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The importance of location and operational fishing factors in estimating and reducing loggerhead turtle (*Caretta caretta*) interactions in U.S. bottom trawl gear

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ABSTRACT

Mortalities due to interactions between loggerhead (*Caretta caretta*) turtles and commercial bottom trawl fisheries impede the recovery of loggerhead populations worldwide. In the U.S. Mid-Atlantic, several hundred loggerheads interact with commercial bottom trawl gear each year despite the implementation of temporal and spatial conservation measures. In this analysis a Generalized Additive Model (GAM) is developed using fisheries observer data to estimate the magnitude of loggerhead interactions and mortalities in U.S. Mid-Atlantic bottom trawl gear from 2009 to 2013. Based on the results, the potential conservation benefits of hypothetical spatial closures or turtle excluder device (TED) requirements in times and areas of high estimated interactions is then evaluated. Loggerhead interaction rates were modeled as a function of retained catch, depth, latitude, and sea surface temperature. From 2009–2013, a total of 1156 (CV = 0.13, 908–1488) loggerheads were estimated to have interacted with bottom trawl gear in the U.S. Mid-Atlantic, of which 479 resulted in mortality. The total number of estimated interactions was equivalent to 166 adults, of which 68 resulted in mortality. The trawl fishery targeting Atlantic croaker (*Micropogonias undulatus*) in the southern Mid-Atlantic had the highest turtle interactions among fisheries investigated; this may be due to larger mesh sizes in the mouth of the trawl and high headline height of the gear. The potential conservation benefit of hypothetical spatial closures or TEDs differs depending on the metric used to define "benefit", and further depends on factors such as the spatial and temporal design of the closure, the magnitude and distribution of effort displacement, the spatial distribution of observed loggerhead life stages, and the assumed survival rate of animals passing through TEDs.

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1. Introduction

Managing incidental catch of loggerhead (*Caretta caretta*) turtles in trawl gear has been recommended as one of the top priorities for conservation of loggerhead populations worldwide (Wallace et al., 2008). As long-lived, late-maturing species, loggerheads are susceptible to population-level impacts of fisheries interactions (Heppell et al., 2005). Roughly 350 interactions between loggerheads and bottom trawl gear were estimated to occur each year from 2005 to 2008 in the U.S. Mid-Atlantic (Warden, 2011), encompassing a triangular area west of 71°W south and north of 35°N (Fig. 1). Loggerhead interactions also occur in several other types of fishing gears, with highest risk typically in warm waters off North Carolina and Virginia (Murray and Orphanides, 2013). Different types of conservation measures have been implemented in this region for commercial fisheries, including turtle excluder device (TED) requirements and time/area restrictions. For instance, TEDs are required on summer flounder trawlers in certain times and areas in the summer flounder- sea-turtle protection area between Cape Charles, Virginia and the North Carolina/South Carolina border (Fig. 1, U.S. Department of Commerce, 1996). In addition, federal waters in this region are closed seasonally to large-mesh gillnets to reduce the potential for sea turtle interactions (U.S. Department of Commerce, 2002).

The Northwest Atlantic distinct population segment (DPS) of loggerhead turtles is protected under the U.S. Endangered Species Act (ESA), which prohibits the "taking" of species. An "interaction" between loggerheads and commercial gear is synonymous with an ESA take, defined as "to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct". Interactions can be categorized as "observable" or "unobservable", where "observable" interactions include animals that are

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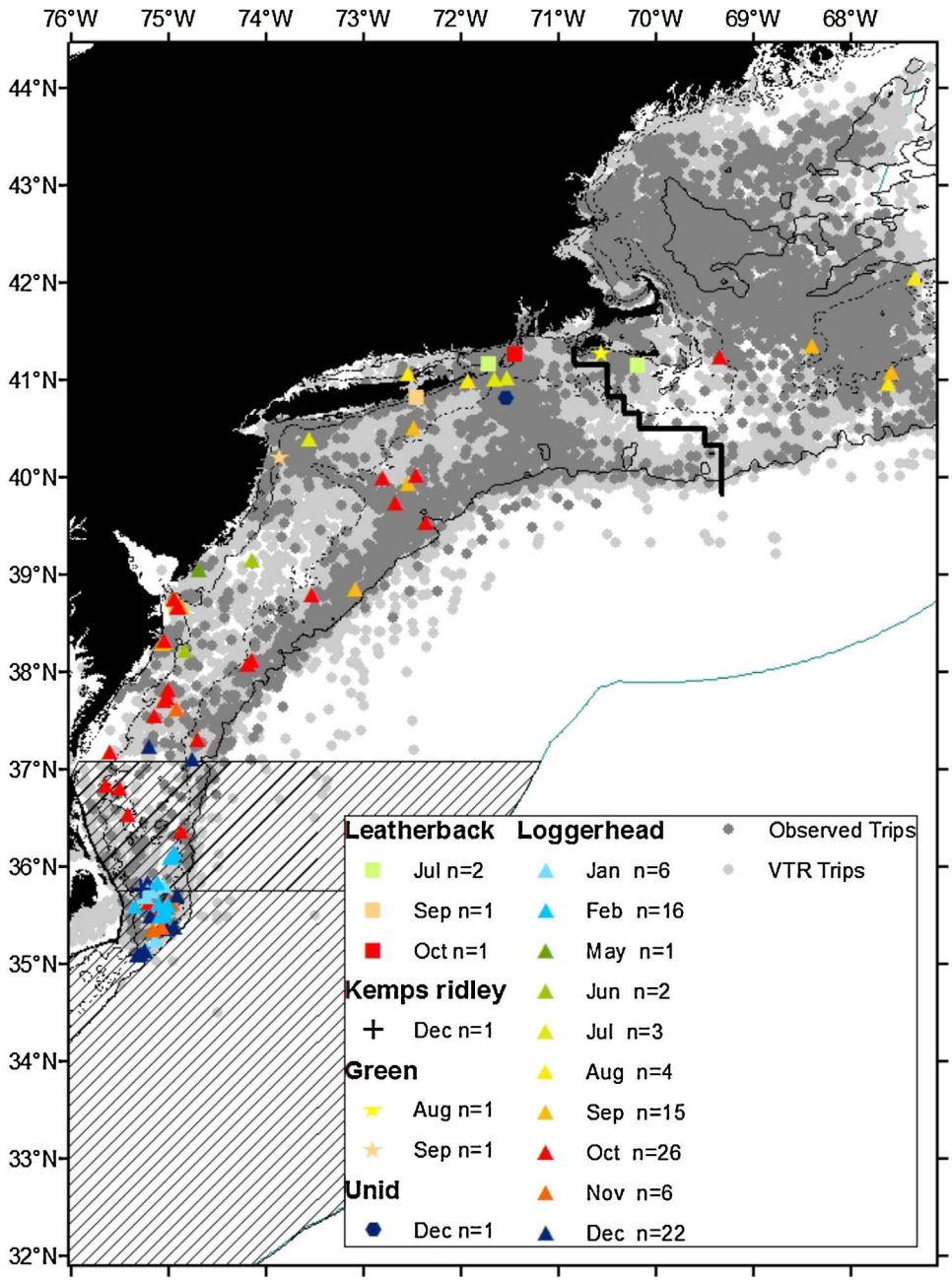

Fig. 1. Observed turtle interactions, observed trips, and commercial trips in U.S. bottom trawl gear from 2009 to 2013 in the Northeast and Mid-Atlantic regions. The "Mid-Atlantic" study region of this analysis includes the area south of the black line westward to the coastline. The hatched lines depict the summer flounder sea-turtle protection area. The 20 m, 50 m, and 200 m bathymetry lines are shown, as well as the U.S. Exclusive Economic Zone (EEZ).

brought onboard the fishing vessel by the gear or that interact with the gear at the surface, and unobservable interactions include animals that interact with the gear exclusively subsurface or away from view (Warden and Murray, 2011). A portion of the unobservable interactions can be quantified, for instance by inference from observed interaction rates in modified gear or from exclusion rates in experimental trials (Murray, 2011; Warden, 2011).

Impacts of fisheries interactions on a population will vary depending on both the location and the magnitude of the threat. Sea turtles utilize different habitats depending on age, so the impacts of fishing activity on a population may be different depending on where the fishing takes place and the age of turtles affected (Warden et al., 2014). Adult loggerheads of the Northwest Atlantic DPS nest mainly on Florida beaches (TEWG, 2009), though both immature and adult turtles migrate north to Mid-Atlantic waters in summer months to forage (Mansfield et al., 2009; Hawkes et al., 2011; Smolowitz et al., 2015). Fisheries observers have documented a higher frequency of immature turtles than adults interacting with Mid-Atlantic commercial fishing gear (Murray, 2009, 2011). Because the age and corresponding size distribution of turtles varies in the Mid-Atlantic, the location and magnitude of fishing activity becomes particularly relevant when evaluating impacts and conservation measures (Warden et al., 2014).

Estimating "adult equivalent" (AE) interactions based on the reproductive values (RVs) of individual turtles can help provide a common currency when comparing threats to a population and the conservation benefit of different management alternatives (Haas, 2010). RVs represent the contribution of individuals within an age-class to current and future reproduction, taking into account age-structured survival rates and current and future fecundity. RVs

are scaled such that they are near 0 for the youngest turtles and reach their maximum value of 1 at sexual maturity (Wallace et al., 2008). Translating RVs to adult equivalent interactions allows one to better assess impacts to a population because they reflect differential effects of removing animals in different life stages (Haas, 2010). Compared to some other gear types worldwide, trawl gears have higher adult equivalent interactions, and therefore a greater impact on loggerhead populations, due to the co-occurrence of trawling effort with larger, more mature turtles (Wallace et al., 2008).

Management options to reduce incidental captures of long-lived species such as turtles include temporary time-area closures or marine reserves, incidental catch (bycatch) limits, and technological or operational changes, among others (Hall et al., 2000). The outcome of each strategy will depend on the species-fishery interaction, fishery characteristics, and socioeconomic context (Senko et al., 2013). Technological changes such as TEDs have the benefit of not displacing effort and may be more popular with fishers depending on how they are developed and implemented. For instance, when fishers are empowered to help develop bycatch reduction technologies and to communicate with scientists about its performance, bycatch reduction may be achieved from better technology and compliance (Campbell and Cornwell, 2008; Senko et al., 2014). On the other hand, time-area closures, if well designed, may be more effective for clustered or multi-species bycatch events, particularly if catch loss from the closure is not high (Hall et al., 2000; Game et al., 2009).

The purpose of this paper is: (1) to estimate the magnitude and distribution of loggerhead interactions, mortalities, and adult equivalent interactions and mortalities, in U.S. Mid-Atlantic bottom trawl gear from 2009 to 2013; and (2) given these results, to evaluate the potential conservation benefit of hypothetical spatial closures and TED requirements in times and areas of high estimated interactions. Results of this analysis emphasize times, areas, and fisheries with elevated turtle interactions, and demonstrate changes in interactions under simulated mitigation scenarios assuming particular patterns of fishing effort displacement and turtle survival rates in TEDs.

2. Methods

2.1. Study region

The northern extent of the study region was defined by the boundaries of the Mid-Atlantic Ecological Production Unit (EPU), characterized by distinct patterns in oceanographic properties, fish distributions, and primary production (Ecosystems Assessment Report, 2012). The study region extended eastward from the continental coastline (not including Bays and internal North Carolina waters) to the Exclusive Economic Zone (EEZ) and southward to the southern extent of Northeast Fisheries Observer Program (NEFOP) data collection (Fig. 1).

2.2. Characteristics of Mid-Atlantic bottom trawl fisheries

Bottom trawl fisheries in the Mid-Atlantic catch a variety of species regulated under federal or interstate Fishery Management Plans (FMPs), using various mesh sizes, gear sizes, and net configurations (Orphanides and Magnusson, 2007). Fish or invertebrates landed in greatest quantity in Mid-Atlantic trawl gear from 2009 to 2013 were squid (*Doryteuthis pealeii* and *Illex illecebrosus*), skate (*Leucoraja and Raja species*), sea scallop (*Placopecten magellanicus*), and summer flounder (*Paralichthys dentatus*). Trawls typically used codend mesh sizes averaging 12.7 cm or less, with tows lasting about 2 h, and covering 13 km per tow, though these characteristics varied depending on specific FMP regulations and fishing practices.

The Mid-Atlantic trawl fisheries use different net types to target catch, one of which is termed a "flynet". Fisheries observers have documented sea turtle interactions in flynet gear (Murray, 2006) and experimental trials have been conducted to test bycatch reduction devices in the nets (Gearhart, 2010). Flynets are used to catch croaker (*Micropogonias undulatus*), summer flounder, longfin squid (*Loligo pealeii*), and black sea bass (*Centropristis striata*), among other species. Although there is no standard definition of a flynet, they have been described typically as two-seam fish trawls constructed of graduated mesh sizes beginning with large 40.6-, 81.3-, or 162.6 cm stretched mesh in the wings and mouth of the trawl following a slow 3:1 taper to smaller mesh sizes in the body, extension, and codend sections of the net (Gearhart, 2010). Flynets often use a large number of floats to maximize the height of the trawl opening, to facilitate the catch of more fish that might be higher in the water column or maintain height with large amounts of catch in the trawl.

2.3. Data sources

2.3.1. Observer data

From 2009 to 2013, Northeast fisheries observers (NEFOP) and at-sea monitors (ASM) sampled a total of 101,054 bottom trawl hauls (11,211 trips), of which 26,474 hauls (4100 trips) were located in the Mid-Atlantic and used in this analysis (Table 1). The at-sea monitor portion of the Mid-Atlantic data comprised 15% of hauls. At-sea monitors are deployed on vessels that have been issued a limited access Northeast multispecies permit fishing under Northeast multispecies days-at-sea (DAS) (including monkfish [*Lophius americanus*], skate, and spiny dogfish [*Squalus acanthias*] trips that used a groundfish DAS). At-sea monitors collect data on catch, area fished, and protected species interactions. However, at-sea monitors collect less information than NEFOP observers do on fishing activity (such as depth and sea surface temperature (SST) at the fishing location), and do not collect biological samples from protected species.

Roughly 7% of observed tows used flynets, which caught a disproportionate number of turtles. To examine how characteristics of flynets might affect observable interaction rates, two-sample student's *t*-tests were performed to test the hypotheses that the mean number of floats and mean fishing circle mesh size on flynets catching or not catching turtles was equal.

2.3.2. Commercial fishing data

Mandatory Vessel Trip Reports (VTRs) completed by commercial trawl fishermen during 2009–2013 provided a measure of total fishing effort. Effort was expressed as the amount of fishing time in units of 24 h periods (days fished), computed as:

$$\frac{\text{Average tow time[h]per haul} \times \text{number of hauls}}{24} \quad (1)$$

Because some fisheries or gear types may not be represented in VTR data (Murray, 2009), a comparison of trawl landings between dealer landing reports (which are considered more comprehensive but do not contain the information necessary to model interaction rates) and VTRs was conducted between 2009 and 2013 in the southern New England and Mid-Atlantic regions. This comparison revealed that the amount of dealer landings missing from the VTR tables was <4% annually, which was deemed to have a negligible impact on the analysis, so VTR effort was not adjusted upwards as has been done in other analyses of turtle interactions in U.S. Mid-Atlantic fisheries (Murray, 2009). Thus, commercial data were considered to be representative of overall fishing effort, though estimates of total interactions might be slightly underestimated.

Table 1
Observer and commercial effort in Mid-Atlantic bottom trawl fisheries, 2009–2013.

	Obs hauls	Obs Trips	Obs days fished	Obs Cc[a]	Obs non-Cc	VTR trips	VTR days fished	% Coverage (days fished)
2009	3,900	638	361	41	1 Lk; 1Cm; 1 Dc	16,423	5,983	6%
2010	4,907	852	478	4	1 Dc	15,718	5,665	8%
2011	6,961	917	710	14	1 Dc; 1 Unk	15,947	6,535	11%
2012	4,875	692	528	26	1Cm	14,724	6,944	8%
2013	5,831	1001	565	16	1 Dc	14,778	6,513	9%
Total	26,474	4100	2,642	101	9	77,590	31,640	8%

VTR = Vessel Trip Report; Cc = Loggerhead turtle (*Caretta caretta*); Cm = Green turtle (*Chelonia mydas*); Dc = Leatherback turtle (*Dermochelys coriacea*); Lk = Kemp's ridley turtle (*Lepidochelys kempii*); Unk = unidentified hard-shelled turtle.

[a] Includes 6 unidentified hard-shelled turtles assumed to be loggerheads.

In addition to effort, VTR reports contain information on the average depth and location fished, mesh size of the gear, and kept and discarded catch, but do not contain information about different net types fished or use of TEDs.

2.3.3. Environmental data

Sea surface temperature data were obtained for all VTR trawl trips from AVHRR Pathfinder and MODIS Aqua and Terra satellite data. Median SST data from daily images were used over a 6 km size grid when available (58%), otherwise SST from progressively larger temporal (3-day, 5-day, 9-day, and monthly) and spatial scales (between 6 km and 500 km) were used. A separate analysis conducted with these data indicated that the different temporal and spatial scales used to acquire SST data had negligible changes on estimated interactions when interaction rates were modeled as a function of SST. Similar data were obtained for observed hauls for which SST data were missing (22%). Due to a few evident biases in satellite-derived SST south of 36°N (some satellite values differed from observer-recorded values by as much as 15 °C), SST values on VTR trips fishing south of 36°N ($n = 246$) were replaced with SST predicted from NEFOP-observed values based on area and month ($n = 516$ obs, $R^2 = 0.70$) (Warden, 2011). Similar corrections were not made for the observer data because no satellite sources were used for SST south of 36°N.

2.4. Logger interaction rate model

The observable loggerhead interaction rate (R) on each haul was defined as:

$$R = \frac{\text{Number of observed turtles}}{\text{Days fished}} \tag{2}$$

where days fished is the amount of time trawl nets are fishing in 24 h units.

A Generalized Additive Model (GAM) with a Poisson distribution (GAM function, SPLUS 7.0) was used to model the expected loggerhead interaction rate, described as:

$$\text{Log}(\text{E}[y_j]) = \log(\text{daysfished}_j) + \alpha + \sum_{i=1}^{n} f_i(x_{i,j}) + \xi \tag{3}$$

where y_j = the number of loggerhead turtles observed on the jth haul, log(days fished$_j$) is an offset term for the unit of effort on the jth haul, α = a constant intercept term, f_i = a series of smoothing splines for each predictor variable, x_{ij} = environmental or gear characteristics at the beginning of each haul, ξ = unexplained error.

Candidate variables tested in the model included SST, latitude and depth based on previous associations with loggerhead interaction rates (Murray, 2009; Warden, 2011) and because those variables capture the spatial and temporal variation in loggerhead distributions during the turtles' seasonal migrations (Mansfield et al., 2009; Hawkes et al., 2011) (Table 2). The source of data (ASM vs. NEFOP) was included as a variable to be tested because these two sampling platforms differ with respect to the fisheries and areas sampled. Other variables tested included salinity (Murray and Orphanides, 2013), chlorophyll (McCarthy et al., 2010), codend mesh size (to account for differences in trawl nets), and a "retained catch" categorical variable that described the largest amount of landed fish catch (by weight) on the haul. The "retained catch" variable served as a proxy for different methods of fishing by trawl gear as well as configuration of the gear, which are not always captured by VTR logs. To minimize the number of estimated parameters, values of "retained catch" were grouped into six categories based on species for which trawlers used specialized nets or required TEDs, or for which conservation actions are or were being considered (U.S. Department of Commerce, 2007) (Table 2). Year was tested as a secondary variable to see if it explained significantly more variation (>5% deviance) in the model than what was already explained by the primary candidate variables (Warden, 2011). Models were evaluated with respect to changes in AIC (Burnham and Anderson, 2002), percent deviance explained, and the dispersion parameter (Φ) defined as:

$$\Phi = \frac{\sum (y_i - \hat{\mu}_i)^2 / \hat{\mu}_i}{\text{residualdf}} \tag{4}$$

A combination of criteria was used to select the final model. First, a "preferred" model was selected based on the AIC value (the model with either the lowest AIC or one which differed from the lowest AIC model [delta AIC] by <2 [Burnham and Anderson, 2002]) and a dispersion parameter close to 1, which would indicate no overdispersion (Burnham and Anderson, 2002). However, because AIC evaluations tend to favor complex models for large datasets (Maunder and Punt, 2004), the number of parameters in the preferred model was reduced to a maximum of 12 by limiting the amount of smoothing in the model, to conform to a rule of thumb that there be at least 10 observations of the rarest event per parameter (Peduzzi et al., 1996; Harrell, 2001). The default degree of smoothing in the GAM splines ($k = 4$) was reduced in the preferred model to compare 10-, 11-, and 12- parameter models. Among these comparisons, the "final" model had close to the lowest AIC and a dispersion factor close to 1. The final GAM spline curves were compared to the preferred GAM spline curves to visually confirm that the reduction in smoothing did not differ substantially from the curves in the preferred model.

2.4.1. Excluder devices

Hauls that used TEDs were excluded from the analysis (0.7%) because they are designed to have different catch rates of turtles and there were no observed turtles on hauls with TEDs to allow for estimation of an observable interaction rate. Therefore, the interaction model estimated only the observable, non-TED interaction rate. It is not required that fishers report use of a TED on VTR logbooks, so VTR trips were assumed to be using a TED if they were operating within the times and areas of the sea-turtle summer flounder protection area during seasons when TEDs are required,

Table 2
Candidate variables for interaction rate model development. The 'Other' retained catch category encompasses all other catch species.

Variable	categorical values	(%) of observed hauls	(%) of VTR trips
Retained catch			
	Croaker	2	1
	Summer flounder	26	26
	Scallop	2	9
	Skates	11	11
	Longfin squid	24	16
	Other	35	37

		Observed range (mode)	VTR range (mode)
SST	N/A	0.2–31.9 (10.0)	0.01–28.4 (13.4)
Latitude (°N)	N/A	35–41.7 (41.0)	35–41.5 (41.0)
Depth (m)	N/A	4 –560 (18)	2–2700 (18)
Sampling source			
	ASM	15	N/A
	NEFOP	85	N/A
Salinity (ppt)		28.2–36.6 (32.0)	N/A
Chlorophyll (mg/m^3)		0.08–32.1 (3.6)	N/A
Codend mesh size (cm)		0.5–11.9 (2.0)	0.5–18.0 (6.5)

and landed more than 45 kg (100 lbs) of summer flounder (U.S. Department of Commerce, 1996).

2.5. Total estimated interactions/mortality

The final model was applied to VTR trawl trips to predict an estimated number of loggerhead interactions on each VTR trip. On VTR trips equipped with TEDs (0.4%), predicted interactions were proportioned into observable and unobservable/quantifiable interactions. Observable interactions were 3% of the predicted interactions, and unobservable/quantifiable interactions were 97% of the predicted interactions, based on a 97% experimental TED exclusion rate (Watson, 1981). The total annual estimated interactions (observable and unobservable) were the sum of the predicted number of turtle interactions over all trips in a year.

Immediate and observable mortalities were estimated by applying the mortality rate (49%) for turtles observed in trawl gear interactions from 2009 to 2013 (Upite et al., 2013; updated with data through 2013) to the total estimated observable interactions. The mortality rate for unobservable yet quantifiable interactions was assumed to be 0%. This assumption is consistent with that used in ESA assessments of U.S shrimp trawl fisheries (NMFS, 2014), most of which are also required to use TEDs.

Bootstrap resampling was used to derive CVs and CIs around total model-estimated interactions. Bootstrap replicates were generated by resampling hauls with replacement 1000 times from the original observer dataset, and then computing total interactions by applying each replicate to VTR data. The 95% CI for total estimated interactions was computed from the upper 97.5% and lower 2.5% quartiles of the bootstrap replicates.

2.6. Adult equivalency

To estimate adult equivalent interactions, each observed take with a curved carapace measurement was assigned an RV value based on slow-growth high fecundity RVs in Wallace (2008). The estimated interaction on each VTR trip was then multiplied by the average RV for the trip's latitude zone (<=37°N: RV=0.13; >37°N and <39°N: RV = 0.29; >=39°N: RV = 0.06) to compute an adult equivalent interaction; AEs were then summed over all trips to report total adult equivalent interactions. To compute adult equivalent mortality, a 49% mortality rate was applied to the observable adult equivalent interactions each year (assumed to be the same as the proportion of total observable interactions each year), and a 0% mortality rate was assumed for unobservable yet quantifiable adult equivalent interactions. The method used to compute AE in this analysis followed that used in Warden (2011) rather than in Murray (2011). While the two methods yielded similar results, methods used in Warden (2011) are spatially explicit whereas methods in Murray (2011) are not and it was preferable to report adult equivalency by area in this analysis.

2.7. Total estimated interactions prorated by landed catch

In U.S. federal fisheries, conservation regulations for turtles are promulgated under the Magnuson–Stevens Fishery Conservation and Management Act (MSFCMA) via changes to FMPs, and also under the ESA. To aid in management evaluations of federal actions for specific fisheries, total estimated interactions were subsequently prorated to specific fisheries. When multiple species were landed, the estimated loggerhead interactions per trip were prorated to a managed fish species based on the proportion (by weight) of the species reported landed on the trip (Murray, 2013). Total loggerhead interactions for managed fish species j on trip i (T_{ji}) were calculated by multiplying the total loggerhead interactions on trip i (T_i) by the proportion of reported landings of species j caught on trip i:

$$T_{ji} = \frac{T_i \times L_{ji}}{L_i} \tag{5}$$

where L_{ji} is the amount of tons landed of species j on trip i, and L_i is the total amount of tons landed on trip i of all species. Total estimated loggerhead interactions for species *j* over all trawl trips (N) from 2009–2013 was then:

$$T_j = \sum_{i=1}^{N} T_{ji} \tag{6}$$

2.8. Hypothetical conservation scenarios

Five hypothetical mitigation strategies were evaluated with regards to estimated interactions, estimated mortality, adult equivalent interactions, and adult equivalent mortalities that would result from each strategy, as compared to the number of interactions and mortalities under current (status quo) fishery conditions. These scenarios are listed as Scenario A–E in Table 1. Strategies included either time/area restrictions or TED requirements. The time/area scenarios were based on times and areas of highest

estimated interactions (this analysis). TED scenarios were based on historic considerations for TED use in the Mid-Atlantic (U.S. Department of Commerce, 2007), or spatial and temporal alignment with turtle conservation measures in the large mesh gillnet restrictions in the southern Mid-Atlantic (U.S. Department of Commerce, 2002). TED scenarios considered different possibilities for "summer flounder trawlers", defined as any vessel with one or more trawl nets that was capable of, or used for, fishing for flounder or whose on-board or landed catch of flounder was more than 45 kg (100 lbs) (Code of Federal Regulations, 2012). The gillnet restriction scenarios were seasonally-restricted areas extending from roughly 34° to 38°N, designed around the presence of loggerheads in the region.

To estimate changes in interactions for each time/area closure scenario, VTR effort that was in the restricted area was removed from the dataset and "displaced" to another time and area. The displaced effort was randomly assigned environmental and catch characteristics from trips operating in the new time and area, over 1000 resampling (with replacement) events. In other words, the amount of days fished would displace to another area (or time), and the depth, SST, and main catch, for example, would be characteristic of trips operating in the alternative area. The final GAM model was then applied to the simulated VTR data to estimate changes in estimated interactions compared to status quo conditions. The mean number of interactions was reported over the 1000 simulations.

For the TED scenarios, VTR trips were assigned TED use based on each scenario, and then observable and unobservable yet quantifiable interactions were estimated in the same way as described for this analysis (the observable interactions were adjusted to be 3% of the model-predicted interactions). A 49% mortality rate was applied to observable interactions, and a 0% mortality rate was assumed for unobservable yet quantifiable interactions.

3. Results

3.1. Characteristics of observed turtle interactions

From 2009–2013, NEFOP and ASM observers documented 95 loggerhead turtle interactions in bottom trawl gear, 90 of which occurred in the Mid-Atlantic (Fig. 1). Five turtle interactions were observed northeast of the Mid-Atlantic (Southern New England and Georges Bank) and were excluded from the analysis because there were not enough interactions to develop a robust estimate of interactions in this area, which differs ecologically from the Mid-Atlantic (Ecosystem Assessment Report, 2012). There were 7 turtles in the Mid-Atlantic that could not be identified to species; 6 of these were assumed to be loggerheads (and pooled with the positively identified loggerheads for the model) based on characteristics described by observers and the fact that they were caught on trips during which other positively-identified loggerheads were caught. One loggerhead was removed from the dataset used to compute interaction rates because it was uncertain whether the interaction occurred in trawl gear (according to observers, "it came out of the net with gillnet tightly wrapped around its head and neck".) NEFOP and ASM observers also recorded 2 green turtles, 1 Kemp's ridley turtle, 4 leatherback turtles, and 1 unidentified turtle in trawl gear from 2009 to 2013 (Fig. 1). Moderately and severely decomposed animals ($n = 5$) were removed from the analysis because the state of decomposition suggested they died prior to interacting with the gear.

More than half of observed loggerheads ($n = 61$) were captured in trawl nets described by observers as "flynets". Flynets interacting with turtles were mainly catching croaker (72% of observed loggerheads in flynet gear), but some also caught mainly longfin squid or summer flounder. Flynets caught 2–4 turtles on a single haul on 9 occasions, while other net types typically caught 1 turtle per haul. Mean mesh size in the fishing circle and the mean number of floats in flynets that caught turtles were significantly greater than the mean sizes and number of those that did not catch turtles (Table 3).

The sizes of loggerheads (curved carapace length, measured from the nuchal notch to the carapace tip) in trawl gear ranged from 49 to 103.1 cm ($n = 88$, mean = 76.8 cm). Loggerheads were captured at depths ranging from 13 to 121 m (mean = 40 m) in waters ranging from 8.7 to 25 °C (mean = 16.8 °C).

3.2. Loggerhead interaction rate model

Variables which best explained loggerhead interaction rates in bottom trawl gear were kept catch, depth, latitude, and sea surface temperature. The model with these variables had close to the lowest AIC, was not overdispersed, and explained almost half the variance in the data (Table 4). However, the model was slightly overparameterized using the default smoother splines ($k = 4$), so different levels of smoothing were evaluated (with respect to AIC and dispersion parameters) to limit the model to 12 parameters. The final model maintained these same preferred variables, albeit with a less "curvy" fit to the data, and described 42% of the variation in interaction rates (Fig. 2, Table 4).

3.3. Total Estimated Interactions / Adult Equivalents

From 2009–2013, a total of 1156 (CV = 0.13, 95% CI = 908–1488) loggerheads were estimated to have interacted with bottom trawl gear in the U.S. Mid-Atlantic (Table 5). Of these, 977 were observable and 179 were unobservable interactions. An estimated 479 loggerhead mortalities occurred as a result of interacting with trawl gear. The total number of estimated interactions was equivalent to 166 adults, of which 68 resulted in mortality. Interactions were highest in the southern Mid-Atlantic, and occurred on trips catching croaker from November to mid-April, in waters <=50 m deep and <=37°N (Fig. 3, Appendix A).

3.4. Conservation Scenarios

Based on this analysis, greatest reductions in estimated mortality and adult equivalent mortality would result from implementing TED requirements for all fishers in areas that are aligned with the large mesh gillnet restricted time and area boundaries (Table 6). Implementing TED requirements, however, would not reduce estimated interactions; it would reduce mortality and also influence the proportion of interactions that were observable. Restricting fishing effort south of 37°N would yield the greatest reduction in estimated interactions compared to status quo conditions, if it is assumed that effort displaces northward to 39°N.

4. Discussion

Persistent areas of high estimated loggerhead interactions in U.S. Mid-Atlantic bottom trawl fisheries occur south of 37°N in warm, shallow waters (per this analysis; Warden, 2011). The overall magnitude of estimated loggerhead interactions in trawl gear from 2009 to 2013 was similar to that from 2005 to 2008 (Warden, 2011); however, the distribution of estimated interactions throughout the Mid-Atlantic was different. Interactions were higher south of 37°N in this analysis despite similar amounts of commercial effort compared to 2005–2008 because the model accounted for differences in interaction rates by different fisheries. The "retained catch" variable (which served as a proxy for different methods of fishing) explained almost 30% of the model deviance, and the fisheries with high interaction rates operated mainly south of 37°N.

Table 3
Students *t*-test to test for differences in gear characteristics on flynet hauls catching one or more turtles (Turtle captured = 1) or not catching (Turtle captured = 0) turtles.

Gear characteristic	Turtle captured	N	Mean	S.D	*t*	df	P>|t|	Equality of variance assumed
Number of floats	0	2020	49.4	20.4	−2.25	2064	0.025	Y
	1	46	56.2	19.7				
Mesh size of fishing circle	0	1432	20.4	22.9	−2.66	1471	0.008	Y
	1	41	30.0	19.6				

Table 4
Loggerhead (Cc) interaction rate model development. AIC = Akaike's Information Criterion; delta AIC = the difference between the lowest AIC model and the model tested; k = number of parameters; c = dispersion parameter. The preferred model (in gray) was over-parameterized, so the degree of smoothing was reduced for the final model (in bold). The comparison of models with a reduced number of parameters is not shown.

Model form	AIC	Delta AIC	k	Cumulative % deviance explained	*c*
Cc ~ Retained catch + offset(log(days fished))	864.3	198.8	6	28	1.7
Cc ~ Retained catch + s(depth) + offset(log(days fished))	784.0	118.5	10	35	1.9
Cc ~ Retained catch + s(depth) + s(latitude) + offset(log(days fished))	705.2	39.7	14	42	1.3
Cc ~ Retained catch + s(depth) + s(latitude) + s(SST) + offset(log(days fished))	666.5	1.0	18	46	0.8
Cc ~ Retained catch + s(depth) + s(latitude) + s(SST) + (NEFOP/ASM source) + offset(log(days fished))	665.5	0.0	19	47	0.8
Cc ~ Retained catch + s(depth) + s(latitude) + s(SST) + s(mesh) + offset(log(days fished))	667.2	1.7	22	47	0.9
Cc ~ Retained catch + s(depth) + s(latitude) + s(SST) + s(salinity) + offset(log(days fished))	666.4	0.9	22	47	0.8
Cc ~ Retained catch + s(depth) + s(latitude) + s(SST) + (chlorophyll) + offset(log(days fished))	665.9	0.4	22	47	0.8
Secondary variable:					
Cc ~ Retained catch + s(depth) + s(latitude) + s(SST) + s(year) + offset(log(days fished))	643.4	−22.1	22	49	0.8
Preferred model with # parameters reduced:					
Cc ~ Retainedcatch + s(depth,3) + (latitude) + s(SST,2) + offset(log(days fished))	704.2	38.7	12	42	0.9

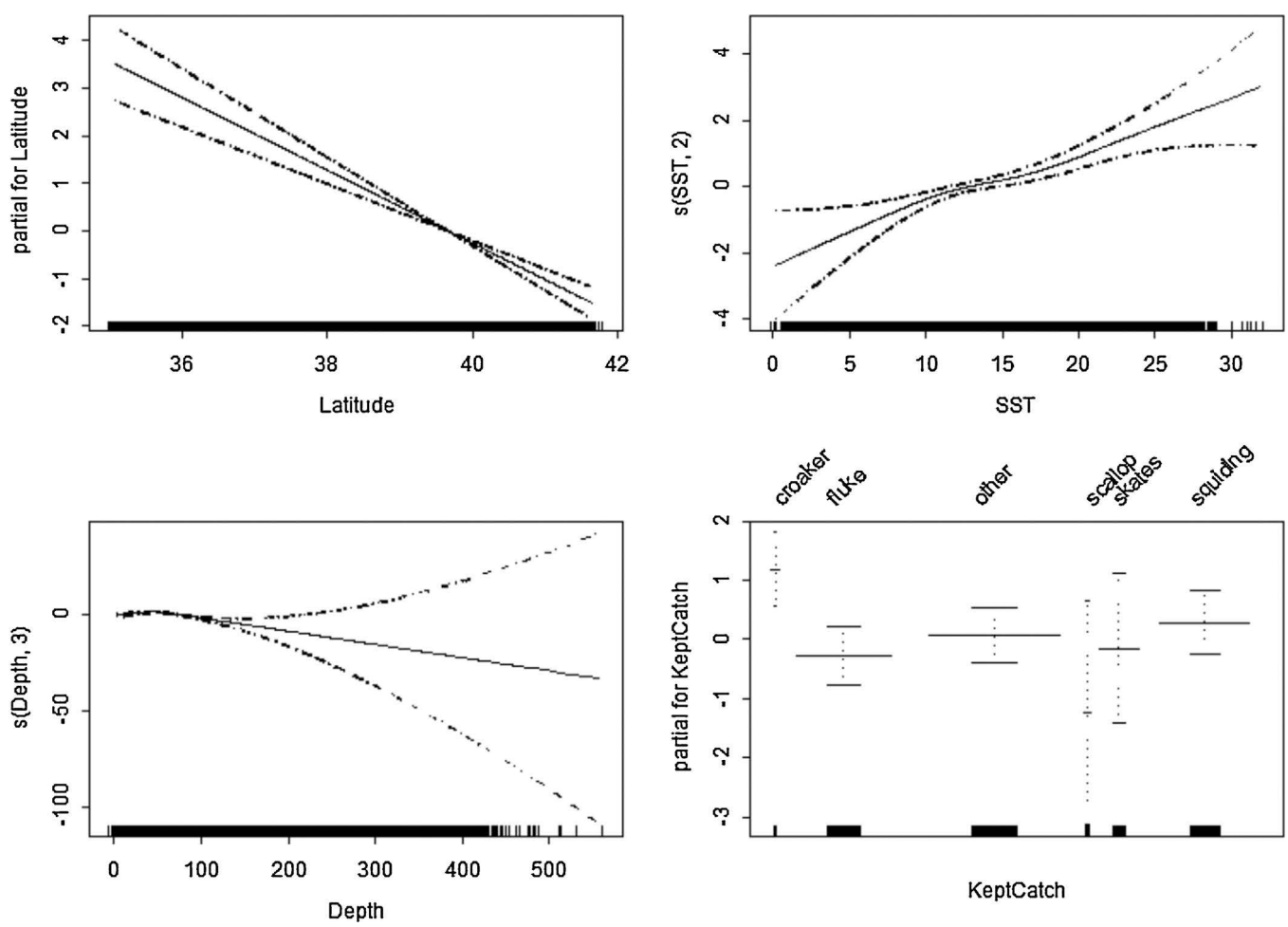

Fig. 2. GAM curves depicting the effect of each covariate on estimated loggerhead interaction rates. Rugplot on x-axis shows number of observations; dashed lines are +/− 2 SE confidence bands. Positive values on the y-axis reflect higher expected interaction rates.

Table 5
Estimated loggerhead interactions in Mid-Atlantic bottom trawl gear, 2009–2013. Numbers in parentheses represent the portion of estimated interactions that are observable (O), and unobservable yet quantifiable (UQ).

	Estimated interactions (O/UQ)	Estimated mortalities	Adult equivalent interactions	Adult equivalent mortalities
2009	391 (306/85)	150	57	22
2010	244 (204/40)	100	37	15
2011	159 (129/30)	63	25	10
2012	183 (161/22)	79	24	10
2013	179 (177/2)	88	23	11
Total	1156 (977/179)	479	166	68
Mean	231	96	33	14
CV (all years)	0.13			
CI (all years)	908–1488			

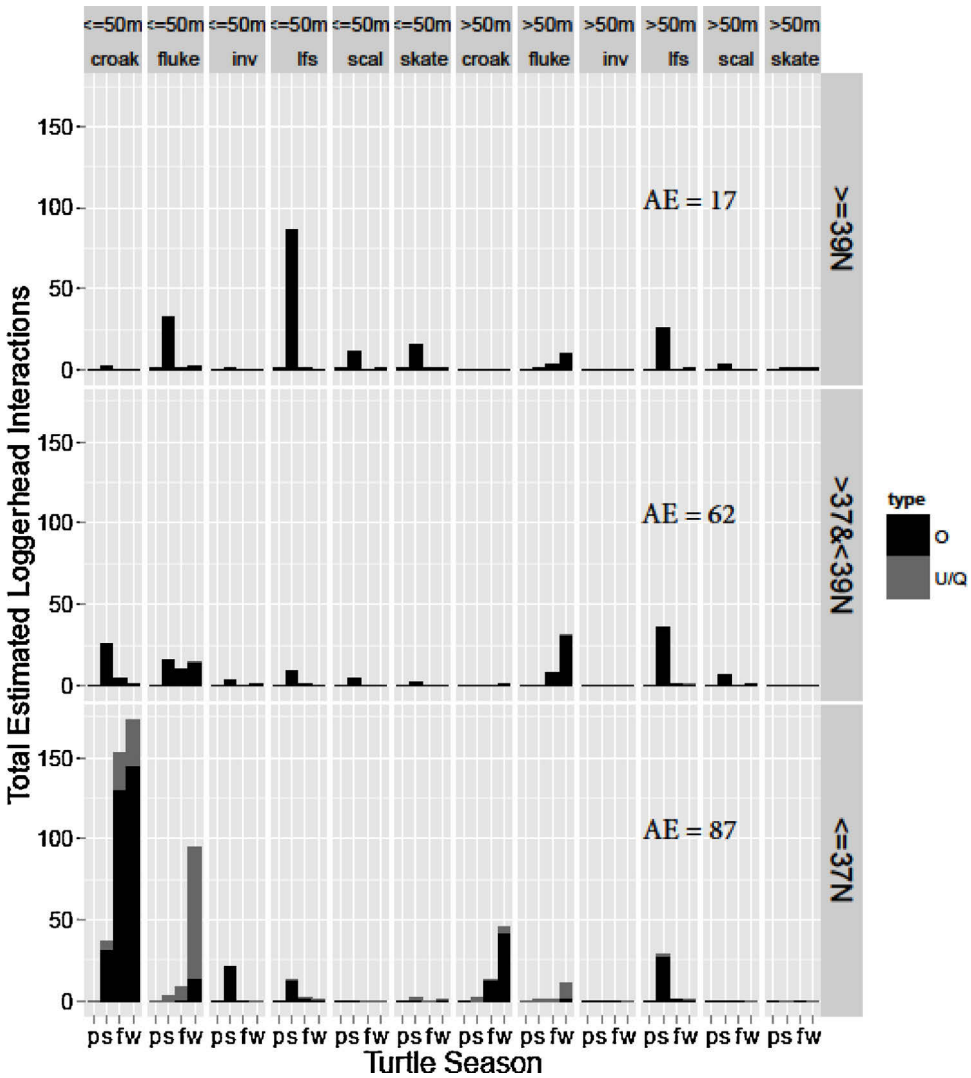

Fig. 3. Estimated loggerhead interactions from 2009 to 2013 in Mid-Atlantic bottom trawl gear by depth zone, latitude zone, and season, prorated by landed catch. Catch species represented comprise 90% of estimated interactions; refer to Appendix for all other managed species with estimated interactions. Seasons are based on SST patterns and loggerhead occurrence (Warden 2011) (p): 16 April–15 May; (s): 16 May–31 October; (f): 1–30 November; (w): 1 December–15 April. AE = Total Adult Equivalent Interactions in that latitude zone. O = Observable; U/Q = Unobservable/quantifiable interactions. Croak = croaker; fluke = summer flounder; inv = invertebrates; lfs = longfin squid; scal = scallops.

Results of this analysis suggest that in warm, shallow waters of the southern Mid-Atlantic, some fisheries have relatively higher levels of interactions based on how gear is configured and fished. Increased probability for turtle interactions in commercial trawl fisheries in the Mid-Atlantic may be a result of both operational fishing factors and the co-occurrence of fishing effort and turtles, and not just simply the latter. For instance, high interactions in the croaker flynet fishery may be a combination of the gear design (large net capacity and method of fishing), operating in times and areas with large concentrations of turtles (Mansfield et al., 2009; Hawkes et al., 2011) and large croaker schools (Gearhart, 2010). The enlarged mouth of the net, designed to accommodate large catch volumes of croaker (Gearhart, 2010), may be more conducive to catching congregations of turtles. Further, flynets that open higher

Table 6
Changes in average annual estimated loggerhead interactions and mortalities under different hypothetical mitigation strategies. Numbers in parentheses represent estimated observable interactions. AE=Adult Equivalent

			Average annual estimated interactions	(%) Change from status quo	Average annual estimated mortality	(%) Change from status quo	Average annual estimated AE interactions	% change from status quo	Average Annual Estimated AE Mortality	% change from status quo
Status quo		Current fishery conditions from 2009 to 2013	231 (195)	N/A	96	N/A	33	N/A	14	N/A
Spatial management approaches	Scenario ID									
Assumes no TED use	A	Restrict fishing south of 37°N year round - assume effort shifts north, between 37°N and 39°N	112	-51%	55	-43%	20	-39%	10	-29%
	B	Restrict fishing south of 37°N from 1 Nov to 15 April – assume effort shifts to Apr 16 – Oct 31 in same latitude zone	196	-15%	96	0%	28	-15%	14	0%
Conservation Engineering approaches										
	C	Expand TED line to 39°N from mid-April to Dec 1, for fishers catching >100 lb summer flounder	231 (184)	0%	90	−6%	33	0%	13	-7%
	D	Align TED lines with large mesh gillnet restricted area boundaries, and require TEDS on all trawl vessels	231 (87)	0%	43	−56%	33	0%	6	-57%
	E	Keep current boundaries, and require TEDS on all trawl vessels	231 (106)	0%	52	−46%	133	0%	7	-50%

and fish a larger portion of the water column, versus other bottom trawl nets, might influence turtle entrapment depending on how turtles behave in the water column. Several types of TEDs designed for flynets have been tested and show promise in reducing interactions while minimizing catch loss of croaker, though further testing is needed before a preferred design is certified and widely adopted by industry (Gearhart, 2010).

The hypothetical conservation strategies evaluated in this analysis suggest that mitigating turtle interactions with the use of TEDs would have a different conservation outcome compared to mitigating with spatial and temporal planning. The difference in terms of conservation benefit depends on the metric (either interactions or mortalities) used to define "benefit." For instance, time and area restrictions may reduce the number of estimated interactions more than TEDs because TEDs do not reduce the number of interactions, only those that are observable. TEDs, however, may provide a greater reduction in the number of mortalities depending on the survival rate of turtles passing through TEDs. Measuring conservation benefit in terms of adult equivalent mortalities, versus interactions, is the most informative metric for studying impacts on the population (Haas, 2010). Other measures of "benefit" could certainly be defined by economic scenarios, including more informed predictions of fishing effort displacement or estimates of changes in target catch with TEDs, but these were not examined for these hypothetical scenarios. This analysis assumed that fishers using TEDs fished in the times and areas allowed and did not displace elsewhere due to target catch loss. The objective here was not to provide predictions of conservation benefits for specific actual situations but rather to use hypothetical scenarios to explore the potential differences in benefits between types of mitigation approaches and how these may differ depending on the conservation metric.

Conservation benefit (as evaluated in this analysis) of mitigation strategies will depend on factors such as the spatial and temporal design of the strategy, the magnitude and distribution of effort and turtle interaction displacement, the spatial distribution of observed loggerhead life stages, and the assumed survival rate of animals passing through TEDs. For instance, a hypothetical elimination of effort south of 37°N would result in a 30% reduction in adult equivalent mortalities (scenario A), assuming all effort shifted north to 39°N. If effort displaced north of 39°N, estimated mortalities may have been lower due to lower estimated interaction rates in higher latitudes. A hypothetical expansion of TED requirements to include waters up to 39°N would result in no change in estimated interactions (scenario C), but more benefit may be gained if the requirement included waters up to 41°N (Haas, 2010). Largest reductions in estimated adult equivalent mortalities were likely to occur if TEDs were required for all fisheries (i.e., without a catch requirement, scenarios D and E), assuming a 100% survival rate of turtles passing through TEDs. If the actual survival rate were lower, the conservation benefit would be reduced.

Quantifying loggerhead "escape" mortality—that is, the mortality rate of organisms that actively escape from a gear prior to the catch being landed by the fishing operation (Broadhurst et al., 2006) – is important to understand the full measure of loss to a population from the fishing operation (Gilman et al., 2013). The survival rate of turtles escaping TEDs might be lower than the 100% assumed here due to factors such as stress or injury associated with the interaction, caused by factors such as extended lack of oxygen as animals seek to escape and/or collision with gear or other organisms in the net (Gilman et al., 2013).

Expressing interactions in terms of adult equivalents allows managers to compare different fishing activities under a "common currency" of expected reproductive output (Wallace et al., 2008). A larger number of adult equivalent interactions implies a greater impact on the population. Other types of fishing gear interact with loggerheads in the Mid-Atlantic, such as sink gillnets and scallop dredges. Assuming the distribution of observed loggerhead life stages and the magnitude of interactions are similar each year, annual estimated adult equivalent loggerhead interactions are almost two times higher in trawl gear (per this analysis) than in scallop dredge gear (Murray, 2011), and almost four times higher than in gillnet gear (Murray, 2013), due to a larger magnitude of total interactions and a higher proportion of larger turtles taken in the fishery. This information should be helpful in informing conservation priorities for mitigation efforts for loggerheads in the U.S. Mid-Atlantic region.

While the conservation scenarios explored in this analysis were merely hypothetical, the results highlight information needed to increase the efficacy of management measures designed to protect loggerheads in the Mid-Atlantic. If managers were aiming to reduce adult equivalent mortalities, the most informative metric for studying impacts to the population, then TEDs might be most effective, thought it would be important to work with the industry to design devices which minimize loss of target species as well as effective reduction of turtle capture, to gain buy-in from the industry and to increase compliance. It is also important to better understand survival rates of turtles passing through TEDs, because if survival is not 100% then the conservation benefit of TEDs would be overestimated. It might also simplify the regulatory environment for both managers and fishers if TED requirements were aligned with other conservation boundaries for turtles. In this sense "sea turtle protection areas" could be delineated by core turtle habitat use, while permitting fishing activity inside these areas with condition on using gears and fishing practices not detrimental to turtles.

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Appendix A.

Estimated loggerhead (Cc) interactions by managed fish species landed in Mid-atlantic bottom trawl gear 2009–2013. For species that were landed on trips that matched the definition of a summer flounder trawl and therefore required TEDs, the observable interactions are also shown (the difference being the estimated number of loggerheads that passed through TEDs at depth). CV = Coefficient of variation; CI = 95% confidence interval.

		Estimated Cc interactions					Average annual		
Managed species	Average VTR landings (t)	2009	2010	2011	2012	2013	Cc	CV	CI
Croaker	1,285	191	112	42	55	61	92	0.16	63–121
Obs only		160	101	28	48	61	80	0.16	64–127
Summer flounder	4,847	80	58	44	48	21	50	0.29	26–84
Obs only		29	34	32	33	20	29	0.29	25–85
Longfin squid	8,013	62	25	38	39	47	42	0.26	23–66
Obs only		61	23	37	39	47	41	0.26	23–64
Scallop	5,648	6	9	5	6	3	6	0.98	0–23
Invertebrates	205	7	2	1	1	16	5	0.59	7–71
Skate	5,710	6	5	5	6	5	5	0.50	1–11
Obs only		6	5	4	6	5	5	0.51	1–12
Scup	4,279	2	3	4	6	6	4	0.28	2–7
Bluefish	295	5	6	2	5	2	4	0.15	3–5
Obs only		5	3	2	5	2	3	0.15	3–5
Silver hake	2,852	3	5	3	5	4	4	0.30	2–6
Illex squid	13,333	2	3	2	3	2	2	0.39	1–5
Horse-shoe crab	110	2	2	1	1	3	2	0.47	1–4
Butterfish	462	2	2	1	2	2	2	0.18	1–2
Southern flounder	68	5	2	0	0	0	2	0.31	1–3
Spiny dogfish	652	1	1	2	1	1	1	0.27	1–2
Other	92	1	1	1	1	1	1	0.13	1–1
Black sea bass	304	1	1	1	1	2	1	0.20	1–2
Monkfish	617	1	1	1	1	1	1	0.16	1–1
Hake, unid	430	1	1	0	1	1	1	0.29	0–1
Striped bass	66	1	1	1	0	0	1	0.35	0–1
King Whiting	121	2	1	0	0	0	1	0.15	1–1
Atlantic Mackerel	1,878	0	0	0	0	1	0	0.29	0–1
Yellowtail flounder	225	0	0	0	1	1	0	0.29	0–1
Winter flounder	91	0	0	0	0	1	0	0.31	0–1
Weakfish	27	1	1	0	0	0	0	0.17	0–1
Smooth dogfish	107	5	2	1	1	2	2	0.13	2–3
Total	57,495	389	243	158	183	183	231	0.13	182–298
Obs only		304	203	129	160	181	195		

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