Magnitude and distribution of sea turtle bycatch in the sea scallop (*Placopecten magellanicus*) dredge fishery in two areas of the northwestern Atlantic Ocean, 2001–2002

Kimberly T. Murray
Northeast Fisheries Science Center
National Marine Fisheries Service
166 Water Street
Woods Hole, Massachusetts 02543
E-mail address: Kimberly.Murray@noaa.gov

Abstract—In May 2001, the National Marine Fisheries Service (NMFS) opened two areas in the northwestern Atlantic Ocean that had been previously closed to the U.S. sea scallop (*Placopecten magellanicus*) dredge fishery. Upon reopening these areas, termed the "Hudson Canyon Controlled Access Area" and the "Virginia Beach Controlled Access Area," NMFS observers found that marine turtles were being caught incidentally in scallop dredges. This study uses the generalized linear model and the generalized additive model fitting techniques to identify environmental factors and gear characteristics that influence bycatch rates, and to predict total bycatch in these two areas during May–December 2001 and 2002 by incorporating environmental factors into the models. Significant factors affecting sea turtle bycatch were season, time-of-day, sea surface temperature, and depth zone. In estimating total bycatch, rates were stratified according to a combination of all these factors except time-of-day which was not available in fishing logbooks. Highest bycatch rates occurred during the summer season, in temperatures greater than 19°C, and in water depths from 49 to 57 m. Total estimated bycatch of sea turtles during May–December in 2001 and 2002 in both areas combined was 169 animals (CV=55.3), of which 164 (97%) animals were caught in the Hudson Canyon area. From these findings, it may be possible to predict hot spots for sea turtle bycatch in future years in the controlled access areas.

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Five species of sea turtles in the northwestern Atlantic Ocean are protected under the U.S. Endangered Species Act of 1973. The loggerhead turtle (*Caretta caretta*) is listed as a threatened species, and the leatherback (*Dermochelys coriacea*), hawksbill (*Eretmochelys imbricata*), Kemp's ridley (*Lepidochelys kempii*), and certain populations of the green sea turtle (*Chelonia mydas*) are listed as endangered. Populations of each of these species have declined principally as a result of human activities (NRC, 1990).

The incidental capture, or bycatch, of sea turtles in commercial fisheries is a major source of mortality (NRC, 1990; Turtle Expert Working Group, 2000). These turtles are captured incidentally in pelagic longlines (Lewison et al., 2004), trawls (Epperly, 2003), gill nets (Julian and Beeson, 1998), pound nets, weirs, pots, and traps (NMFS and USFWS, 1991; Allen, 2000). Such threats occur at various life stages of a population and at different intensities, and consequently have implications for management policy (Heppell et al., 2003).

The U.S. National Marine Fisheries Service (NMFS) has implemented management measures in both the Atlantic and the Pacific in the form of gear modifications or time and area closures to reduce sea turtle bycatch. For example, since the early 1990s, turtle excluder devices (TEDs) have been required in all inshore and offshore shrimp trawl nets in southeastern U.S. waters (Epperly, 2003) to reduce sea turtle mortality (Henwood and Stuntz, 1987). Bycatches of sea turtles in the U.S. pelagic longline fisheries for swordfish and tuna (Witzell, 1999) led to a year-round closure of a 2.6 million nmi^2 area in the northwestern Atlantic Ocean to these fisheries beginning in 2002.

In recent years, documented interactions have occurred between sea turtles and sea scallop dredges, a previously unidentified threat in recovery planning efforts (NMFS, 1991). During 2001 and 2002, fisheries observers aboard commercial sea scallop vessels documented the bycatch of sea turtles in two small regions of the Mid-Atlantic Bight (MAB). These areas, termed the "Hudson Canyon Controlled Access Area" (approximately 3150 km^2) and the "Virginia Beach Controlled Access Area" (approximately 900 km^2) were closed to scallop fishing in April 1998 but reopened in May 2001 on a conditional basis (Fig. 1). This study uses the generalized linear and generalized additive models to identify environmental factors and gear characteristics affecting the bycatch rate of sea turtles in these two areas and to predict total bycatch by sea scallop dredge vessels in these two areas in 2001 and 2002.

Methods

The fishery

In 2001 and 2002, 137 and 93 commercial vessels, respectively, participated in the Controlled Area Access Program sea scallop fishery. Although

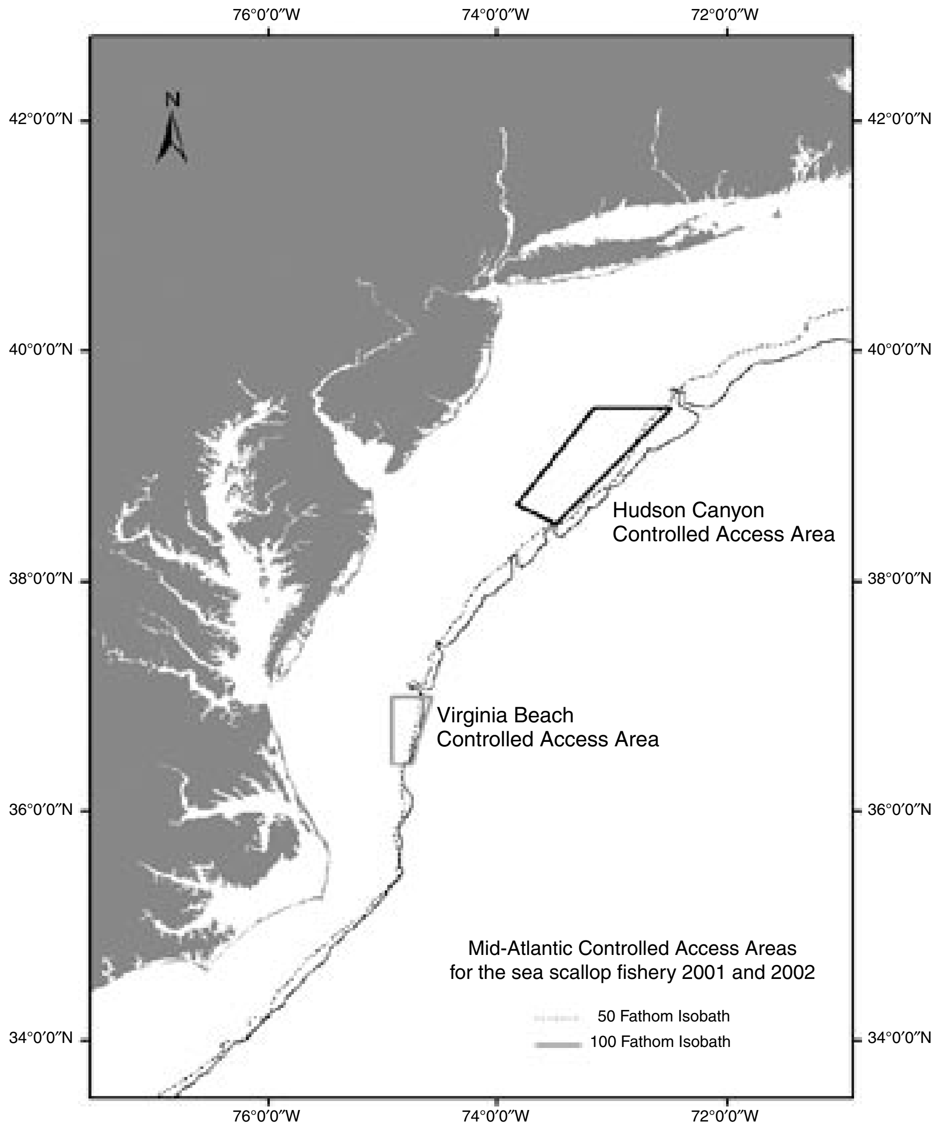

Figure 1

Mid-Atlantic controlled access areas for the sea scallop fishery 2001 and 2002.

the U.S. commercial scallop fishery operates year-round, the area access program in 2001 began on 1 May, and in 2002 on 1 March, and ended on 28 February following the respective fishing year (1 March–28 February). Vessels in the controlled access areas fished around the clock for approximately 5–12 days, accomplishing between 40 and 160 hauls per trip. Dredges in the controlled areas were generally fished at depths between 45 and 75 m. The average haul duration was about 1 hour. Most vessels fished two dredges simultaneously (one from each side of the vessel), which were generally either 3.9 or 4.5 m (13 or 15 ft) wide.

Vessels in the Mid-Atlantic typically fish with a New Bedford style scallop dredge equipped for soft-bottom substrates. In this configuration, tickler chains strung from the sweep chain run horizontally between the dredge frame and the ring bag and are designed to raise scallops off the bottom and into the bag. Turtles become entrapped in the ring bag or on the dredge frame. For dredging on hard bottom, such as in New England, vertical up and down chains hang over the tickler chains, preventing boulders from entering the ring bag (Smolowitz, 1998). New Bedford style scallop dredges have also been used in U.S. fisheries in the Pacific (PSMFC[1]).

[1] Pacific States Marine Fisheries Commission (PSMFC). 2003. Description of fishing gears used on the Pacific Coast. http://pcouncil.org/habitat/geardesc.pdf. [Accessed 6 April 2004.]

Data sources

Observer data Observers were placed on randomly selected vessels fishing in the controlled areas to record the bycatch of turtles and other protected species. From May to December in 2001 and 2002, observers sampled 11% of the commercial fishing effort in the Hudson Canyon region, and in October 2001, 16% of the effort in Virginia Beach. No trips were observed in the Virginia Beach region during 2002 because of low commercial fishing effort in the area. Observers were on- and off-watch on an irregular schedule throughout a 24-hour period, observing on average 65% of the hauls on a trip. When a dredge was hauled on board, observers recorded the haul location, time, depth, tow speed, tow duration, number of dredges observed, and the presence or absence of turtle bycatch. In 2001, observers identified 20% of the turtles that came aboard as loggerhead sea turtles but were unable to identify the remaining 80%. As a result of improved observer training (NMFS 2003), observers identified 88% of the turtles as loggerhead sea turtles in 2002, but they were unable to identify the remaining 12%. Given that observers document the loggerhead species most commonly in the Mid-Atlantic area, and that all sea turtles positively identified were loggerhead sea turtles, bycatch estimates in this analysis are considered to be those of loggerhead sea turtles. Although some turtles may have been released alive or injured, this analysis does not differentiate between live, dead, and injured animals.

Fishing effort data Under the 1982 Atlantic Sea Scallop Fishery Management Plan, all vessels targeting scallops must complete a vessel trip report (VTR) log (as of 1994) indicating area fished, kept and discarded catch, and fishing effort. These data were used to estimate the total fishing effort of the fleet. In calculating fishing effort, one unit of effort equals a single dredge haul because vessels may fish one or two dredges simultaneously on each haul. Because a preliminary analysis showed that tow duration or dredge length does not significantly affect the probability of turtle capture, dredge haul effort was not standardized for these two variables. All VTR trips from May to December in the controlled areas were used in the analysis. Because completion of vessel trip reports is mandatory and trips to the controlled areas were closely monitored, it was assumed that the VTR data represented 100% of total fishing effort.

Sea surface temperature Sea surface temperature at each position reported in the observer and VTR databases was extracted from NOAA AVHRR (advanced very high resolution radiometer) coastwatch satellite images. A Visual Basic (Microsoft Corp., Redmond, WA) routine was used to extract temperatures from 7-day composite images (3 days forward and backward from the haul date), by using a 3×3 cell window at 1-km resolution. Therefore, a 9-km^2 area of coverage around each coordinate position was used to extract sea surface temperature. Within the 3×3 cell search radius, the pixel representing the warmest temperature was used to avoid temperatures affected by cloud coverage.

Data analysis

Missing temperature data Sea surface temperature values could not be obtained for 33% of the VTR data and 10% of the observer data because of either missing coordinate positions on the VTR logs or bad satellite images. For these fishing events, sea surface temperature was predicted by using a linear regression based on year, month, and area. For the observer data, area was defined as either Hudson Canyon or Virginia Beach access areas (r^2=0.88). For the VTR data, the vessel's home state served as a proxy for area fished because most of the missing temperature values were due to missing coordinate positions (r^2=0.86).

Modeling approach Generalized linear model (GLM) and generalized additive model (GAM) fitting techniques were used to understand and predict bycatch rates of sea turtles in relation to environmental variables, fishing practices, and gear characteristics in the commercial sea scallop fishery. Unlike classic linear regression models, GLMs and GAMs allow for nonlinearity and nonconstant variance structures in the data (Guisan et al., 2002). GAMs differ from GLMs in that smooth functions replace the linear predictors in GLMs (Hastie and Tibshirani, 1990). Smooth functions, or "smoothers," summarize the trend of a response measurement as a function of multiple predictors (Hastie and Tibshirani, 1990) and therefore some form of parametric relationship between the response and explanatory variables is not assumed (Guisan et al. 2002). Both frameworks have been used to model abundance or probability events as a function of environmental variables (Frost et al., 1999; Denis et al., 2002; Guisan et al., 2002; Hamazaki, 2002).

A modeling approach to estimate bycatch of sea turtles in the sea scallop dredge fishery was preferred over the ratio method (Cochran, 1977) that has been used to estimate bycatch of marine mammals and turtles in other fisheries (Epperly et al., 1995; Rossman and Merrick, 1999). With the ratio method, the observed number of sea turtles divided by the observed effort is used to calculate a bycatch rate, and this rate is then multiplied by total commercial fishing effort to derive a bycatch estimate. Bycatch data in the sea scallop dredge fishery violate the underlying assumptions of the ratio method (Cochran, 1977), largely because sea turtle bycatch is binomially distributed with a nonconstant variance. An analyis of binary response data derived from a statistical model allows bycatch rates to be predicted by using factors that account for variability in bycatch. Moreover, stratifying bycatch rates according to these factors will reduce variability in total bycatch estimates. For the sea turtle data analyzed in the present study, the GLM approach provided a more accurate and less biased mortality estimate than that derived using the ratio method.

GAM smoothers Before a GLM was constructed, a GAM helped group continuous variables into categories. Fitting the GLM model with categorized variables was necessary to extrapolate bycatch rates in order to derive a total estimate of the bycatch of sea turtles in scallop dredges in the controlled access areas. All of the variables tested in the GLM model were first fitted to a GAM, in which the parameters of the continuous prediction variables were estimated by a smoothing spline. Variable values were grouped according to whether they had a positive or negative influence on the bycatch rate (i.e., the group explained more or less of the bycatch rate).

Development of a GLM bycatch model Because bycatch events were counts ranging from zero or one, a logistic regression was used to model the probability of sea turtle bycatch (GLM function, SPLUS 6.1, Seattle, WA). Each dredge haul is a data point and the response was whether turtle bycatch was zero or one. Probability of sea turtle bycatch (p) was calculated as

$$p = e^y / 1 + e^y$$
$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i,$$

where β_i is a parameter coefficient;
x_i is a predictor variable; and
y is a sea turtle bycatch event.

Dredge hauls are assumed to be independent because turtles were never simultaneously caught in both dredges operating from a vessel during a single haul.

A forward stepwise selection method was used to determine the best fitting model. Model parameters were estimated by maximizing the log-likelihood function. The null model was the first model in the stepwise process and was specified with a single intercept term as

$$H_0\text{: } \log(\textit{turtle bycatch}) = 1.$$

At each step, a new variable was added to the null model (Appendix 1) and tested against the former model formulation (ANOVA function, chi-square test) to determine the better fitting model. A preliminary assessment of a broad suite of gear characteristics and environmental factors indicated that 10 variables could significantly affect bycatch rates. The main effects of each variable were tested in the stepwise selection process as well as the interaction between season and temperature. Because the order of the predictor variables affects their significance, main effects were entered in various orders. If a P-value was less than 0.05, then the additional variable was considered to explain more of the variability in bycatch than a model without that variable. Each new model was also compared against the former model by using the Akaike information criterion (AIC), which is defined as

$$AIC = -2\log\left(L(\theta \mid y)\right) + 2K,$$

where $\log\left(L(\theta \mid y)\right)$ = the numerical value of the log-likelihood at its maximum point; and
K = the number of estimable parameters (Burnham and Anderson, 2002).

The AIC is a measure of the level of parsimony, defined as a model that fits the data well and includes as few parameters as necessary (Palka and Rossman, 2001). If the AIC value decreases, the new combination of variables in the model fit the data better.

To investigate whether the bycatch data are over-dispersed, that is, where the sampling variance exceeds the theoretical variance, the GLM model was refitted by using a quasi-likelihood function. When data are over-dispersed, the estimated over-dispersion parameter is generally between 1 and 4 (Burnham and Anderson, 2002). The over-dispersion parameter fitted to the global model was 0.61, indicating these data were not over-dispersed and error assumptions of the binomial model were appropriate for analyzing these data.

Alias patterns in the final model were examined to assess correlation among the explanatory variables. The fit of the final model was assessed by plotting the observed turtle bycatch against the predicted turtle bycatch. The r^2 value indicated how well predictions from the linear model fit the actual data.

Bycatch rate estimates The spatial and temporal stratification of bycatch rates in each of the controlled access areas was determined by the explanatory variables in the best-fitting GLM. Parameter estimates from the model were used to predict the bycatch rate for each stratum.

The coefficient of variation (CV) for each bycatch rate was estimated by bootstrap resampling (Efron and Tibshirani, 1993). The resampling unit was a scallop dredge haul. Replicate bycatch rates were generated with the best-fitting GLM model, by sampling with replacement 1000 times from the original data set. The CV was defined as the standard deviation of the bootstrap replicate bycatch rates in a stratum divided by the bycatch rate for that stratum estimated from the original data. Variances and CVs of combined estimates were based on means weighted by their respective variances (Wade and Angliss, 1997).

Total bycatch The total estimated turtle bycatch in each stratum was calculated as the product of predicted bycatch per dredge haul (i.e., the predicted bycatch rate) for that stratum and the total number of dredge hauls accomplished by the commercial fishery in that stratum:

$$\frac{\sum \textit{Predicted bycatch}}{\sum \textit{Dredge hauls}_i} \times (\textit{Total dredge hauls})_i,$$

where i = stratum

Table 1

Analysis of deviance for significant factors affecting sea turtle bycatch. Significant factors were used to stratify bycatch rates and to contruct a model to predict total bycatch. AIC = Akaike information criterion.

Model	df	Deviance	Residual df	Residual deviance	*P* (chi)	AIC
null model only		18,071	405.29	407.2989		
null + year	1	–2.33	18,070	402.96	0.12626	406.9611
null + season	2	19.81	18,069	385.48	0.00004	391.4807
null + season + temp	1	9.34	18,068	376.13	0.00223	384.1319
null + season + temp + depth	2	17.23	18,066	358.89	0.00018	370.8983
null + season + temp + depth + time of day	1	7.86	18,065	351.03	0.00503	365.0318
null + depth + time of day + season (temp)	1	1.64	18,064	349.39	0.20011	365.3903
null + season + temp + depth + time of day + state	4	3.77	18,061	347.25	0.43746	369.2579
null + season + temp + depth + time of day + dredge frame width	2	3.27	18,063	347.76	0.19487	365.7611
null + season + temp + depth + time of day + number of up and down chains	1	0.54	18,064	350.48	0.45955	366.4849
null + season + temp + depth + time of day + number of tickler chains	1	3.18	18,064	347.84	0.07436	363.8480

Annual bycatch was the sum of the stratified bycatch estimates. The finite population correction factor (Cochran, 1977) was applied to bycatch estimates in stratas where the observer coverage was greater than 10%.

Number of dredge hauls in the VTR database without coordinate positions (32%) were prorated between the stratified areas according to the percentage of dredge hauls with known coordinates from the same year, state, and stratified areas.

Results

Observed bycatch

Nine and 16 turtle bycatch were observed in 2001 and 2002, respectively, in the Hudson Canyon controlled access area. Of the 25 turtles taken in the Hudson Canyon area across both years, 21 (84%) were taken during summer months. Two turtle bycatch were observed in the Virginia Beach access area during fall 2001—the only time when there was observer coverage in this area across both years.

GAM smoothers

Plots of the smoothed functions in the GAM revealed whether the continuous variable in the model explained any error in the bycatch rate estimates. For example, a plot of the smooth function for depth as a covariate revealed that bycatch rates may be higher between 49 m (27 fm) and 57 m (31 fm) and lower around this zone (Fig. 2). Likewise, a plot of the smooth function for temperature as a covariate revealed that bycatch rates may be higher above 19°C. These plots helped bin the continuous variables into categories (Appendix 1) which could then be tested in the GLM. All continuous variables in the GAM were categorized in a similar manner.

GLM bycatch model

Significant factors affecting sea turtle bycatch were season, sea surface temperature, depth zone, and time-of-day (Table 1). These variables were significant despite the order in which they were tested in the model. The model with the lowest AIC value was considered the "best" model, although time-of-day could not be included in the final model to predict bycatch rates. This level of information is not recorded in commercial fisheries logbooks; therefore bycatch rates based on time-of-day could not be extrapolated to total bycatch. Width of the scallop dredge frame, number of tickler chains, and number of up and down chains were not significant variables.

Model fit

The number of predicted sea turtle bycatch closely matched the observed bycatch in both years in all bycatch strata (Table 2). Strata were defined according to variables identified in the GLM as having a significant effect on bycatch rates. The relationship between actual and observed takes was strong (r^2=0.93), indicating that the predictions from the model fitted the data well.

Bycatch rate estimates

Bycatch rates were stratified by season, temperature interval, and depth zone (Table 3). Because year was not a

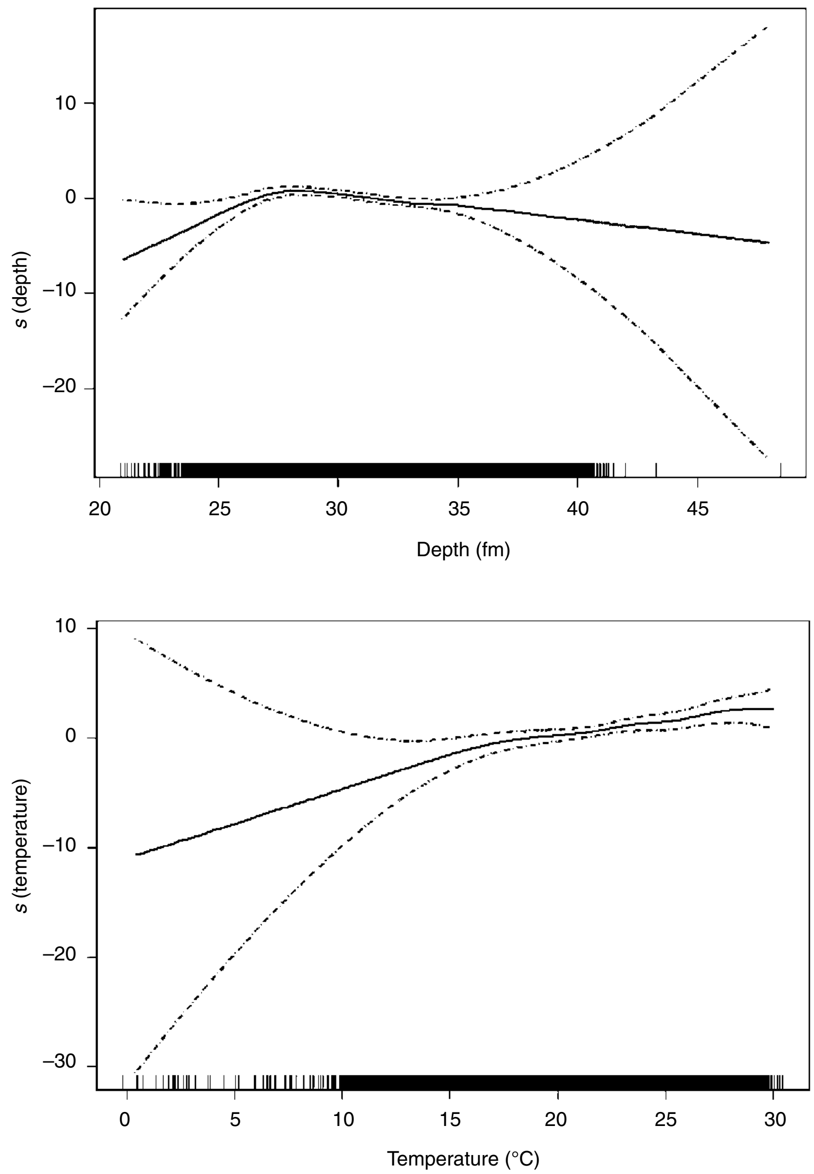

Figure 2

Partial fits for the general additive model (GAM) of sea turtle bycatch with depth and temperature as covariates, showing the relationship estimated by a smoothing spline. Depths between 27 fm (49 m) and 31 fm (57 m), and temperatures above 19°C, have a positive influence on the bycatch rate. 95% confidence bands are also shown. All continuous variables in the GAM were categorized in a similar manner. The "s" on the y-axis represents a smoothed function for each variable and explains the effect of each variable on sea turtle bycatch per haul.

significant factor in the final model, predicted bycatch rates were the same for 2001 and 2002. Highest sea turtle bycatch rates occurred during the summer season (Aug–Sep), in temperatures warmer than 19°C, in water depths from 49 to 57 m. Lowest bycatch rates occurred during the fall (Oct–Dec) and spring (May–June), in temperatures cooler than 19°C, and in water depths less than 49 m.

Total bycatch

The total estimated bycatch of sea turtles in the Mid-Atlantic controlled access areas in 2001 and 2002 combined was 169 animals (CV=55.3) (Table 4). Of this total, 164 animals (97%) were caught in the Hudson Canyon area: 69 (42%) in 2001 and 95 (58%) in 2002. Total esti-

Table 2
Observed versus predicted number of turtle bycatch, by stratum, 2001 and 2002. Obs.=observed; Pred.=predicted.

		Spring		Summer		Fall	
Water depth	Temp.	Number of obs. turtle bycatch	Number of pred. turtle bycatch	Number of obs. turtle bycatch	Number of pred. turtle bycatch	Number of obs. turtle bycatch	Number of pred. turtle bycatch
Shallow	High	0	0	0	0	0	0
	Low	0	0	0	0	0	0
Mid-depth	High	2	1	17	16	1	2
	Low	0	0	0	0	1	0
Deep	High	1	1	4	5	1	0
	Low	0	0	0	0	0	0

Table 3
Stratification of turtle bycatch rates with associated CVs. N.C.E.=no commercial effort.

Water depth	Temperature	Spring (May–June)	Summer (Aug–Sep)	Fall (Oct–Dec)
Shallow (<49 m)	High (>19°C)	0.0000027 (82.5)	0.0000052 (62.1)	0.0000030 (87.7)
	Low (<19°C)	0.0000002 (99.5)	N.C.E.	0.0000002 (106.6)
Mid-depth (49–57 m)	High (>19°C)	0.0032018 (64.9)	0.0061179 (25.4)	0.0035838 (57.2)
	Low (<19°C)	0.0002117 (95.4)	N.C.E.	0.0002371 (98.3)
Deep (>57 m)	High (>19°C)	0.0007578 (73.8)	0.0014512 (41.9)	0.0008485 (80.5)
	Low (<19°C)	0.0000500 (92.9)	N.C.E.	0.0000560 (103.8)

Table 4
Total bycatch estimates by year and season with weighted CVs (%) N.C.E.=no commercial effort.

		Spring	Summer	Fall	Total
Hudson Canyon	2001	10 (89.2)	50 (61.5)	9 (105.8)	69
	2002	13 (89.2)	78 (61.5)	4 (105.8)	95
Virginia Beach	2001	N.C.E.	N.C.E.	5 (105.8)	5
	2002	0	0	N.C.E.	0
Totals		23	128	18	169 (55.3)

mated bycatch of turtles in the Virginia Beach area was five animals in 2001 and zero animals in 2002.

Across both areas, the highest bycatches occurred in summer (128 turtles; 76%), followed by spring (23 turtles; 14%) and fall (18 turtles; 10%) (Table 5). One hundred thirty-two (78%) (CV=49.6) sea turtles were caught in the mid-depth zone from 49 to 57 m, whereas 37 (22%) (CV=59.6) sea turtles were caught in waters deeper than 57 m. One-hundred fifty-eight (93%) (CV=51.2) sea turtles were caught in waters warmer than 19°C, and 11 (7%) (CV=74.9) in waters cooler than 19°C.

Discussion

Use of bycatch models

Generalized linear and generalized additive models help to identify environmental variables or fishing practices that influence the probability of sea turtle bycatch. In estimating total mortality, bycatch rates can then be stratified according to these factors, reducing unexplained variability in the total estimate. Moreover, understanding factors that lead to a high or low

Table 5

Total bycatch estimates by season, depth, and temperature strata in Hudson Canyon and Virginia Beach controlled access areas in 2001 and 2002 with 95% confidence intervals. Spring=May–Jun; Summer=Jul–Sep; Fall=Oct–Dec. N.E.C.= no commercial effort; N.O.=no observer coverage.

		2001			2002			
Water depth	Temperature	Spring	Summer	Fall	Spring	Summer	Fall	Total
Shallow (<49 m)	High (>19°C)	0	0	0	0	0	0	0
	Low (<19°C)	0	N.O.	0	0	N.C.E.	0	0
Mid–Depth (49–57 m)	High (>19°C)	6 (0–13)	37 (21–59)	2 (0–5)	8 (0–21)	65 (34–96)	5 (0–9)	123
	Low (<19°C)	2 (0–8)	N.C.E.	4 (0–19)	1 (0–2)	N.C.E.	2 (0–10)	9
Deep (>57 m)	High (>19°C)	2 (0–5)	13 (4–25)	2 (0–5)	4 (0–11)	13 (4–24)	1 (0–1)	35
	Low (<19°C)	0 (0–1)	N.C.E.	1 (0–6)	0 (0–1)	N.C.E.	1 (0–2)	2
Total		10	50	9	13	78	9	169

probability of bycatch can motivate bycatch mitigation research. Finally, the ability to predict bycatch on the basis of explanatory variables allows one to examine the relative effectiveness of different management measures designed to reduce bycatch (Kobayashi and Polovina[2]). Ultimately this framework can improve the assessment of threats to turtles and broaden conservation options.

Magnitude of bycatch

During May–December in 2001 and 2002, an estimated 169 animals were captured incidentally by commercial sea scallop dredge vessels in two areas of the Mid-Atlantic Bight. Throughout the entire Mid-Atlantic Bight, the magnitude of bycatch was probably larger, particularly because the factors associated with the high bycatch rates were not specific to the controlled access areas. Of the 11 observed turtles measured for size, 9 (82%) were between 70–80 cm straight carapace length (the large juvenile stage). Stage class models indicate that the long-term survivability of loggerhead sea turtles is sensitive to mortality at this life stage (Crouse et al., 1987).

Factors influencing bycatch

The incidental capture of turtles occurs where there is overlap between fishing effort and turtle habitat. The elevated probability of turtle bycatch occurring in warm waters, during summer, at depths between 50 and 60 m is consistent with the habitat regime of loggerhead sea turtles in the Mid-Atlantic (Shoop and Kenney, 1992; Epperly et al., 1995; Coles and Musick, 2000). During the oceanic phase of their life cycle, sea turtles occupy habitats at specific temperatures or with bathymetric features that concentrate prey and other areas of enhanced productivity (Polovina et al., 2000). In Mid-Atlantic waters, high aggregations of loggerhead sea turtes have been observed in the summer, in waters 22–49 m deep, at temperatures from 20° to 24°C (Shoop and Kenney, 1992). In the Hudson Canyon and Virginia Beach controlled access creas, the bycatch of sea turtles was associated with habitat conditions rather than gear characteristics. From these findings, it may be possible to predict future hotspots for sea turtle bycatch in the controlled access areas where fishing effort and sea turtles overlap in time and space. These hotspots may be centered over the portion of the Hudson Canyon where depths are between 50 and 60 m, after waters warm to 19˚C.

Because of the low amount of observer data in the Virginia Beach area, predicted bycatch rates for this area were based largely on conditions within the Hudson Canyon area. Sea scallop fishing effort occurs year-round both north and south of the Hudson Canyon, and high concentrations of loggerhead sea turtles (determined from migratory patterns) exist in spring and fall from North Carolina to northern Maryland (Shoop and Kenney, 1992). It is probable that the distribution of turtles and scallop fishing effort co-occur in other regions of the Mid-Atlantic, particularly south of the Hudson Canyon. The scallop dredge fishery in the Mid-Atlantic is a complex, dynamic system; there may be other factors influencing the bycatch of sea turtles in the fishery south of the Hudson Canyon that were not observed. However, without additional data on turtle interactions in these areas, it is unwise to extrapolate bycatch estimates beyond the scope of the data in this analysis.

Conservation management options

Time and area closures Models of turtle migrations can be used to predict interactions with fisheries in time and space to maximize the efficiency of time and area

[2] Kobayashi, D. R., and J. J. Polovina. 2000. Time/area closure analysis for turtle take reductions. Appendix C, Environmental Impact Statement, FMP for Pelagic Fisheries of the Western Pacific, 44 p. NMFS Honolulu, Hawaii, 96822.

closures (Morreale, 1996). The results of this analysis indicate that bycatch rates are affected by season, depth, and sea surface temperature. Within certain months and depth zones, therefore, the time when sea surface temperature reaches a threshold level may be the time to trigger an area closure. For example, this type of management approach has been taken in the southeastern United States to regulate turtle bycatch in the large-mesh gill-net fishery.[3] The timing of seasonally adjusted area closures is based upon analyzing sea surface temperatures in relation to the presence or absence of sea turtles throughout the area (Epperly et al., 1995; Epperly and Braun-McNeill[4]). In addition, temperature thresholds currently trigger area closures in the southern California driftnet fishery during El Niño conditions to prevent the incidental capture of loggerhead sea turtles.[5]

Results from the present study can be used to help evaluate potential bycatch reduction under different management scenarios, given certain assumptions. For example, had the portion of the Hudson Canyon controlled access area between depths of 49 and 57 m been closed after surface waters reached 19°C in the summer (the stratum with highest bycatch), the closure would have reduced bycatch by 39%. For this estimate, it is assumed that surface temperatures remain above 19°C throughout the summer and drop below 19°C thereafter. Further, this bycatch reduction scenario also assumes that fishing effort shifts proportionately to the fall and spring season within the same depth zone and that bycatch rates remain the same as those that are calculated. Alternatively, fishing effort could shift within a season to shallow and deep depth zones if scallop catch-per-unit-of-effort were not affected. Under this assumption, bycatch would be reduced by 60% under the same time and area closure. However, unless there are concurrent reductions in fishing effort, bycatch reductions achieved by these measures could well be offset by increases in bycatch in other depth strata and seasons.

Gear or fishing modifications Management actions to modify gear or fishing practices can be evaluated in a similar manner. For instance, this analysis indicates that bycatch rates are influenced by the time-of-day when dredges are in the water. Time-of-day was not used to stratify bycatch rates or to extrapolate total bycatch estimates because of limitations in the fishing effort data (VTR records). If time-of-day had been incorporated into the bycatch model, the model would have predicted higher bycatch rates when dredges were set between 4 am and 4 pm (day tows). If the stratum with the highest bycatch rate (summer, high surface temperatures, and depths between 49 and 57 m), had been further stratified by time-of-day, the model would have predicted a bycatch rate of 0.008 sea turtles/dredge hauls during the day, and 0.002 turtles/dredge hauls during the night. If all the commercial vessels had been fishing during the day in this stratum (n=6352 dredges in 2001), the estimated bycatch would have been 51 turtles. If the vessels had been fishing during the night, the total estimated bycatch would have been 13 turtles. According to these rates and effort, restricting vessels to night-time tows between the hours of 4 pm and 4 am has the potential to reduce bycatch by 75% in this particular stratum.

Although specific gear characteristics did not show a strong relationship to sea turtle bycatch in this analysis, further work should be conducted to evaluate whether specific gear characteristics could be modified to decrease bycatch. For example, the near significance with the model incorporating number of tickler chains (P=0.07) warrants further testing of this gear characteristic. Tickler chains cover the mouth of the dredge in a grid-like configuration with the vertical up and down chains. The number of chains on the bag and distance between the chains may help to prevent sea turtles from entering the dredge bag. This dredge configuration is currently being tested for sea turtle bycatch reduction in the Hudson Canyon area (DuPaul and Smolowitz[6]). Further research should also examine the behavior of sea turtles in relation to dredge gear for a more complete understanding of how and when turtles are entrapped.

Sea turtles and scallop dredge interactions cannot be viewed in isolation from other gear types and conservation measures. Some fisheries that co-occur with sea turtles may have an equal, if not greater, impact on turtles than do scallop dredges (e.g., the shrimp trawl fishery in the Gulf of Mexico [Henwood and Stuntz, 1987]). Changes in sea turtle abundance, or shifts in fishing effort, may increase the likelihood of encounters in both net and dredge fisheries. If environmental conditions associated with high bycatch rates in the Hudson Canyon and Virginia Beach areas are consistent across years, it may be possible to anticipate and deter future interactions from occurring.

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[3] Final Rule, FR 67: 71895-71900, 3 December 2002.

[4] Epperly, S. P. and J. Braun-McNeill. 2002. Unpubl. data. The use of AVHRR Imagery and the management of sea turtle interactions in the Mid-Atlantic Bight. NMFS Southeast Fisheries Science Center, Miami, Florida, 33149.

[5] Final Rule, FR 68: 69962-69967, 16 December 2003.

[6] DuPaul, W. P., and R. Smolowitz. 2003. Unpubl. data. Industry trials of a modified sea scallop dredge to minimize the catch of sea turtles. Virginia Institute of Marine Science, Gloucester Point, Virginia, 23062, and Coonamessett Farm, East Falmouth, Massachusetts, 02536.

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Literature cited

Allen, L. K.
2000. Protected species and New England fisheries: an overview of the problem and conservation strategies. Northeastern Naturalist 7(4):411–418.

Burnham, K. P. and D. R. Anderson.
2002. Model selection and multimodel inference: a practical information-theoretic approach, 2nd ed., 488 p. Springer-Verlag, New York, NY.

Cochran, W.G.
1977. Sampling techniques, 3rd ed., 428 p. John Wiley & Sons, New York, NY.

Coles, W. C. and J. A. Musick.
2000. Satellite sea surface temperature analysis and correlation with sea turtle distribution off North Carolina. Copeia 2:551–554.

Crouse, D. T., L. B. Crowder, and H. Caswell.
1987. A stage-based population model for loggerhead sea turtles and implications for conservation. Ecology 68(5):1412–1423.

Denis, V., J. Lejeune, and J. P. Robin.
2002. Spatio-temporal analysis of commercial trawler data using General Additive models: patterns of Loliginid (*sic*) squid abundance in the north-east Atlantic. ICES J. Mar. Sci., 59:633–648.

Efron, B. and R. J. Tibshirani.
1993. An introduction to the boostrap, 436 p. Chapman & Hall, New York, NY.

Epperly, S. P.
2003. Fisheries-related mortality and turtle excluder devices (TEDs). *In* The biology of sea turtles, vol. II (P. L. Lutz, J. A. Musick, and J. Wyneken, eds.), p. 339–353. CRC Press, Boca Raton, FL.

Epperly, S. P., J. Braun, A. J. Chester, F.A. Cross, J. V. Merriner, and P. A. Tester.
1995. Winter distribution of sea turtles in the vicinity of Cape Hatteras and their interactions with the summer flounder trawl fishery. Bull. Mar. Sci. 56(2): 547–568.

Frost, K. J., L. F. Lowry, and J. M. Ver Hoef.
1999. Monitoring the trend of harbor seals in Prince William Sound, Alaska, after the *Exxon Valdez* oil spill. Mar. Mamm. Sci. 15(2):494–506.

Guisan, A., T. C. Edwards, and T. Hastie.
2002. Generalized linear and generalized additive models in studies of species distributions: setting the scene. Ecol. Model. 157:89–100.

Hamazaki, T.
2002. Spatiotemporal prediction models of cetacean habitats in the mid-western North Atlantic ocean (from Cape Hatteras, North Carolina, USA to Nova Scotia, Canada). Mar. Mamm. Sci. 18(4):134–151.

Hastie, T. J., and R. J. Tibshirani.
1990. Generalized additive models, 329 p. Chapman and Hall, London.

Henwood, T. A., and W. E. Stuntz.
1987. Analysis of sea turtle captures and mortalities during commercial shrimp trawling. Fish. Bull. 85: 813–817.

Heppell, S. S., L. B. Crowder, D. T. Crouse, S. P. Epperly, and N. B. Frazer.
2003. Population models for Atlantic loggerheads. *In* Loggerhead sea turtles (A. Bolten and B. Witherington, eds.), pp. 255–273. Smithsonian Books, Washington, D.C..

Julian, F., and M. Beeson.
1998. Estimates of marine mammal, turtle, and seabird mortality for two California gillnet fisheries: 1990–1995. Fish. Bull. 96:271–284.

Lewison, R. L., S. A. Freeman, and L. B. Crowder.
2004. Quantifying the effects of fisheries on threatened species: the impact of pelagic longlines on loggerhead and leatherback sea turtles. Ecology Letters 7:221–231.

Morreale, S. J., E. A. Standora, J. R. Spotila, and F. V.Paladino.
1996. Migration corridor for sea turtles. Nature 384: 319–320.

NMFS (National Marine Fisheries Service).
2003. Fisheries observer program manual, 217 p. Northeast Fisheries Observer Program, Northeast Fisheries Science Center, Woods Hole, MA.

NMFS and USFWS (National Marine Fisheries Service and U.S. Fish and Wildlife Service).
1991. Recovery plan for U.S. population of loggerhead turtle, 64 p. National Marine Fisheries Service, Washington, D.C.

NCR (National Research Council).
1990. Decline of the sea turtles: causes and prevention, 259 p. National Academy Press, Washington, D.C.

Palka, D. L., and M. C. Rossman.
2001. Bycatch estimates of coastal bottlenose dolphin (*Tursiops truncatus*) in U.S. Mid-Atlantic gillnet fisheries for 1996–2000. Northeast Fisheries Science Center Reference Document 01-15, 77 p.

Polovina, J. J., D. R. Kobayashi, D. M. Parker, M. P. Seki, and G. H. Balazs.
2000. Turtles on the edge: movement of loggerhead turtles (*Caretta caretta*) along oceanic fronts, spanning longline fishing grounds in the central North Pacific, 1997–1998. Fish. Oceanogr. 9:71–82.

Rossman, M. C., and R. L. Merrick.
1999. Harbor porpoise bycatch in the Northeast multispecies sink gillnet fishery and the Mid-Atlantic coastal gillnet fishery in 1998 and during January–May 1999. Northeast Fish. Sci. Cent. Ref. Doc. 99-17, 36 p.

Shoop, R. C. and R. D. Kenney.
1992. Seasonal distributions and abundances of loggerhead and leatherback sea turtles in waters of the northeastern United States. Herpetol. Monogr. 6:43–67.

Smolowitz, R.
1998. Bottom tending gear used in New England. *In* Effects of fishing gear on the sea floor of New England (E. Dorsey and J. Pederson, eds.), p. 46–52. Conservation Law Foundation, Boston, MA.

Turtle Expert Working Group.
2000. Assessment update for the Kemp's ridley and loggerhead sea turtle populations in the western North Atlantic. U.S. Dep. Commer. NOAA Tech. Memo. NMFS-SEFSC-444, 115 p.

Wade, P. R., and R. P. Angliss.
1997. Guidelines for assessing marine mammal stocks: report of the GAMMS workshop April 3–5, 1996, Seattle, Washington. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-OPR-12, 93 p.

Witzell, W. N.
1999. Distribution and relative abundance of sea turtles caught incidentally by the U.S. pelagic longline fleet in the western North Atlantic Ocean, 1992–1995. Fish. Bull. 97:200–211.

Appendix 1

Categorical variables examined in an analysis of factors affecting sea turtle bycatch in the sea scallop dredge fishery. Frequency of observed dredges in each category is also shown.

Variable	Category	Number of observed dredges in Hudson Canyon 2001	Number of observed dredges in Virginia Beach 2001	Number of observed dredges in Hudson Canyon 2002	Number of observed dredges in Virginia Beach 2002
Year	2001 or 2002	9493	520	8059	0
Season	Spring = May and June	3919	0	1987	0
	Summer = July, August, September	2719	0	3764	0
	Fall = October, November, December	2855	520	2308	0
State in which scallops were landed	Connecticut	199	0	595	0
	Massachusetts	4925	0	5628	0
	New Jersey	2849	0	740	0
	Rhode Island	112	0	474	0
	Virginia	1408	520	622	0
Frame width[1] category	Small = 3.0–3.9 m (10–13 ft)	560	0	443	0
	Medium = ≥3.9 m and <4.5 m (15 ft)	3987	122	3013	0
	Large = <4.5 m–4.8 m (15–16 ft)	4946	398	4603	0
Number of up and down chains used[2]	Code 1 = 0 chains	4256	520	2171	0
	Code 2 = 1–4 chains	4089	0	5378	0
	Code 3 = >4 chains	1148	0	510	0
Number of tickler chains used[3]	Code 1 = ≤2 chains	6890	520	4469	0
	Code 2 = >2 chains	2603	0	3590	0
Time-of-day	Day = 4 am–4 pm	5514	346	4854	0
	Night = 4 pm–4 am	3979	174	3205	0
Sea surface temperature	Hi = >19°C	3910	518	4883	0
	Low = ≤19°C	5583	2	3176	0
Depth	Shallow = 40–<49 m (22–27 fm)	1089	42	782	0
	Mid-Depth = 49–57 m (27–31 fm)	3371	280	3642	0
	Deep = >57–88 m (31–48 fm)	5033	198	3635	0

[1] Width of the dredge frame.

[2] Vertical chains attached to the sweep on the bottom of the dredge that prevent rocks from entering the chain bag. Number of up and down chains were influenced by bottom type.

[3] Horizontal chains attached to the sweep on the bottom of the dredge that help stir up contents of the sea bottom. Number of tickler chains were influenced by bottom type.