Cascading effects of the loss of top predators from the ocean

Supporting Online Material

Materials and Methods

Species

Large sharks

Large shark species in the Northwest Atlantic were considered for inclusion in this category based on their size, presence of elasmobranchs in their diet, and availability of data with which to assess trends in abundance. Ten shark species met these criteria (Table S1). These species are among the largest sharks (notable exceptions being basking and whale sharks, which feed at much lower trophic levels) reaching maximum lengths ranging from ~2.4m in blacktip and sandbar sharks up to 5-6m in great hammerhead and great white sharks (S1-S3). Bull, blacktip, sandbar, and scalloped hammerhead reach sexual maturity below or close to 2m, but all others mature at a greater length (S1-S3). These large fishes are all tertiary consumers (trophic level ≥4) with catholic diets. Four species, bull, great hammerhead, tiger, and great white sharks are true apex predators, while the remaining six species feed at and near the top of the food web.

Smaller elasmobranchs form a key component of the diet of large sharks (S1, S2, S4, S5), and conversely, sharks are the most common predators of other elasmobranchs (S6, S7). Among the large sharks, however, there is considerable variation in the proportion of elasmobranchs consumed in their diet. Bull, great hammerhead and great white sharks are each considered to be important predators on other elasmobranchs, with about 35-40% of their diet comprised of these fishes (S5). For the other species, the presence of elasmobranchs in their diet has ranged in different studies between approximately 1 and 15% (see Table S1 references; S5). We compiled data on elasmobranch consumption for each of the large shark species, with particular consideration of the species included in the elasmobranch mesopredator category (see below). At the species level there is evidence that large sharks are predators of five of the elasmobranch mesopredator species, little and clearnose skates, cownose ray, bonnethead and Atlantic sharpnose sharks (Table S1). This reflects the dearth of species-specific prey information for most sharks (most information in the literature is reported at higher taxonomic levels (usually Family or genus)), and the lack of biological information in general for several of the little known mesopredator species. For example, there is no information in the literature (that we are aware of) on predators of six of the mesopredator species (rosette skate, spiny and smooth butterfly ray, bullnose eagle ray, and chain catshark). However, there is evidence that large sharks predate on species in nine out of the ten mesopredator genera, and on the Family (Scyliorhinidae) of the only other species, chain catshark (Table S1).

Evidence suggests that the sand tiger shark (*Carcharias taurus*), one of the only important predators of small elasmobranchs not included in our analyses, has experienced declines similar to those of the other large shark species. We could not estimate trends in abundance for this large apex predator because of a lack of data. Of all the data sets we examined, only one sand tiger was caught. This is thought to reflect the fact that this species has declined greatly in this region. Evidence from a shark-targeted bottom longline survey in Chesapeake Bay (not available for analysis) indicates that this species declined by *% between 1974 and 1993 (S8). The sand tiger shark has been considered for the U.S. Endangered Species Act, and is currently listed as a species of Special Concern and a prohibited species (to land) by the U.S. National Marine Fisheries Service (S9). This is consistent with the evidence presented in the main text, which indicates that all shark species that consume mesopredator elasmobranchs have declined substantially.

Mesopredatory elasmobranchs

We considered all small shark, skate, and ray species that have sufficient data available to assess their trends in relative abundance. All small shark species are subject to commercial and recreational fishery removals to some extent. To allow detection of possible increases in abundance of small sharks following a loss of top predators, we only included those species that mature at an early age (< 3 years). We did not include stingrays in our analysis because they are subject to high rates of post-discard mortality (*S10*), likely due to their thin body type relative to thicker bodied skates. Very large species,

Comment [TDS1]: Sustainability of elasmobranchs caught as bycatch in a tropical prawn (shrimp) trawl fishery. In their study, they were able to directly examine mortality of two members of the family Dasyatidae. Mortality rates, Females: 27 and 43%, males: 95 and 78%, overall: 59 and 53%. They didn't offer any explanation except that in general, smaller individuals seemed to have higher mortality rates for all species. This also explains why males were more susceptible.

including spotted eagle ray (*Aetobatus narinari*) and Atlantic angel shark (~~*guitarfish Rhinobatos lentiginosus is only 75cmTL*~~*Squatina dumeril*), were also excluded. Three northern species of skates (thorny (*Amblyraja radiata*), winter (*Leucoraja ocellata*), and barndoor (*Dipturus laevis*) skate) were excluded because they have been subject to high rates of exploitation.

Thirteen elasmobranch mesopredator species met our criteria (Table S1). These species are all smaller than 1.5m in length, mature at a relatively early age (<7 years; for all species with known age at maturity) and reproduce annually (unlike many of the large sharks). They comprise 10 different genera from 6 Families, and range from fairly well known species (e.g. Atlantic sharpnose, blacknose, and finetooth sharks, cownose rays) to very poorly known species (bullnose eagle ray, lesser devil ray, chain catshark, smooth and spiny butterfly ray).

Comment [TDS2]: This is questionable for spiny butterfly ray ~ 1.4m

Invertebrates

The North Carolina inshore trawl survey were used to analyze the aggregate group of mollusks. These wer primarily bivalves. Bay scallops were assessed using the University of North Carolina bay scallop surveys. Landing of the four inshore commercial species known to be prey of cownose rays were also used.

Comment [R3]: Travis, can you check on t his??

~~(Pete to write?)~~

Data sources

We sought to obtain all available scientific research surveys from along the U.S. Atlantic coast that recorded elasmobranch and/or molluscan bivalve species, which began prior to 1990 and were conducted using a consistent, standardized methodology over at least twelve years. The seventeen surveys (Table S2) which met these criteria covered U.S. coastal waters from the Gulf of Maine to Cape Hatteras, Florida (Fig S1). They included two surveys that used longlines and were carried out specifically to sample sharks, the UNC survey (detailed below) and the SC survey (see Low and Ulrich, Ulrich for details). The other fifteen surveys used either bottom trawls or seines, and were designed to sample a variety of finfish and invertebrate species. All seventeen of the surveys caught elasmobranch mesopredator species; twelve caught large sharks (Table 2).

The long-term UNC research survey of sharks has been conducted each year since 1972 by the University of North Carolina at Chapel Hill Institute of Marine Sciences off the central coast of North Carolina near Cape Lookout (Fig. S1). Survey methods have remained essentially identical over this 30+ year period. Longlines have been set biweekly during the months of April to November (a total of * sets from 1972-2003, the most recent year for which data are available) using a design employing the same 2 fixed stations. Two successive, perpendicularly oriented sets of baited hooks constituted the sampling for every date (except a small number when bad weather prevented establishment of the second set). All sampling was carried out during the day between the hours of 0900 and 1400hr. ~~Fish (predominantly spot, croaker, pinfish, and ribbonfish in sizes typical of by-catch in local shrimp fisheries) were obtained for bait by making 1-2 15-min trawls 2-3 miles off Shackleford Banks from 0800-0900 hr. The otter trawl employed a legal mesh for commercial shrimp trawling in North Carolina and included a tickler chain.~~ The East-West set was established first, inshore about 1.5 miles off and approximately parallel to the beach of Shackleford Banks in 15 m depth, running eastward from 34^0 38.029' N. lat, 76^0 37.835' W. long. Sets employed between 49 and 400 hooks (mean = 151), with approximately 1 mile of rope for every 100 hooks and one international orange 30-inch buoy for every 15 hooks. Because hooks close to each buoy were suspended near the sea surface, whereas those in the middle of each stretch fished at the bottom, this deployment fished the entire water column. Case-hardened steel hooks were 9/0 Mustang attached to a length of porch swing chain (7-8 feet long until 1996 and 6 feet thereafter). Soak time after setting was 1 hr. During the 45 min required to pull in the line, the species, sex, and fork length of each hooked shark was recorded and all live sharks were tagged and returned to the sea. After 35-40 travel time, the North-South set was established beginning about 7.3 miles offshore in 18 m depth, running southwards from 34^0 33.071' N. lat, 76^0 37.422' W. long. The procedures followed identically those of the East-West set. Occasionally, trawling for bait was required between sets.

Comment [J4]: We need to say something about the timing of the sets – is this correct?

For the large sharks, we also examined data from the U.S. pelagic longline fishery. Fisheries data is the only type that covers a substantial proportion of the range of these shark populations, and pelagic longline gear is particularly suitable for catching these species. The U.S. pelagic longline fleet fishes off the Grand Banks (0ºN), along the U.S. coast, within the Gulf of Mexico, and as far south as the equator. The broad geographic coverage of these data (Fig. S1) therefore complements the long temporal coverage of the research surveys. These data also sampled two species, shortfin mako and the great white shark, which consume elasmobranchs, but are not usually caught in research surveys. We analysed both logbook (1986-2000) and observer (1992-2005) data from this fishery. Details of the former analysis are contained in (Baum et al. 2003 and its Supplementary Material); details of the latter are presented in (Baum et al. 2006).

Only twoone research surveys in the geographical range of the study recorded molluscan bivalves (NCDMF and UNC bay scallop surveys?? Table S2). From the NCDMF survey we examined data for the aggregate species group, mollusks. These were primarily bivalves.

~~Ram or Pete to add something about the new survey data being examined for bivalves~~.

The University of North Carolina bay scallops surveys assessed at 5 sites in 1983 and 84 (Peterson et al. 1989), using approximately 80 quadrats at each site using 0.5 meter square quadrats. Four of the locations were resampled in 2003, 2004, and 2005 using 10 1 meter square quadrats at each location and sampling time. One of these locations (Bald Hill Bay) had lost *Zostera marina* between the time period, so was not included in the analysis as bay scallop larvae virtually never settle without Zostera cover. The average densities in October, after the fall migration south of cownose rays, were used to estimate trends between 1983 and 2004 using a generalized linear model with gamma errors and a log link.

We used landings data for four bivalve species that are known to be preyed upon by cownose rays: oyster, hard-shell clam (quahogs), soft-shell clams, and bay scallops. Data on U.S. landings were obtained from NMFS commercial landings database, while those for Canada came from the Food and Agriculture Organization (FAO). Data on eastern U.S. landings were available from Maine to Texas and are an aggregate of both fishery and aquaculture production. For one species, hard-shell clam, aquaculture makes up a large portion of production (up to 82%) since the mid-1980s (based on comparison of FOA aquaculture production data and NMFS commercial landings data for the US east coast). Without a reasonable method of partitioning these two production sources by state, we were required to source fishery landings data for hard-clams in U.S. states from other sources. Data were available for Virginia and Rhode Island. Data for Virginia landings were obtained from Virginia public fishery hard clam production database (1973-1999, ***reference***). Data for Rhode Island were obtained from ???. For the purposes of detecting the effect of cownose ray abundance on bivalves, only landings from states where cownose rays would be expected to interact with bivalves were included in the meta-analysis.

Trends in relative abundance models

Research survey data

Trends in relative abundance of each species, from each fishery-independent survey, were analyzed using generalized linear models with a negative binomial error structure and a log link. The negative binomial error structure is appropriate for data with a large number of zero (no catch) observations. The log link allows the long-term trend in relative abundance to be characterized. All analyses were conducted using SAS v9.1 (SAS Institute Inc., Cary, NC, USA). We estimated trends in relative abundance only for those species occurring for three or more years in a given survey. The probability of catching C_i individuals of a given species in survey tow i was assumed to follow a negative binomial distribution with the mean μ_i,

Comment [TDS5]: Check to see if this is true

Comment [TDS6]: Is this even needed?

$$p(C_i;k;\mu_i)=\frac{\Gamma\left(C_i+\frac{1}{k}\right)}{\Gamma(C_i+1)\Gamma\left(\frac{1}{k}\right)}\frac{(k\mu_i)^k}{(1+k\mu_i)^{C_i+\left(\frac{1}{k}\right)}}$$, for C_i = 0, 1, 2,…,

where Γ is the gamma function and k is the negative binomial dispersion parameter. The expected mean catch of a given species is then,

$$\log(\mu_i) = \boldsymbol{x}_i'\boldsymbol{\beta} + \log(offset)$$

where $\boldsymbol{x}_i'$ is a vector of explanatory covariates for observation *i*, $\boldsymbol{\beta}$ is a vector of unknown coefficients for the explanatory variables and offset is the offset term.

The breadth of ancillary data which could be used as explanatory covariates in estimating trends in relative abundance varied among surveys. For all surveys and species, we employed the general strategy of using the following covariates in the generalized linear models as the vector of explanatory variables ($\boldsymbol{x}_i'$): year, the second order polynomial of depth, the second order polynomial of bottom temperature and *q* (the seasonal cycle) (Table S3). The seasonal cycle, *q*, was characterized by a series of sine and cosine terms, with periods, *j*, of ½ and 1 year as,

$$q(d_i) = \sum_{j=1}^{2}\left[\varsigma_j \cos\left(\frac{2\pi j d_i}{365.25}\right) + \sigma_j \sin\left(\frac{2\pi j d_i}{365.25}\right)\right]$$

where d_i is the sequential day of the year that observation *i* occurred in, and ς_i and σ_i are estimated parameters.

The NMFS surveys and the SEAMAP surveys covered relatively large latitudinal ranges (Fig S1) and there was some inter-annual variation in the timing of these surveys. For species which do not under take seasonal migrations out of each survey area, this was not a concern. However, changes in the timing of the survey could have significant effects on estimates for those species that do migrate out of the area surveyed. To account for this effect, we used the additional term of latitude when modeling the NMFS and SEAMAP survey data. Further, for these surveys we allowed the seasonal cycle, *q*, to vary by latitude by including the interaction term between latitude and *q*.

There were exceptions to our general strategy of parameter selection for the generalized linear models

(Table S3). Data from the CTDEP trawl survey was only available in the form of mean annual estimates so only year could be included in the model. When surveys followed a fixed station design (DMNR trawl survey and NC longline survey), we included a unique station identifier as a model factor. In some cases, other covariates were available, rather than our standard list, such as river basin for the VIMS seine survey, and the second order polynomial of salinity for the Maryland seine survey.

Shellfish landings data

Trends in relative abundance of each shellfish species for each state, from landings data, were analyzed using generalized linear models with a gamma error structure and a log link. No covariates were available in the analysis of landings data.

Meta-analysis of trends in relative abundance (Ram to write)

Meta-analytic mean estimates for instantaneous rate of change in abundance were estimated for both large sharks and meso-predators with a random effects meta-analysis…,

Predator exclusion experiment (from Sean)

Bay scallop density

To evaluate the spatial extent of bay scallop decline coincident with cownose ray migration, scallop densities were measured bi-weekly at six seagrass beds located within Core (Cedar Island, Yellow Shoal), Back (Oscar Shoal, Straights) and Bogue (Marker 34 and 40) Sounds from August through October in 2002 and 2003. Bay scallop density was measured in early August and again in mid-October with each seagrass bed. At each site 5 replicate 1-m^2 quadrats were haphazardly thrown near the edge of the seagrass bed and at the center of each bed (10 quadrats total per seagrass bed). All bay scallops within the quadrat were counted, measured and returned to their original location. Physical parameters (% cover of seagrass, salinity, temperature, sediment type) were also recorded during sampling. In the Back Sound portion of our study area, the North Carolina Division of Marine Fisheries (NCDMF) allowed a limited hand harvest of scallops coincident with the expected timing of cownose ray populations. Six harvest days were permitted between mid August and early September with a daily harvest rate of 10 bushels/fishermen. To prevent our density estimates from being confounded by this additional treatment and to quantify the relative impact of this harvest, the NCDMF established two 25 m^2 shellfish sanctuary areas within all sea grass beds. A substantially longer data base exists for one of the sites Oscar Shoals. Although some differences exist among years in methodologies, bay scallop density were measured in July or August and Again in September or October in 1992, 1993, 1994, 1996, 1998, 1999 and 2000 (a detailed description of the sampling is reported in Peterson et al. 2001). For all years, bay scallop mortality was calculated by dividing densities measured on the last sampling date by the density measured on the initial sampling date.

Experimental assessment of cownose ray predation

To determine to what extent any decrease in scallop density is attributable to ray predation, we established four 2-m^2 exclosures at the center and four 1-m^2 exclosures at the edge of the 6 seagrass beds where NCDMF shellfish sanctuary areas were established. The exclosures, short (50 cm) PVC poles arranged as a stockade, exclude cownose rays while allowing other predators (crabs and whelks) into the matrix of poles (Woodin 1981, Peterson et al. 2001). The number of scallops surviving within the stockade is compared to areas of free access (controls). The experiment was performed during the fall of 2002 and 2003. The stockades were constructed *in situ* and bay scallops allowed to move into and out of the exclosure. Exclosures were erected in mid August of each year and bay scallop density measured within the enclosure in late September. A similar set of experiments was performed at the Oscar Shoal site in 1996 and 1998 (Peterson et al. 2001). As in the later experiments naturally occurring bay scallop were allowed free access to the exclosure, but in addition ten marked and tethered bay scallops were placed within the stockades. Mortality within the stockade should be substantially less than in the control areas if large mobile consumers are the chief predator on bay scallops during this time period. Bay scallop mortality within the stockades was calculated by dividing densities measured on the last sampling date within the stockade by the density measured on the initial sampling date prior to construction of the enclosure. .

Gonad analysis

Comment [J7]: We don't need this section, do we?

To determine whether bay scallops spawned prior to ray predation, we monitored gonad condition in bay scallop populations throughout Bogue Sound, Back and Core Sounds. Within grassbeds in each sound we collected 20 adult scallops on a weekly basis during our spring and early fall sampling. Upon collection, the coloration of the gonadal mass and shell dimensions will be recorded before the entire scallop is frozen. For each frozen scallop, the gonadal mass (including both male and female sections) and adductor muscle will be dissected, dried and weighed. Briceljet al. 1987 used these data to monitor gamete release (as determined through reduction in gonadal mass) for Long Island Sound populations of bay scallops and achieved resolution of 1 week, which corresponded to her sampling intervals. A ratio of gonad weight/adductor muscle weight was calculated to account for differing size of bay scallops (Briceljet al. 1987). A significant decrease in this ratio (i.e., the gonad mass in the numerator decreases) would indicate spawning.

Results

Trends in relative abundance

(refer to Table S3) – explain cases where we have contradictory estimates e.g. scalloped hammerheads…

References

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Table S1. Taxa of elasmobranch (sharks, skates, rays) consumed by the apex (or near apex) shark species included in the large shark group. Prey are listed as individual species, and also at the genus and family level because of the paucity of species-specific diet data available in the literature. For most elasmobranch mesopredator species, there is little to no species-specific information on their predators, but large sharks are presumed to be their primary predators.

	Large Sharks									
Elasmobranch Mesopredators **Family** Genus Common name, Scientific name	Bull shark, *Carcharhinus leucus*	Blacktip shark, *C. limbatus*	Dusky shark, *C. obscurus*	Sandbar shark, *C. plumbeus*	Tiger shark, *Galeocerdo cuvier*	White shark, *Carcharodon carcharias*	Shortfin mako, *Isurus oxyrinchus*	Great hammerhead, *Sphyrna mokarran*	Scalloped hammerhead, *S. lewini*	Smooth hammerhead, *S. zygaena*
Rajidae (Skates)	■	■	■	■	■	■	■	■	■	■
Little skate, *Leucoraja erinacea*				■						
Rosette skate, *L. garmani*										
Clearnose skate, *Raja eglanteria*				■						
Gymnuridae (Butterfly rays)	■	■	■		■			■	■	
Gymnura species		■	■					■	■	
Smooth butterfly ray, *Gymnura altavela*										
Spiny butterfly ray, *G. micrura*										
Myliobatidae (Mantas and eagle rays)	■	■	■	■	■	■	■	■		■
Mobula species (devil rays)	■		■							
Lesser devil ray, *M. hypostoma*										
Myliobatus species						■				
Bullnose eagle ray, *M. freminvillii*										
Rhinoptera species (cownose rays)	■	■	■	■			■	■		
Cownose ray, *R. bonasus*		■		■						
Scyliorhinidae (catsharks)	■	■	■			■	■	■	■	
Chain catshark, *Scyliorhinus rotifer*										
Sphyrnidae (hammerhead sharks)	■	■	■	■	■	■	■			
Sphyrna species				■		■	■			
Bonnethead shark, *S. tiburo*		■								
Carcharhinadae (requiem sharks)	■	■	■	■	■	■	■	■	■	
Carcharhinus species	■	■	■		■	■	■			
Blacknose shark, *C. acronotus*										
Finetooth shark, *C. isodon*										
Rhizoprionodon species	■	■	■	■	■	■	■	■	■	
Atlantic sharpnose shark, *R. terraenovae*		■								

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Table S2. Survey, fisheries and landings data sets obtained from: Connecticut Department of Environmental Protection (CTDEP); Delaware Department of Marine and Natural Resources (DMNR); Graduate School of Oceanography at the University of Rhode Island (GSO-URI); Maryland Department of Natural Resources (MDNR); North Carolina Department of Marine Fisheries (NCDMF); National Marine Fisheries Service (NMFS); South Carolina Department of Natural Resources (SCDNR); Southeast Area Monitoring and Assessment Program (SEAMAP); University of North Carolina - Institute of Marine Sciences (UNC-IMS); Virginia Institute of Marine Science (VIMS). Species sampled in each data set: large shark species (L), mesopredator species (M), shellfish species (S).

Data type	Acronym	Source	Area	Fishing gear	Season	Years	Samples	Species
Survey	CTDEP		Long Island Sound	Trawl	Fall/Spring	1984 – 2004	42	M
	DMNR		Delaware Bay	Trawl	Year round	1966 – 2004	1874	L,M
	GSO-URI	Collie et al.	?	Trawl	?	1959 – 2002	?	M
	MDNR	MDNR	Chesapeake Bay	Seine	Summer	1960 – 2005	8022	M
	NCDMF		North Carolina inner bays, Pamlico Sound(?)	Trawl	Summer/Fall	1987 – 2004	1889	M,S
	NMFS-Off	NMFS	Northeast U.S. Offshore	Trawl	Spring	1963 – 2005	10185	L,M
	NMFS-Off	NMFS	Northeast U.S. Offshore	Trawl	Fall	1968 – 2005	8829	L,M
	NMFS-Off	NMFS	Northeast U.S. Offshore	Trawl	Summer	1963 - 1995	1758	L,M
	NMFS-In	NMFS	Northeast U.S. Inshore	Trawl	Spring	1976 – 2005	2084	L,M
	NMFS-In	NMFS	Northeast U.S. Inshore	Trawl	Fall	1977 – 1981	2228	L,M
	NMFS-In	NMFS	Northeast U.S. Inshore	Trawl	Summer	1989 – 2005	351	L,M
	SC	SCDNR	Coastal South Carolina	Bottom longline	Year round	1983-84, 1993-95	131	L,M
	SEAMAP	SEAMAP	Coastal Southeast U.S.	Trawl	Spring	1989 – 2005	1441	L,M
	SEAMAP	SEAMAP	Coastal Southeast U.S.	Trawl	Fall	1989 – 2005	1389	L,M
	SEAMAP	SEAMAP	Coastal Southeast U.S.	Trawl	Summer	1989 – 2005	1393	L,M
	UNC bay scallop	UNC-IMS	Coastal North Carolina	.5 and 1 m^2 quadrat	October	1983 – 2004	1010	Bay scallops
	UNC	UNC-IMS	Coastal North Carolina	Longline	April - November	1972 – 2003	702	L,M
	VIMS	VIMS	Chesapeake Bay	Seine	Summer	1968 – 2003	3166	M
Fisheries	Logbook	NMFS	Northwest Atlantic	Pelagic longline	Year round	1986 – 2000	214234	L
	Observer	NMFS	Northwest Atlantic	Pelagic longline	Year round	1992 – 2005	6967	L

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Landings	Landings	NMFS	Coastal Eastern U.S.	Various	Year round	1950 – 2003	-	S
	Landings	FAO	Atlantic Canada	Various	Year round?	1950-2003?	-	S

Table S3. Summary of generalized linear models used to estimate trends in abundance for large sharks, meso-predators and shellfish in the Northwest Atlantic. All data were modeled using generalized linear models, except for the observer data set which was modeled using generalized estimating equations. All models included year as a covariate; *q* represents a seasonal term composed of a series of sine and cosine terms with periods of one year and one half year.

Data Source	Covariates	Error distribution	Link	Offset
CTDEP	No covariates available	Gamma	Log	None
DMNR	depth, depth^2, station, *q*	Negative binomial	Log	Swept area
GSO	?	?	?	?
NMFS-Off	depth, depth^2, temperature, temperature^2, latitude, *q*, latitude**q* interaction	Negative binomial	Log	Swept area
NMFS-In	depth, depth^2, temperature, temperature^2, latitude, *q*, latitude**q* interaction	Negative binomial	Log	Swept area
SEAMAP	depth, depth^2, temperature, temperature^2, latitude, *q*, latitude**q* interaction	Negative binomial	Log	Swept area
SC	depth, depth^2, *q*, time of set, soak time,	Negative binomial	Log	Number of hooks
MDNR	month, temperature, temperature^2, salinity, salinity^2	Negative binomial	Log	None
UNC bay scallop	station	Gamma	Log	None
UNC	station, *q*	Negative binomial	Log	Number of hooks
VIMS	River basin	Negative binomial	Log	None
Logbook	area, season, temperature, use of light sticks, area*season, area*light sticks	Truncated negative	Log	Number of hooks
Observer	area, *q*, depth, depth^2, temperature, time of set, number of light sticks, hook depth, hook type, target species, soak time, area**q* interaction, fishing trip	Negative binomial	Log	Number of hooks
NMFS	no covariates available	Gamma	Log	None
FAO	no covariates available	Gamma	Log	None

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Supplementary Material - Figures

Figure S1. Map of a) the U.S. Atlantic coast showing the location of each of the seventeen research surveys, and b) the Northwest Atlantic showing the distribution of effort in the U.S. pelagic longline observer data set, categorized by number of sets (0 to 100). The 200m and 1000m isobaths (dotted lines) are given for reference.

Figure S2. Change in length of large sharks between 1972 and 2003 from the University of North Carolina shark-targeted longline research survey (UNC): a) instantaneous rates of change (± 95% confidence intervals); b) overall trend (solid line) and individual year estimates (■). Species with length samples in more than three years were modeled in a) and b); only raw data are shown for great and smooth hammerheads.

Figure S3. Changes in landings by individual states of the U.S.A. plus east coast of Canada for a) oysters, b) bay scallops, c) hard clams (quahogs) and d) soft-shell clams.