bycaught each year in mid-Atlantic bottom-trawl fisheries (Epperly et al. 1995, 2002; Murray 2007, 2008). Bottom-trawl fisheries operating off the U.S. East Coast catch a wide variety of species, including Atlantic cod *Gadus morhua*, black sea bass *Centropristis striata*, summer flounder *Paralichthys dentatus*, windowpane *Scophthalmus aquosus*, winter flounder *Pseudopleuronectes americanus*, witch flounder *Glyptocephalus cynoglossus*, yellowtail flounder *Limanda ferruginea*, goosefish (also known as monkfish) *Lophius americanus*, haddock *Melanogrammus aeglefinus*, longfin inshore squid *Loligo pealeii*, Northern shortfin squid, *Illex illecebrosus*, silver hake *Merluccius bilinearis*, and scup *Stenotomus chrysops* (Murawski et al. 1983; Orphanides and Magnusson 2007). Nearly one-half of the bycatch of loggerhead turtles *Caretta caretta* in the mid-Atlantic finfish bottom-trawl fishery is estimated to occur in association with the summer flounder, scup, and black sea bass fisheries (Murray 2008).

Turtle excluder devices (TEDs; Figure 1) are gear modifications designed to reduce the likelihood of capturing turtles in the cod end of a trawl net. The distance between the vertical deflector bars and the size of the escape opening affect how a TED interacts with fish and turtles. A wider distance between the vertical bars may improve retention of the target catch (such as summer flounder) but also allow small turtles to pass through the TED and become trapped in the cod end rather than being released through the escape opening. A larger escape opening would allow larger-sized turtles and other large nontarget species (e.g., skates [family Rajidae] and dogfish [order Carcharhiniformes]) to exit the net. Increasing the size of the escape opening would help with the retention of the target catch if the escapement of large bycatch keeps

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Received April 1, 2009; accepted January 11, 2010
Published online August 25, 2010

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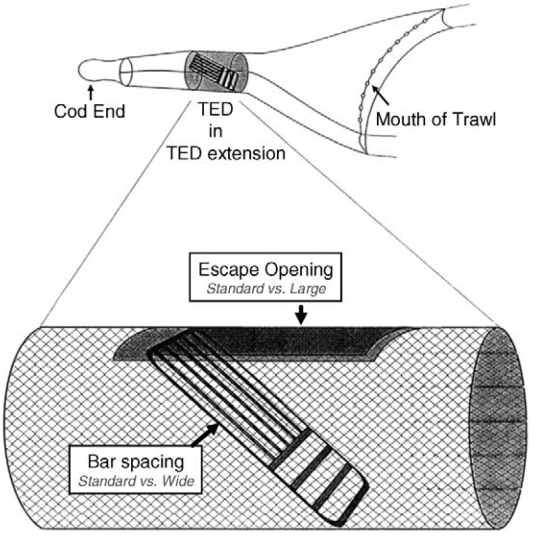

FIGURE 1.—Schematic of a turtle excluder device (TED) extension in a summer flounder bottom otter trawl. The term "bar spacing" refers to the space between the deflector bars as well as that between the bars and the TED frame.

the TED grid clear and permeable to the target catch, but it could also enable more of the target catch to escape.

Turtle excluder devices have been required in most of the southern Atlantic and Gulf of Mexico U.S. shrimp trawl fishery south of Virginia since 1987 (USOFR 1987) and in the summer flounder trawl fishery off of North Carolina and southern Virginia since 1992 (USOFR 1992). Turtle excluder devices are currently used in approximately 2% of the mid-Atlantic (nonshrimp) commercial bottom-trawl fishery (Murray 2008). The most common TEDs in shrimp fisheries are inclined metal grids that guide turtles to the escape opening (Eayrs 2007). Currently, TEDs used in the summer flounder fishery must have vertical deflector bars spaced no more than 10.2 cm (4 in) apart, and the escape opening must measure at least 88.9 cm (35 in) in horizontal taut length and 30.5 cm (12 in) in vertical taut height (50 CFR 223.207). The minimum size of the escape opening in the U.S. summer flounder fishery is smaller than that required in the offshore (and some inshore) areas of the U.S. shrimp fishery.

The National Marine Fisheries Service is considering the implementation of new sea turtle conservation regulations in several mid-Atlantic fisheries, including (1) increasing the size of the TED escape opening required in the summer flounder fishery; (2) requiring the use of TEDs in the flynet, whelk (family Melongenidae), calico scallop *Argopecten gibbus*, and mid-Atlantic sea scallop *Placopecten magellanicus* trawl fisheries; and (3) moving the current northern boundary of the Summer Flounder Fishery–Sea Turtle Protection Area north from Cape Charles, Virginia (USOFR 2007). Trawl fishing industry members have suggested that NMFS develop a TED with wider bar spacing to increase target catch retention rates (DeAlteris 2007). The TED commonly used in the summer flounder fishery can result in the loss of about one-third of its targeted catch (Lawson et al. 2007).

The U.S. National Environmental Policy Act requires NMFS to consider the environmental impacts of fishing regulations. These environmental evaluations are particularly important in cases in which fishing vessels incidentally catch animals protected by the U.S. Endangered Species Act (ESA). The ESA requires NMFS to conserve ESA-listed species and ensure that federally managed fisheries not jeopardize the continued existence of those species.

Because the continued existence of a species is determined by its population dynamics, any changes in the regulations affecting fisheries in which turtles are incidentally captured should be evaluated with regard to their impacts on turtle population dynamics. Demographic sensitivity analysis (also called elasticity analysis) has frequently been used to estimate population responses to proposed management actions (de Kroon et al. 1986, 2000; Crouse et al. 1987; Gerber and Heppell 2004; Heppell 2007; Allen et al. 2009; Romine et al. 2009), but this approach requires knowing the proportional changes in demographic parameters, which are often not known for proposed regulations. Reproductive values (RVs) can also be used to evaluate the population impacts of proposed management actions, and for sea turtles such impacts can be estimated from the available information on sea turtle bycatch in mid-Atlantic trawl fisheries. The RV of an individual is the contribution that it makes to current and future reproduction (Fisher 1930). The smallest, youngest animals typically have RVs close to zero, whereas larger, older animals typically have RVs close to one (Caswell 1989). Translating bycatch into RVs allows multiple management actions to be compared in terms of the "common currency" of the expected reproductive output from the affected individuals (Wallace et al. 2008). The higher the sum of the RVs for the affected individuals, the higher the impact on the population.

In this paper, I combine previously published results on loggerhead bycatch in the mid-Atlantic bottom-trawl fishery (Murray 2008) and an estimate of loggerhead reproductive values (Wallace et al. 2008) with new data analysis (related to the characteristics of observed sea turtle bycatch in mid-Atlantic bottom otter trawl fisheries) to present a new framework for

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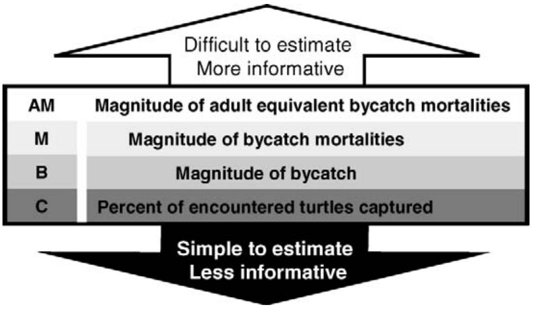

FIGURE 2.—The four conservation metrics used to evaluate sea turtle bycatch. Higher values for these metrics represent larger impacts on the species.

evaluating the conservation values of various gear-based bycatch mitigation alternatives. The cumulative size frequency distribution of all observed bycaught sea turtles in the mid-Atlantic bottom otter trawl fisheries is presented, and the size-groups of turtles are then evaluated in terms of the expected protection afforded by various trawl gear modifications. Four conservation metrics are also provided (Figure 2) for comparing the effects of the different bycatch mitigation alternatives. The lowest-level metric is simple to calculate but not informative as to population impacts because it does not adequately incorporate the magnitude and demographics of the affected population. The highest-level metric incorporates both magnitude and demographics and, though more difficult to calculate, is much more informative as to population impacts. The four metrics were used to evaluate the conservation value of 12 alternatives for reducing the population impact of loggerhead bycatch in mid-Atlantic bottom otter trawl fisheries.

Methods

Data on the bycatch of sea turtles in commercial bottom otter trawl fisheries in the mid-Atlantic region (from the Gulf of Maine through North Carolina) were obtained primarily from the NMFS Northeast Fishery Observer Program (NEFOP, unpublished data), which assigns trained observers to commercial fishing vessels. These observer data have previously been analyzed for percent observer coverage, turtle catch per unit effort, and environmental correlates (Murray 2007, 2008). The present analysis builds on Murray (2007, 2008) by analyzing additional data and assessing the performance of different management alternatives for reducing turtle bycatch. The observed commercial fishing trips represent a subsample of the bottom-trawl fisheries operating in the mid-Atlantic and include trips targeting Atlantic cod, haddock, black sea bass, flounders, monkfish, squid, silver hake, and scup. The observers are instructed to identify turtles by species, photograph identifying characteristics and injuries, describe new and old injuries, obtain body measurements, look for flipper and passive integrated transponder tags, draw diagrams of the turtles, and write a description of the interactions between the animals and the gear. Turtles reported to be moderately or severely decomposed were excluded from subsequent analysis because they were probably not alive when captured. Data from 1989 through 2007 were examined from all NEFOP-observed hauls in mid-Atlantic bottom otter trawl fish and scallop gear. During this period, more than 80,000 bottom otter trawl net deployments south of 42°N latitude were observed by NEFOP personnel. These deployments were distributed (both temporally and spatially) in general proportion to the commercial fishing activities during the period.

For some analyses, observer data from the NMFS Southeast Fisheries Science Center (SEFSC; Epperly et al. 1995) were also used. Between November 1991 and February 1992, SEFSC staff observed about 1,500 trawl net deployments (about 16% north of Cape Charles, 44% between Cape Charles and Cape Hatteras, North Carolina, and 40% south of Cape Hatteras). The SEFSC observer effort focused on vessels using bottom otter trawls to target summer flounder. All of the SEFSC-observed turtle interactions were south of Cape Charles, about two-thirds of them below Cape Hatteras.

Characteristics of sea turtles caught in bottom otter trawls.—Only turtles actually measured by observers (standard curved carapace length) were included in the size frequency analysis because the accuracy of estimated length measurements is not known. Curved carapace length (CCL) is the curvilinear length of the carapace from the nuchal notch to the posterior marginal tip (measured to the nearest 0.10 cm). Excluding unmeasured turtles should not bias the size frequency results unless a certain size turtle is less likely to be measured than another. For example, the measurements could be biased if small turtles disproportionately fell through or out of the gear before being brought aboard or large turtles were disproportionately excluded because they were more difficult to bring aboard. Both of these issues were investigated by examining whether turtles with missing CCL measurements but with estimated lengths in the bottom and top 10% of the measured size distribution were brought aboard the fishing vessel. All turtles with estimated measurements less than 55 cm ($n = 2$) were brought aboard. Seven of eight turtles with estimated measurements greater than 100 cm were also brought on board. The one turtle not brought aboard was trapped in a

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TABLE 1.—Sea turtle size-classes based on possible trawl gear modifications. The third column shows the reproductive value (RV) for loggerheads. The size limit column lists the maximum turtle dimensions included in each of the size-classes; the species-specific curved carapace length (CCL) columns convert these limits into CCL measurements. Morphological limits that limit the size of the size-class are shown in bold italics.

				Species-specific CCL (cm) limits[b]			
Size-class	Theoretical turtle excluder device (TED) protection	RV	Size limit (cm)[a]	CC	LK	CM	OS
SC1	Not protected by any current or proposed TEDs because small enough to pass through standard (10.16-cm) bar spacing	0.0028	***<10.16 BD***	***≤26.8***	***≤24.7***	***≤28.9***	***≤28.9***
SC2	Protected by standard bar spacing but small enough to pass through wider (15.24-cm) spacing	0.0065	***>SC1*** ***<15.24 BD***	***>26.8*** ***≤39.7***	***>24.7*** ***≤38.7***	***>28.9*** ***≤43.6***	***>28.9*** ***<43.6***
SC3	Protected by 30.48-cm (height) and 88.9-cm (horizontal length) standard escape opening	0.0240	***>SC2*** ***≤30.48 BD*** ≤88.90 SCW	***>39.7*** ***≤80.6*** ≤119.3	***>38.7*** ***≤83.0*** ≤98.5	***>43.6*** ***≤87.9*** ≤118.9	***>43.6*** ***≤80.6*** ≤98.5
SC4	Protected by 53.34-cm (height) and 101.6-cm (width) of large escape opening but not standard escape opening	1.0000	***>SC3*** ≤53.34 BD ***≤101.60 SCW***	***>80.6*** ≤145.8 ***≤136.7***	***>83.0*** ≤153.8 ***≤112.0***	***>87.9*** ≤154.3 ***≤136.3***	***>80.6*** ≤145.8 ***≤112.0***
SC5	Too large to be protected from current or proposed escape openings	1.0000	***>SC4***	***>136.7***	***>112.0***	***>136.3***	***>112.0***

[a] BD = body depth; SCW = straight carapace width.
[b] CC = loggerheads; LK = Kemp's ridleys; CM = green sea turtles *Chelonia mydas*; and OS = other sea turtles, including hawksbills *Eretmochelas imbricata* and unidentified species.

TED with "several of his flippers sticking out of the mesh" during a time (1999) when the TED extension was required to have large mesh. These findings suggest that the extent of size bias due to turtles not being brought aboard and measured is small.

Outliers were investigated to assess whether any other observer information supported these data. The two smallest (28 and 30 cm) and largest (135.0 cm) loggerhead measurements are unusual for mid-Atlantic loggerhead bycatch. The reported weights of the two smallest loggerhead turtles support the small reported sizes, but the species identification could not be confirmed with photographs or biopsy samples. The largest loggerhead was reported to be "too big to handle" and "bigger than most loggerheads." The observer recorded that the "notch to tip [CCL measurement is an] actual not estimated measurement"; nevertheless, this measurement exceeds previous reports for loggerhead carapace length (TEWG 2009). Because there was no contradictory information in the observer records, all three of the outliers were kept in the database analyzed.

Latitudinal patterns in the size composition of the observed turtle bycatch were examined by plotting turtle size against latitude. Data from both the SEFSC and NEFOP programs were used. Although the number of turtles observed at each degree of latitude is a function of the number of observed trips, the pattern of observed turtle sizes is informative as to the geographic pattern of turtle bycatch within each latitude zone.

The size composition of all NEFOP-observed turtles with CCL measurements was derived by plotting the cumulative size distribution (in percent) versus measured size. A cumulative size distribution of bycaught animals should reflect the expected size distribution in the commercial fishery if the observer coverage represents a random sample. Both the NEFOP and SEFSC programs strive for random sampling, but the SEFSC coverage is limited to vessels fishing for summer flounder in the southern mid-Atlantic during the winter. Hence, only the NEFOP data were used to calculate the cumulative size distribution. Most turtles were loggerheads (87 of 91). There was one unidentified species (61 cm), one leatherback *Dermochelys coriacea* (155 cm), and two Kemp's ridleys *Lepidochelys kempii* (27.2 and 30 cm).

Gear-based size categories of sea turtles.—Gear-based size categories of turtles were created to assess which size-classes would be protected by various TED configurations (Table 1). The two main gear variables were bar spacing (the standard 10.16 cm required in the summer flounder fishery versus the wider 15.24-cm spacing) and the size of the escape opening (the standard size required in the summer flounder fishery versus the larger size required in portions of the shrimp trawl fishery). The purpose of the gear-based size categories was to translate the geometry of the TED gear configurations into standard morphometric turtle measurements. The minimum space between the bars and the minimum height of the escape opening (e.g.,

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for the standard summer flounder TEDs, the vertical measurement taken at the midpoint of the horizontal measurement) translate into a theoretical maximum body depth for a turtle. The minimum horizontal measurement of the escape opening translates into a theoretical maximum turtle body width (e.g., straight carapace width). Conversions between various morphometric values were calculated based on species-specific equations for loggerhead, Kemp's ridley, and green turtles. Body depth and straight carapace width were converted to straight carapace length based on relationships in Epperly and Teas (2002), and conversions between curved carapace length and straight carapace length were based on Teas (1993).

Turtle size-class 1 (SC1) consists of animals that are not expected to be protected by any of the gear modifications discussed in this article. Size-class 2 (SC2) encompasses turtles expected to be protected by a TED with standard bar spacing but not by one with wider bar spacing. Turtles in classes larger than SC2 (i.e., SC3–SC5) are expected to be protected by either bar spacing. Size-class 3 consists of turtles that are expected to be able to exit through either escape opening. (Turtles in classes smaller than SC3 are also expected to be able to fit through either escape opening.) Size-class 4 consists of turtles that are expected to escape through a large escape opening but not the standard summer flounder opening. Size-class 5 consists of turtles that may be too large to exit even through the large escape opening (which is a 180-cm [71-in] stretched opening designed to accommodate leatherback and large hardshell turtles). Because it is difficult to translate this single dimension into the maximum size of a turtle that is expected to escape, I set the upper bound of SC4 to the size of the pipe-framed leatherback model (101.6 cm at its widest point, 53.34 cm at its highest point, and 152 cm at its longest point; John Mitchell, SEFSC, personal communication) used in testing the large escape opening (USOFR 2001). This is a conservative approach because larger turtles may also be able to pass through the large escape opening but, because the true upper bound is unknown, the size of the leatherback model was used as a proxy. To evaluate the percentage of observed bycatch associated with each size-class, the five size-class categories were superimposed on the cumulative size distribution of the NEFOP-observed turtles measured in the bottom otter trawl fisheries.

Because the size-classes were based on turtle morphometrics and the geometry of gear designs, they represent theoretical rather than empirical protection. The lower bound of each size-class was defined by default from the upper bound of the previous size-class (zero in the case of SC1). The upper bound of each size-class was set to the smallest standard curved carapace length (CCL) of the relevant size limits. The upper bound of each "other species" size-class was set to the most conservative value of the other known species (i.e., the value that assigned TED protection to the smallest number of "other species" turtles). Leatherbacks were not included in the gear-based size categories because there is inadequate published morphometric data on them. The only leatherback in this analysis (CCL = 155 cm, straight carapace length [SCL] = 148.4; Teas 1993) was assigned to SC4 because it was smaller than the pipe-framed leatherback model in the only dimension measured by the observer (length).

The latitudinal patterns in the observed size distribution of bycaught sea turtles were examined by plotting the frequency of observed turtle interactions by latitude zone and size-class. Three latitude zones were created based on the results of a previous bycatch analysis (Murray 2008) as well as geographic and management considerations. Murray (2008) identified two latitudinal bycatch strata. Her northern stratum (which included latitudes from 39°N to 41.5°N) was used as is, but her southern stratum was divided into two zones: latitudes up to 37°N and latitudes between 37°N and 39°N. This was done so that each latitude zone would encompass approximately the same area. The 37°N boundary aligns closely with the current northern boundary of the summer flounder TED requirement area (37.0833°N). Turtle size data from both the SEFSC and NEFOP programs were analyzed for latitudinal patterns in size frequency because the inclusion of the latitude strata alleviated the concern about disproportionate sampling in the lower latitudes. As the sample sizes were sufficiently large, the observed size distribution of sea turtles by latitude zone was thought to approximate the true size distribution of the turtle bycatch within these same zones. The similarity between the size distribution of bycaught and stranded loggerheads (TEWG 2009) also limits speculation that the true size structure of bycaught loggerheads differs from that in these observations.

Conservation value of bycatch mitigation alternatives for loggerheads.—Twelve loggerhead bycatch mitigation alternatives were evaluated with respect to four conservation metrics (Table 2). Conservation metric values were calculated only for loggerheads because there was sufficient information on bycatch rates only for this species. The two gear options used in these alternatives are the same as those used to develop the turtle size categories, that is, the spacing between bars in a TED (standard versus wider bar spacing) and the size of the escape opening (standard versus large).

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TABLE 2.—Conservation value of bycatch mitigation alternatives. The upper portion of the table lists the various bycatch mitigation alternatives. The shaded cells in the latitude zone categories indicate the latitudes with TED requirements; those in the bar spacing and escape opening categories indicate the gear configuration required (see text). The lower portion of the table shows the conservation values (turtles affected) of four metrics: AM = adult-equivalent mortalities, *M* = mortalities, *B* = bycatch, and *C* = the refined estimate of the percentage of turtles encountered that are captured. The shading in this section indicates the magnitudes of the metrics relative to no TED: none, <10%; light, 11–50%; medium, 51–90%; and dark, >90%.

		Bycatch mitigation alternatives											
	No TED	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
Latitude (°N)													
≤37		■	■	■	■	■	■	■	■	■	■	■	■
37-39						■	■	■	■	■	■	■	■
39-41.5										■	■	■	■
Bar spacing													
Standard (10.16 cm)		■	■	■	■	■	■	■	■	■	■	■	■
Wide (15.24 cm)		■	■			■	■			■	■		
Escape opening													
Standard		■		■		■		■		■		■	
Large			■		■		■		■		■		■
Metrics													
AM	73	70	59	70	59	69	26	69	26	68	2	68	2
M	308	186	175	185	174	115	72	114	71	84	18	75	9
B	716	432	407	429	404	267	168	264	165	195	43	174	21
C	100	12	4	11	3	21	4	20	3	27	6	24	3

The spatial options include three latitude zones (southern, intermediate, and northern).

The baseline loggerhead bycatch scenario ("no TED" in Table 2) represents the estimated number of loggerheads that would be captured annually in mid-Atlantic commercial finfish bottom otter trawl gear if no mitigation alternatives (including TEDs) were used. These estimates were obtained for 12 latitude–depth–temperature strata by multiplying the average annual commercial finfish bottom otter trawl fishing effort (southwest of 41°30′N and 66°W) by published loggerhead bycatch rates for bottom trawls without working TEDs (Murray 2008; see Table 3). Average annual effort was calculated from vessel trip reports (VTR) of finfish bottom otter trawl trips conducted in the mid-Atlantic region (south of 41.5°N) from 1996 to 2004 adjusted upward by an average of 11% to match the landings (lb) reported in the federal dealer landings database (Murray 2008). The difference between the VTR and dealer landings represents trips with erroneous information, trips not required to submit a VTR, and trips that failed to file a VTR as required. Vessel trip report data have been routinely used in management analyses and stock assessments (Wigley et al. 2007). Commercial effort was pooled from hauls with and without working TEDs and prorated among the three latitudinal zones according to the proportion

TABLE 3.—Estimated annual number of loggerheads bycaught under baseline conditions (no TEDs) for each stratum. The abbreviation SST stands for sea surface temperature. Fishing effort is the annual commercial bottom trawl fishing effort expressed in units of 24 h fished. The bycatch rate is the estimated number of loggerheads caught per 24 h of fishing effort with no TED.

Stratum	Latitude (°N)	Depth (m)	SST (°C)	Fishing effort	Bycatch rate	Total bycatch
1	39–41.5	<50	>18	3,280	0.0282	92
2	39–41.5	≥50	>18	1,977	0.0007	1
3	39–41.5	<50	≤18	6,071	0.0086	53
4	39–41.5	≥50	≤18	10,660	0.0002	2
5	37–39	<50	>18	292	0.4813	140
6	37–39	≥50	>18	389	0.0119	5
7	37–39	<50	≤18	652	0.1474	96
8	37–39	≥50	≤18	1,417	0.0036	6
9	≤37	<50	>18	421	0.4813	203
10	≤37	≥50	>18	189	0.0119	2
11	≤37	<50	≤18	788	0.1474	116
12	≤37	≥50	≤18	215	0.0036	1

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of adjusted VTR effort in each zone. The bycatch rates in Murray (2008) were for broad areas, and actual bycatch rates may vary on a finer scale than what was modeled. For example, bycatch rates could be locally high in North Carolina waters in winter owing to a concentration of overwintering loggerheads (Epperly et al. 1995). Nevertheless, the Murray (2008) bycatch rates for trawls without working TEDs were used because these represent the most comprehensive data available on loggerhead bycatch in the mid-Atlantic region.

Four conservation metrics (Figure 2) were calculated for each of the 12 bycatch mitigation alternatives (Table 2) to quantitatively compare the alternatives. The calculation of the metrics did not consider possible shifts in commercial effort as a result of a regulation, were based on 100% compliance with TED requirements (and no nonworking TEDs), and incorporated all of the assumptions and caveats in the cited research. The value of a metric indicates how many loggerheads would have been captured under a given bycatch mitigation alternative. A low value implies that the population impact would be low and therefore that the alternative has high conservation value. Because the ESA definition of "take" includes harassing, harming, pursuing, hunting, shooting, wounding, killing, trapping, and collecting as well as capturing, none of the conservation metrics evaluated in this paper are informative as to the absolute number of takes because turtles that pass through a net (by swimming out of the mouth of the trawl or escaping through the TED opening) would not be not seen by the observer.

The first conservation metric (the percentage of encountered turtles captured and not released from an otter trawl [C]) represents the lowest level of information typically considered in bycatch mitigation scenarios. When no other information is available, the value of this metric can be estimated from gear experiments. Here the experimental rate of TED failure (EX = 3%; Watson 1981) is used to estimate the percent of captured turtles, that is,

$$C^{\text{experimental}} = \text{EX}. \tag{1}$$

This metric is not informative as to the number of observed ESA takes or the population impact, which depends on the magnitude, mortality, and demographics of the loggerhead captures.

The second conservation metric (the estimated number of bycaught turtles [B]) is calculated by summing the expected loggerhead bycatch (BASE) in each size–latitude stratum, the bycatch within strata with TED requirements being adjusted by the size-specific expected TED failure rate. The relevant equations are

$$B = \sum_{i=1}^{12} \sum_{j=1}^{5} B_{ij}, \tag{2}$$

and

$$B_{ij} = \text{BASE}_i \cdot P_{ij} \cdot S_j \cdot T_i,$$

i = the latitude–depth–temperature stratum (Table 3);
j = the size-class;
BASE = the estimated annual number of loggerheads caught under baseline conditions;
P = the percentage of NEFSC-observed loggerheads;
S = 0 if the size-class is expected to be protected by a TED, 1 otherwise;
T = the proportion of loggerheads unprotected by a TED regulation (= EX when the stratum has a TED regulation, 1 otherwise)

Bycaught loggerheads may be dead, injured, or uninjured. This metric provides more population-level information than the percent captured because it explicitly considers the efficiency of the bycatch mitigation method with respect to the number of loggerheads captured and not released from the trawl. However, it is not informative as to population impacts because it does not consider turtle mortality and capture demographics.

After the magnitude of the bycatch (B) is calculated, the estimate of the percentage of encountered turtles that are captured can be refined by summing the expected loggerhead bycatch in each size-class and latitude zone and dividing this by the baseline loggerhead bycatch for this zone and time period, that is,

$$C^{\text{refined}} = \frac{B}{\sum_{i=1}^{12} (\text{BASE}_i \times T_i)}. \tag{3}$$

Because Epperly and Teas (2002) have shown that some loggerheads are too large to fit through TEDs, the 3% experimental rate of capture was only used for size-classes expected to be retained by the bars and subsequently released through the TED escape opening.

The third conservation metric (the estimated number of turtle mortalities due to capture in the trawl [M]) is calculated by multiplying the estimated bycatch by the expected mortality rate induced by the gear interaction, that is,

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$$M = \sum_{j=1}^{5} M_j \tag{4}$$

and

$$M_j = \sum_{i=1}^{12} B_{ij} \times \text{MR},$$

where MR is the mortality rate.

Based on the percentage of bycaught loggerheads that were dead, injured, resuscitated, or of unknown condition, a conservative mortality rate of 0.43 (Murray 2008) was assigned to all turtles. The true mortality rate probably varies with loggerhead size and environmental conditions and lies somewhere between 0.12 (the observed fraction of dead loggerheads; see Murray 2008) and 0.43. The number of mortalities provides some information about the severity of observed ESA takes but is not informative as to population impacts because demographic information is lacking.

The fourth conservation metric (the number of adult-equivalent mortalities [AM]) is calculated by multiplying the estimated number of mortalities due to trawl capture by the scaled reproductive value for each turtle size-class, that is,

$$\text{AM} = \sum_{j=1}^{5} (M_j \times \text{RV}_j). \tag{5}$$

This yields the sum (over the affected individuals) of the expected lost reproductive output scaled to adults. "Slow growth, high fecundity" reproductive values were used because these most closely represent the reported population parameters for North Atlantic loggerheads (see Figure 1 in Wallace et al. 2008). The RVs were not adjusted for sex because (1) the sex of the bycatch was unknown in most cases, (2) little sex-specific RV information is available, and (3) the Wallace et al. (2008) RVs were derived from samples of both sexes (using female-based Leslie matrices). For each turtle size-class, an RV was selected that corresponded to the approximate midpoint of the size range of the turtles in that size-class (Table 1). The Wallace et al. (2008) RV values are similar to those reported elsewhere (NMFS and USFWS 2008). Other reasonable assignments of RVs by size-class would probably not produce appreciable changes in the adult-equivalent mortalities. For example, had the RVs been assigned using the mean observed length in each size-class, they would be nearly identical for all classes but slightly lower (though still large) for SC4. Hence, using the midpoint of the range appears to be a conservative approach to assigning RVs. Of the four conservation metrics, the number of adult equivalents is the most informative as to the expected population-level impacts because it contains magnitude, mortality, and demographic information.

To evaluate the ability of each conservation metric to approximate the most informative metric (AM), the correlation coefficient (R^2) of each of the other three metrics with AM was computed.

Results

Characteristics of Sea Turtles Caught in Bottom Otter Trawls

Bycatch of small turtles of all species occurred most frequently in the southern mid-Atlantic (Figure 3). Most of the turtles less than 40 cm CCL were observed south of 36°N and were Kemp's ridleys, but there were also small loggerhead, green, and hawksbill turtles. North of 36°N, the observed bycatch consisted primarily of loggerheads larger than 50 cm CCL.

The cumulative size frequency distribution of NEFOP-observed turtles indicates that most were between 50 and 85 cm, with about 10% above and 10% below these values (Figure 4). Turtles of various sizes have been caught in trawls equipped with TEDs. Most were caught in 1999, when the mesh size in the TED extension was larger than previously (and subsequently) required. Two Kemp's ridleys occurred in the cod end of a trawl (past the TED) and hence must have passed through the bars of the TED. At least one of these animals was thought to be large enough (30 cm CCL) to be protected by a TED having the standard 10.16-cm bar spacing. In trawls with TEDs, no turtles that were too big to fit through the TED escape opening were observed.

Gear-Based Size Categories

Based on the cumulative size distribution of all species of NEFOP-observed turtles bycaught in the mid-Atlantic bottom otter trawl fishery, about 75% of these animals would have been protected by a TED with a standard opening and wider bar spacing (SC3; Figure 4). None of the observed turtles were too small to theoretically be protected by any TED (SC1). Fewer than 5% of the turtles were in the size-class expected to fit through TEDs with wider bar spacing but not standard bar spacing (SC2). Almost 20% of the turtles were in the size-class expected to be able to exit through a large escape opening but not a standard escape opening (SC4). No turtles were in the size-class expected to be too large to fit through the large opening (SC5).

Loggerheads were the most commonly observed species in the combined NEFOP and SEFSC data set ($n = 134$), and SC3 was the most commonly observed

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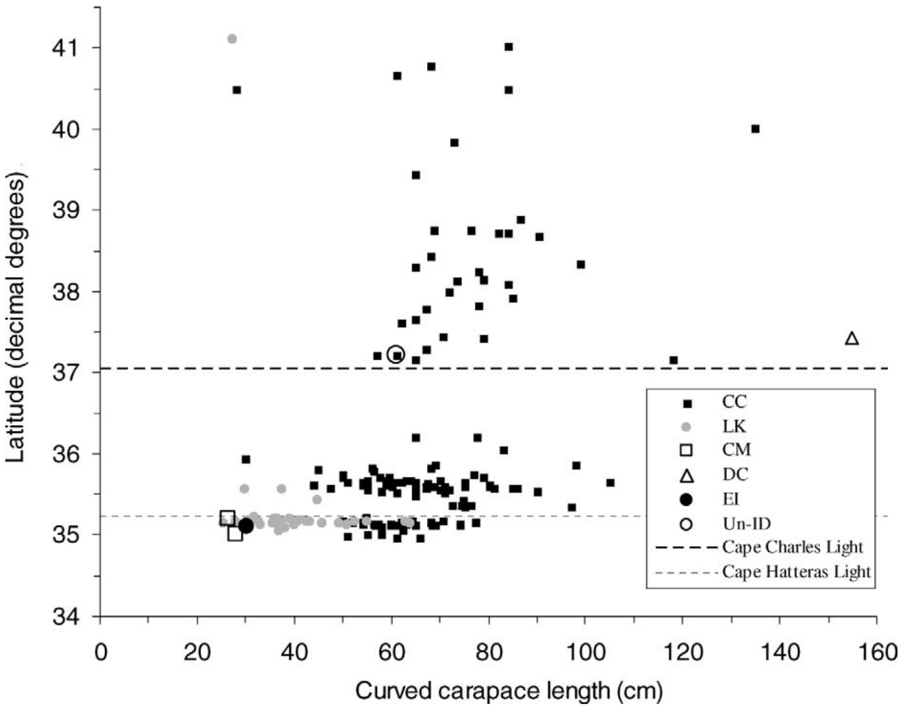

FIGURE 3.—Turtle size by latitude and species from the NEFOP ($n = 91$) and SEFSC ($n = 78$) observer programs. Species abbreviations are as follows: CC = loggerhead, LK = Kemp's ridley, CM = green, DC = leatherback, EI = hawksbill, and Un-ID = unidentified.

size-class in all latitude zones (Figure 5). Latitudes south of 37°N had more turtle species and smaller turtles. North of 37°N, the observed bycatch was predominately loggerheads (~94%), mostly in size-classes SC3 and SC4 with only one animal in SC2. The southern latitude zone (<37°N) had more nonloggerhead bycatch (2 green, 1 hawksbill, and 30 Kemp's ridleys) than the northern zone (1 Kemp's ridley and 1 unidentified species). The southern zone was the only zone with turtles in SC1 ($n = 2$).

Conservation Value of Mitigation Alternatives

The four conservation metrics can be ranked according to the quality of information provided relative to population impacts. The most informative metric is adult-equivalent bycatch mortality (AM). The next two conservation metrics (M and B) are closely related to one another (because size-based mortality rates were not used) and thus were similarly correlated with the AM metric ($R^2 = 0.52$, $P < 0.001$). The percent captured (C) is least informative as to population impact and also the least correlated with AM ($R^2 = 0.29$, $P < 0.01$).

The conservation values associated with the 12 different bycatch mitigation alternatives indicate that a TED with a large escape opening has the highest conservation benefit for loggerheads (Table 4). Such a TED could annually provide protection for up to 66 more adult-equivalent loggerheads than one with a standard escape opening (assuming that all of the other bycatch reduction methods are the same). A similar number (up to 57) of adult-equivalent loggerheads could be protected by extending TED use from 37°N to the whole mid-Atlantic region. Bar spacing, however, had a negligible effect (only up to 0.06 more adult equivalents) on the number of loggerheads that were protected (Table 4).

Discussion

Although there is uncertainty associated with the higher-level conservation metrics, the amount of uncertainty per metric is probably less than the added informational value. This was explored by calculating new estimates incorporating various sources of uncertainty for the three higher-level conservation metrics. For example, when the number of bycaught turtles (B) was recalculated first on the basis of the upper 95% confidence limit and then on the basis of the lower limit (from a coefficient of variation = 0.23; Murray 2008), the range of the new estimates was about 90% of that

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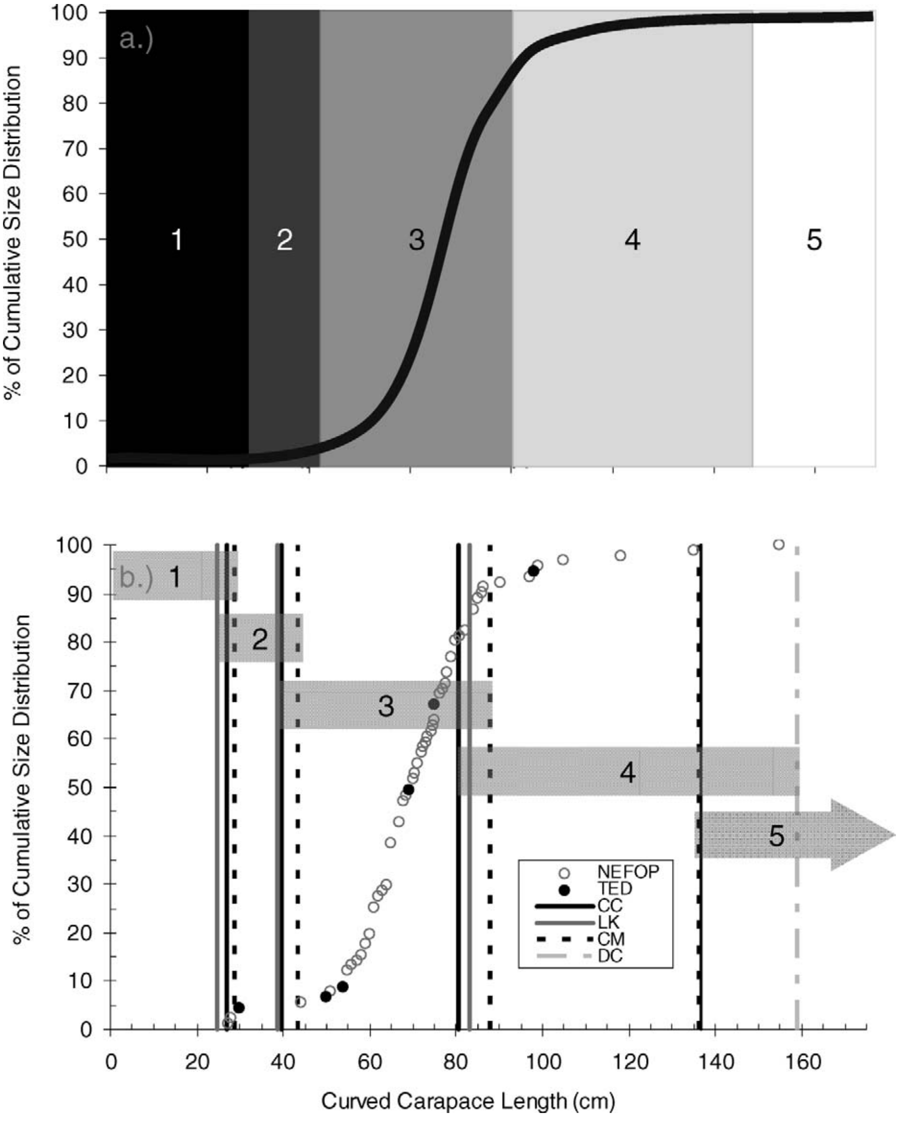

FIGURE 4.—Panel **(a)** shows a generalized cumulative size distribution of bycaught sea turtles and their gear-based size-classes (1–5). Panel **(b)** shows the cumulative size distributions for all species in the NEFOP database. Open circles are turtles caught in bottom otter trawls without TEDs. Closed circles are turtles caught in TEDs. The vertical bars represent the size-classes for the particular species; the shaded bands represent gear-based size-classes. The division between size-classes 4 and 5 is not shown for Kemp's ridley turtles because this species does not grow large enough for this to be necessary. The 155-cm turtle represented by the open circle in the upper right was a leatherback in size-class 4.

of the original estimates. Similarly, when the number of mortalities (*M*) was recalculated based on the least conservative mortality estimate (MR $= 0.12$), the range of the new estimates was about 73% of that of the original estimates. When adult-equivalent mortalities (AM) were derived from the means of the observed size-classes rather than the mid-points, the range between the new and original estimates was about 56% of the original estimates. By comparison, the average range of the lowest metric (*C*) to that of the highest metric (AM) is approximately 500% of the low metric. Because the expected range of the conservation metrics due to uncertainty in parameter estimates is smaller than the range between the lowest and highest metrics, the highest metric probably provides the most accurate measure of the population impacts of the

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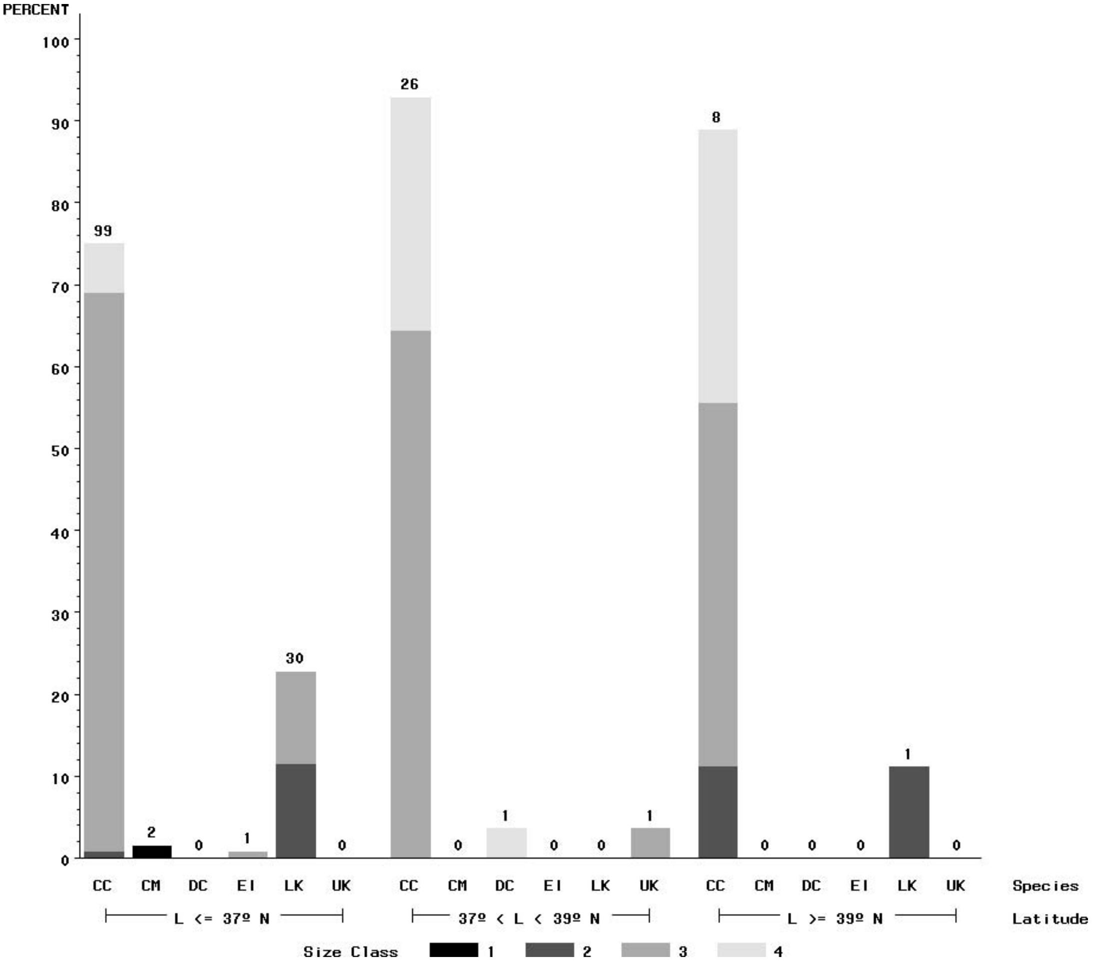

FIGURE 5.—Distributions of sea turtle bycatch by species, latitude, and size-class for both the NEFSC and SEFSC observer programs. The numbers above the bars are the numbers of turtles observed; see Figure 3 for species abbreviations.

various mitigation alternatives. Future research could extend this examination of variation by doing a formal analysis of the propagation of uncertainty.

A comparison of mitigation alternatives A4 and A12 illustrates the value of using adult-equivalent mortalities (AM). Both alternatives involve TEDs with large escape openings and standard bar spacing, but A4 only requires TED use south of 37°N while A12 requires it throughout the mid-Atlantic. The percent captured (3% of encountered turtles) is the same for both alternatives. In contrast, A4 results in an estimated loss of 59 adult-equivalent loggerheads whereas A12 results in an estimated loss of only 2 (Table 2). This example is particularly illuminating in that both alternatives comply with the NMFS criterion for a 97% exclusion rate ($C \leq 3$), yet the population impacts of the two alternatives are markedly different (by about 30×).

This quantitative approach to the evaluation of bycatch mitigation alternatives provides essential information that typically would not be provided by a qualitative approach. For example, alternatives A1 and A5 both require TEDs with standard escape openings and wider bar spacing; the difference is that A1 only applies to areas south of 37°N whereas A5 applies to areas south of 39°N. A qualitative approach might conclude that the conservation benefit of A1 is much lower than that of A5 because A5 covers essentially twice as much area. However, the estimated number of adult-equivalent mortalities in the two alternatives differs by only a single animal (70 versus 69; Table 2).

The expected population impact of the standard bar spacing is almost identical to that expected from the wider bar spacing; the maximum difference in adult-equivalent mortalities is less than 1. The difference is

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TABLE 4.—Number of adult-equivalent mortalities of loggerhead turtles under different bycatch mitigation alternatives. The table is structured so as to compare the impact of one factor at a time; the first row, for instance, compares three alternatives that differ only with respect to the latitudes in which TEDs are required. Adult-equivalent mortalities are given in parentheses; the minimum, maximum, and range are for the row in question. The different bycatch mitigation alternatives are listed in Table 2. Three latitudes are compared (≤37°, ≤39°, and <41.5°N), along with two bar spacings (standard and wide) and two escape opening sizes (standard and large).

Factor	Alternatives compared			Minimum	Maximum	Range
	1	2	3			
Latitude	A1 (70.3)	A5 (68.6)	A9 (67.9)	68	70	2
	A2 (59.5)	A6 (26.2)	A10 (2.3)	2	59	57
	A3 (70.3)	A7 (68.6)	A11 (67.8)	68	70	3
	A4 (59.5)	A8 (26.2)	A12 (2.2)	2	59	57
Bar spacing	A1 (70.3)	A3 (70.3)		70	70	0
	A2 (59.5)	A4 (59.5)		59	59	0
	A5 (68.6)	A7 (68.6)		69	69	0
	A6 (26.2)	A8 (26.2)		26	26	0
	A9 (67.9)	A11 (67.8)		68	68	0
	A10 (2.3)	A12 (2.2)		2	2	0
Escape opening	A1 (70.3)	A2 (59.5)		59	70	11
	A3 (70.3)	A4 (59.5)		59	70	11
	A5 (68.6)	A6 (26.2)		26	69	42
	A7 (68.6)	A8 (26.2)		26	69	42
	A9 (67.9)	A10 (2.3)		2	68	66
	A11 (67.8)	A12 (2.2)		2	68	66

small because the affected size-class (SC2) is narrow (see Figure 4; Table 1) and has a low reproductive value. Although the conservation values were only calculated for loggerheads, the observed size frequency distributions of other sea turtle species (Figure 4) suggest that the population impacts of the standard and wide bar spacing would be similar for them, especially north of 37°N. Less than 5% of the observed bycatch of all species combined (Figure 4) is theoretically protected by the standard bar spacing but not the wider bar spacing (SC2). As with loggerheads, size-class SC2 represents juveniles with low reproductive values for all sea turtles, even the smallest species (Kemp's ridley [adult stage defined as >60 cm SCL]; TEWG 2000). Moreover, north of 37°N the bycatch of nonloggerhead species is rare (Figures 2, 5). Hence, the distribution of the observed bycatch suggests that the standard bar spacing may not provide much more conservation benefit than the wider bar spacing for any sea turtle species north of 37°N.

This study demonstrates how conservation metrics can be used to evaluate various bycatch mitigation alternatives, but it does not include all reasonable management options or analytical approaches. For example, one could also evaluate mitigation alternatives based on temperature or month.

Given the mandate of NMFS to conserve, protect, and manage living marine resources in ways that afford economic opportunities, bycatch mitigation alternatives that use TEDs with wider bar spacing merit serious consideration. Turtle excluder devices with wider bar spacing are expected to protect most turtles north of 37°N and may also improve target catch retention (DeAlteris 2007). If target catch retention is indeed enhanced using TEDs with wider bar spacing, this would provide ancillary conservation benefits to sea turtles by decreasing bottom-trawling time (less time would probably be needed to catch a desired amount of fish, so that there would be fewer turtle encounters) and increasing TED compliance (if TED compliance is related to loss of the target catch). High compliance is necessary to obtain maximum sea turtle conservation benefits from TED regulation (Lewison et al. 2003).

Although evaluating adult-equivalent mortalities is not new in population ecology (Caswell 1989), it does represent a new way to assess the conservation benefits to sea turtles of gear-based mitigation alternatives. To date, the primary guiding principle for TED development and implementation is that a TED must be "97% effective in releasing sea turtles from trawls" (USOFR 1990). The *Code of Federal Regulations* states that new TEDs may be approved if they demonstrate "a sea turtle exclusion rate of 97% or greater" (50 CFR 223.07(e)(1)). New information on loggerhead bycatch (Murray 2007, 2008) and reproductive values (Wallace et al. 2008) has become available and now allows more informative conservation metrics to be calculated for loggerheads. The conservation metrics presented here demonstrate that the percentage of encountered turtles caught in a trawl is not an adequate proxy for the number of adult-equivalent mortalities. For example, mitigation alternative A4 meets the 97% efficiency

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criterion ($C = 3$), yet the estimated number of adult-equivalent mortalities for loggerheads (59) is high—81% of the baseline value. By comparison, A10 does not meet the 97% efficiency criterion ($C = 6$) but would result in only 2 adult-equivalent mortalities—3% of the baseline value. The difference in the conservation value of these two alternatives is noteworthy. Hence, using adult-equivalent mortalities rather than the percentage of encountered turtles captured to evaluate sea turtle bycatch better links protective strategies to population dynamics and recovery.

Estimating adult-equivalent mortalities is also useful because it facilitates comparisons across disparate mitigation alternatives (Wallace et al. 2008). For example, the adult-equivalent mortalities resulting from a gear modification in the scallop dredge fishery can be compared with those resulting from a rolling closure in the gill-net fishery. A cumulative bycatch assessment (expressed in adult-equivalent mortalities) for all U.S. fisheries could help prioritize management actions while reducing the chance of unnecessarily restricting fisheries (Moore et al. 2009). An additional, important advantage of using adult-equivalent mortalities is that these values can be input into population viability assessment models and used to evaluate how removing individuals from a population affects its probability of survival.

Acknowledgments

I thank the Southeast Fisheries Science Center, particularly S. Epperly and J. Braun McNeil for observer data in the summer flounder fishery and J. Mitchell for information on the development and testing of turtle excluder devices. I also thank the observers and data managers from the Northeast Fisheries Observer Program as well as the fishing vessel captains and crews. This paper was improved by input from K. Bisack, S. Epperly, G. Magnusson, R. Merrick, H. Milliken, J. Mitchell, K. Murray, D. Palka, F. Serchuk, C. Upite, B. Wallace, and anonymous reviewers.

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