New England Fishery Management Council
50 WATER STREET | NEWBURYPORT, MASSACHUSETTS 01950 | PHONE 978 465 0492 | FAX 978 465 3116
John F. Quinn, J.D., Ph.D., *Chairman* | Thomas A. Nies, *Executive Director*

"FISHING EFFECTS MODEL NORTHEAST REGION"

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This document was prepared by the following members of the Habitat Plan Development Team of the New England Fishery Management Council:

Michelle Bachman, NEFMC staff*
Peter Auster, University of Connecticut
Jessica Coakley, Mid-Atlantic Fishery Management Council
Geret DePiper, NMFS/Northeast Fisheries Science Center
Kathryn Ford, Massachusetts Division of Marine Fisheries
Julia Livermore, Rhode Island Division of Marine Fisheries
Dave Packer, NMFS/ Northeast Fisheries Science Center
Chris Quartararo, NEFMC staff
David Stevenson, NMFS Greater Atlantic Regional Fisheries Office
Page Valentine, U.S. Geological Survey
Alison Verkade, NMFS Greater Atlantic Regional Fisheries Office

And the following members of the Fisheries, Aquatic Science, and Technology Laboratory at Alaska Pacific University:

Felipe Restrepo
T. Scott Smeltz

*Please forward any comments, questions, or suggestions to mbachman@nefmc.org

Table of Contents

Appendices
Appendix A: Fishing effort as area swept annotated R script
Appendix B: Fishing effort overlap/recovery parameter assignment annotated R script
Appendix C: Fishing Effects Model annotated R script

Tables

Figures

Maps

1.0 Overview of the Fishing Effects Northeast Model

The Magnuson-Stevens Fishery Conservation and Management Act (MSA) requires fishery management plans to minimize, to the extent practicable, the adverse effects of fishing on fish habitats. To meet this requirement, fishery managers would ideally be able to quantify such effects and visualize their distributions across space and time. The Swept Area Seabed Impact (SASI) model provides such a framework, enabling managers to better understand: (1) the nature of fishing gear impacts on benthic habitats, (2) the spatial distribution of benthic habitat vulnerability to particular fishing gears, and (3) the spatial and temporal distribution of realized adverse effects from fishing activities on benthic habitats. Additional details about the original SASI model are provided in NEFMC 2011. Managers and scientists from the North Pacific adapted the SASI model into what they termed the Fishing Effects Model (FE), revising and refining certain aspects of the approach to address concerns raised during reviews of SASI and to reflect regional data availability. This document describes 2018 updates to SASI, hereafter FE Northeast.

Both SASI and FE increase the utility of habitat science to fishery managers via the translation of susceptibility and recovery information into quantitative modifiers of swept area. The models combine area swept fishing effort data with substrate data and benthic boundary water flow estimates in a geo-referenced, GIS-compatible environment. Contact and vulnerability-adjusted area swept, a proxy for the degree of adverse effect, is calculated by conditioning a nominal area swept value, indexed across units of fishing effort and primary gear types, by the nature of the fishing gear impact, the susceptibility of benthic habitats likely to be impacted, and the time required for those habitats to return to their pre-impact functional value.

The vulnerability assessment and associated literature review to support SASI were originally developed over an approximately two year period by members of the New England Fishery Management Council's Habitat Plan Development Team. The assessment served two related purposes: (1) a review of the habitat impacts literature relevant to Northeast US fishing gears and seabed types, and (2) a framework for organizing and generating quantitative susceptibility and recovery parameters for use in the SASI model. As a model parameterization tool, the vulnerability assessment quantifies both the <u>magnitude of the impacts</u> that result from the physical interaction of fish habitats and fishing gears, and the <u>duration of recovery</u> following those interactions. This vulnerability information is used to condition area swept (i.e. fishing effort) in both SASI and FE via a series of susceptibility and recovery parameters. Related to the vulnerability assessment, this document summarizes additional literature reviewed, susceptibility and recovery parameters for additional habitat types fished by hydraulic dredges, as well as the development of parameters for deep-water coral habitat features. Specifically, the section on **gear impacts literature review (2.0)** summarizes the recent fishing impacts literature that supports vulnerability assessment, and the section on **susceptibility and recovery matrices (3.0)** presents S and R scores in tabular format, with updates to reflect the additional studies reviewed in section 2.0, assumptions about additional habitat types fished by hydraulic dredges, and the need for deep-sea coral habitat parameters.

The section on **estimating contact-adjusted area swept (4.0)** summarizes how Northeast region fishing effort data is converted to area swept. Spatially-specific monthly seabed area swept for each gear type is used as the starting point for estimating the adverse effects from fishing. The section on **updates to the model base grid (0)** summarizes how the model domain (area of interest/inference) was selected, and how energy and sediment type were assigned to each location.

The section on **model implementation (6.0)** summarizes how the vulnerability assessment parameters, habitat data from the base grid, and fishing effort data are combined in space and time to generate estimates of percentage of each grid cell impacted by fishing. The section on **results and sensitivity analyses (7.0)** presents initial results of the model using figures and maps, including caveats and cautions about interpretation of the results.

The final section of the document, **next steps (8.0)**, describes future work that can be done to refine various aspects of the approach and apply the model results to fishery management decisions.

2.0 Gear impacts literature review

A goal of the vulnerability assessment is to base estimates of susceptibility and recovery of features to gear impacts on the scientific literature to the extent possible. As with the original SASI model, new studies were selected for evaluation based on their broad relevance to Northeast Region habitats and fishing gears.

A Microsoft Access database was developed for SASI to organize the review and to identify in detail the gear types and habitat features evaluated by each study. This database was updated to support updates to the model. In addition to identifying gear types and features, the database includes fields to code for basic information about study location and related research; study design, relevance and appropriateness to the vulnerability assessment; depth and energy environment; whether recovery of features is addressed; and substrate types found in the study area. The fields are explained in NEFMC 2011. For easy reference, a list of citations by study number is provided on the last page of this document (Table 23).

This section covers only references added during 2018. Studies evaluated for the SASI model are summarized in NEFMC 2011. The tables that follow reproduce the contents of the literature review database in a format amenable to a written document. They list, by study, attributes (Table 1), gears evaluated (Table 2), physical environment (Table 3), geological features evaluated (Table 4), and biological features evaluated (Table 5).

Table 1. Study attributes. MS column indicates a multi-site study; MG column indicates a multi-gear study. Design (D) values are coded as follows: 1 – Compartive, 2 – Experimental; 3 – Observational. Relevance (R) values are coded as follows: 1 – similar gears, different habitats; 2 – similar gears, similar habitats; 3 – similar gears, overlapping habitats; 4 – Northeast gears, Northeast habitats. Appropriateness (A) values are coded as follows: 1 – Study tangentially supports VA evaluation; 2 – Study supports VA evaluation; 3 – Study perfectly aligned with VA evaluation.

Citation	*Related studies*	*MS*	*MG*	*D*	*R*	*A*	*Summary/notes*
Coggan et al 2001 (414)	372, 11	Y	N	1	2	1	Good discussion of trawl effects, with interesting pictures, good info on classification of functional groups and sediment. This lengthy report compares methods used to evaluate fishing impacts, detailed results are in other pubs summarized in database.
Probert et al 1997 (541)	64, 209	Y	N	1	1	1	Evaluated bycatch in hill sites and flat sites during a survey for orange roughy.
Lindgarth et al 2000 (575)	313, 407, 149	N	N	2	2	1	BACI design with multiple before and after samples (see Hansson et al 2000, study #149), area closed to shrimp trawling for 5 years
Simboura et al 1998 (599)	-	N	N	1	2	1	Assessed the structure of the benthic communities in relation to natural and anthropogenic factors; two sites compared, one w/o fishing and one fished, results componded by differences in sediment composition
Hinz et al 2009 (658)	292	N	N	2	2	2	Quantified response of macrofaunal community along a gradient of otter trawling effort, epifauna sampled with beam trawl at 20 sites (15 sites analyzed), infauna with grab samplers
Thorarinsdottir et al 2008 (669)	-	N	N	2	2	2	Three experimental dredge tows in unfished area, 3 core samples collected inside/outside dredge tracks imm after and 3,13, and 25 months after dredging
Gilkinson et al 2015 (670)	121, 122	N	N	3	2	2	Follow-up side scan sonar survey 5 and 10 years after 1998 dredge impact study, includes obs of commercial dredge tracks and their degradation in nearby, shallower water and analysis of seabed recovery due to bottom currents and storm wave action
Lindholm et al 2015 (671)	101	N	N	2	2	2	Exp study with low and high intensity trawling (3 passes per unit area in 2009 + 5 more a year later in same plots), two control areas surveyed in 2012; ROV surveys of benthic features and epifauna imm after and after 2 wks, 6 mos and 1 yr
Atkinson et al 2011 (672)	-	N	N	1	1	1	Infauna sampled at 4 sites with paired heavily and lightly trawled areas (HT, LT) based on commercial effort data from hake fishery; epifauna sampled at two sites
Ragnarsson & Lindegarth 2009 (673)	-	N	N	2	2	1	Experimental fishing (10 tows in each of 4 plots) in un-fished area with grab sampling for infauna in treatment and 4 control plots imm after fishing and 2 and 7 months later.
LeBlanc et al 2015 (674)	-	Y	N	2	2	2	BACI design at two sites closed to scallop dredging for 2 yrs (lightly fished in previous 3 yrs), effects of varying intensities of dredging (0-15 passes) on infauna and epifauna evaluated at two sites 10 days and and one year after dredging.
Sciberras et al 2013 (675)	-	N	N	1	2	1	Comparison of temporal variation and recovery of epifauna in a seasonal and year-round area closure 6,12,18, and 22 mos after year-round closure went into effect; effect of varying fishing intensity for open seasons evaluated using VMS data
Cook et al 2013 (676)	-	Y	Y	3	1	1	Assessed impacts of single pass of an otter trawl and a scallop dredge on large epifauna and infauna in undisturbed mussel beds at two sites
Hinz et al 2012 (677)	-	N	Y	3	2	2	Exp BACI study of effects of single pass of two scallop dredges and an otter trawl used in commercial fishery on scallop catch, by-catch, and impacts on epifauna and infauna, with controls and replication; post-impact sampling 7 days after fishing

Citation	*Related studies*	*MS*	*MG*	*D*	*R*	*A*	*Summary/notes*
Buhl-Mortensen et al 2016 (678)	-	N	N	1	2	2	Spatial variation in fishing intensity (FI=number of speed-processed VMS "hits" for per 5x5 km grid cell) was related statistically to number of trawl marks and to density and diversity of megabenthic fauna observed along 149 video transects on shelf.
Pitcher et al 2009 (679)	38, 39, 285, 680	N	N	2	1	1	BACI study at two different times of year in replicate impact and control plots in an inter-reef/shoal portion of an area closed to prawn trawling 6 yrs prior to study; post-impact sampling done after 6 mos with prawn and fish trawls + benthic dredge.
Pitcher et al 2016 (680)	38, 39, 285, 679	N	N	2	1	1	Summary of previous gear impact studies inside and outside of closed area, including unpublished monitoring of recovery 1,2, and 5 years after depletion experiment (see #38) using video surveys with ROV and towed camera sled.
Ragnarsson et al 2015 (681)	-	N	N	2	2	3	3 experimental tows 150 m apart in unfished area, impacts and recovery of infauna assessed inside/outside dredge tracks (sediment cores) imm after and 3 mos, 1,2, and 5 yrs after dredging.
Goldberg et al 2012 (682)	683	N	N	2	2	2	BACI study of benthic community effects of hydraulic dredges in a cultivated hard clam bed (M. mercenaria) 2 yrs after most recent commercial harvesting, 3 treatment and 3 control plots sampled with a Smith-McIntyre grab at 1 or 2 wk intervals for 24 wks
Goldberg et al 2014 (683)	682	N	N	2	2	2	BACI study of effects on benthic assemblages and sediment biogeochemistry in a cultivated hard clam bed, 3 treatment and 3 control plots sampled with a Smith-McIntyre grab at 1 or 2 wk intervals for 5 mos
Oberle et al 2015 (684)	-	N	N	1	2	2	Study relating trawling intensity to surface and sub-surface sediment characteristics (clay content/loss, porosity, mixing) in bottom cores (up to 50cm deep), with descriptions of 5 impact scenarios

Table 2. Gears evaluated, by study. Note that all trawl types and both trap types were grouped for the matrix-based assessment.

Citation	*Generic otter trawl*	*Shrimp trawl*	*Squid trawl*	*Raised footrope trawl*	*Scallop dredge*	*Hydraulic dredge*	*Lobster trap*	*Deep-sea red crab trap*	*Longline*	*Gillnet*	*Gear notes*
Coggan et al 2001 (414)	x	x	x	x							
Probert et al 1997 (541)	x										
Lindgarth et al 2000 (575)		x									
Simboura et al 1998 (599)	x										
Hinz et al 2009 (658)	x		x								Nephrops and gadid trawl fisheries, trawling intensity ranged from 1.3 to 18.2 times trawled/yr, area fished for >100 yrs
Thorarinsdottir et al 2008 (669)						x					
Gilkinson et al 2015 (670)						x					
Lindholm et al 2015 (671)	x										Bottom trawl with 20 cm diameter footrope configured with 10 and 20 cm spaced evenly along footrope at 1-m intervals, allowing smaller discs to ride above the bottom; area not trawled since before 2000
Atkinson et al 2011 (672)	x										Lightly trawled = less than 1 time per yr; Heavily trawled = 1 to 2.5 times per yr
Ragnarsson & Lindegarth 2009 (673)	x										Headrope 25 m, rigged with 45cm rockhoppers, swath 80-120m wide towed 10x in each of 4 plots at 3.5 kts in June 1997.
LeBlanc et al 2015 (674)					x						4 m wide Digby scallop dredge with a 4.3 m wide 300 kg steel tow bar, referred to as a "rock dredge" and has fixed teeth in front.
Sciberras et al 2013 (675)					x						Commercial scallop dredge used in area presumably a toothed Newhaven dredge
Cook et al 2013 (676)	x										Otter trawl impact at one site, scallop dredge at the other (not NB dredge); gear impacts result of unplanned single tows through mussel beds by commercial vessels
Hinz et al 2012 (677)	x				x						Two gangs of 4 spring-loaded Newhaven dredges, a modified dredge (no teeth), and an otter trawl with rock hopper ground gear, each towed over same area in 4 replicated 40m wide tracks in a scallop fishing ground not fished in previous 7 months
Buhl-Mortensen et al 2016 (678)	x										Norwegian trawlers fish for whitefish (gadids) at 100-400 m in this area.
Pitcher et al 2009 (679)		x									Two vessels towed side-by-side parallel tracks that covered each exp plot uniformly with a single pass, nets with ground chains, NOT same as New England shrimp nets
Pitcher et al 2016 (680)		x									
Ragnarsson et al 2015 (681)						x					

Citation	***Generic otter trawl***	***Shrimp trawl***	***Squid trawl***	***Raised footrope trawl***	***Scallop dredge***	***Hydraulic dredge***	***Lobster trap***	***Deep-sea red crab trap***	***Longline***	***Gillnet***	***Gear notes***
Goldberg et al 2012 (682)						x					
Goldberg et al 2014 (683)						x					
Oberle et al 2015 (684)	x										Sampling (18 cores) in untrawled and locations trawled by commercial vessels up to 12-15 times a year, mostly at 100-130m

Table 3. Study environment. For the matrices, the following categories were combined to designate studies belonging in particular cells: If energy was listed as high, high-inferred, both, or unknown, the study was added to the high energy column; similarly, low, low-inferred, both, or unknown was added to the low energy column. For substrate, clay-silt and muddy sand were assigned to mud; muddy sand and sand were assigned to sand. Rock outcrop was assigned to boulder.

Citation	*Location*	*Energy*	*Energy notes*	*Depth range*	*Clay-silt*	*Muddy sand*	*Sand*	*Granule-pebble*	*Cobble*	*Boulder*	*Rock outcrop*	*Substrate notes*
Coggan et al 2001 (414)	Clyde Sea and Aegean Sea	2	Clyde Sea site depths ranged 30-100 m, water column remains stratified much of year; Aegean Sea sites 70-250 m	30-250	x	x	x					Clyde Sea - mud, muddy-sand, or sandy-mud at all depths; Aegean Sea - sand/maerl at shallower depths, mud at deeper depths
Probert et al 1997 (541)	New Zealand seamounts on Chatham Rise: Graveyard, Spawning Box, NE Area	2	-	662-1524							x	Hills and flats examined; substrate not well specified
Lindgarth et al 2000 (575)	Gullmarsfjorden, Sweden	2	Inferred from depth and sediment type	75-90	x							Study area is described in Hansson et al (2000)
Simboura et al 1998 (599)	Two adjacent gulfs in the Aegean Sea.	4	Most sites 60-70 m, some shallower	31-70	x	x	x					Approx. 100% finer sed at S. Evvoikos and sand (70-83%) at Petalioi
Hinz et al 2009 (658)	Northeastern Irish Sea off the Cumbrian coast (same area as #292)	1	shear stress at 15 sites that were analyzed averaged 0.21 N/m2 (based on 2D hydrographic model): 0.21 N/m2 is moderate energy, but see #292.	31	x	x						Mostly fine sand and muddy sediment deposits, average 67% (+- 14%) silt and clay at 15 analyzed sites
Thorarinsdottir et al 2008 (669)	Iceland	3	High energy zone as evidenced by removal of substrate by a storm	10			x					-
Gilkinson et al 2015 (670)	Banquereau Bank, Scotian Shelf, eastern Canada	1	-	65-75			x					-
Lindholm et al 2015 (671)	Outer continental shelf in central California	1	-	170		x	x					Low relief, unconsolidated sediments
Atkinson et al 2011 (672)	West coast of South Africa	1	-	350-450		x	x					Signif differences in sediment compostion among the four sites, but only two with differences between trawling treatments
Ragnarsson & Lindegarth 2009 (673)	Iceland	3	Storms are frequent at study site	32-35		x	x					-
LeBlanc et al 2015 (674)	Southern Gulf of St Lawrence	3	Both sites exposed to ice scour in winter and moderate currents at other times of year	8-27			x	x	x			Sand-gravel over bedrock at NS site (20.6-26.5m) and gravel-cobble at BdC site (7.8-10.6m).

Citation	*Location*	*Energy*	*Energy notes*	*Depth range*	*Clay-silt*	*Muddy sand*	*Sand*	*Granule-pebble*	*Cobble*	*Boulder*	*Rock outcrop*	*Substrate notes*
Sciberras et al 2013 (675)	Cardigan Bay, Wales	3	Moderate, exposed to SW and W gales	30			x	x	x			Mostly sand and gravel with some cobble
Cook et al 2013 (676)	Irish Sea	4	-	30-33			x					*Modiolus* (horse mussel) reefs
Hinz et al 2012 (677)	Isle of Man, Irish Sea	4	-	20-23			X					Fine sand with shell debris
Buhl-Mortensen et al 2016 (678)	Southern Barents Sea in northern Norway	5	-	50-400	x	x	X	x	x	x	x	Six classes of substrata (mud, sand, pebbles, cobbles, boulders, and outcrops) condensed to mud, sand, and hard bottom for analysis.
Pitcher et al 2009 (679)	Great Barrier Reef, NE Australia	4	-	15-50		x	x					Shallow plots (15-25m) located on sandy tops of shoals, deep plots (30-50m) off the banks
Pitcher et al 2016 (680)	Great Barrier Reef, NE Australia	4	-	0								See individual publications
Ragnarsson et al 2015 (681)	Iceland	3	Study site subject to severe storms	10			X					Tightly packed fine sand
Goldberg et al 2012 (682)	Long Island Sound	4	-	5-6			X					-
Goldberg et al 2014 (683)	Long Island Sound	4	-	3-5			X					-
Oberle et al 2015 (684)	NW Iberian Shelf	1	Storms in study area rare	95-251	x							Mid-shelf region where most cores were collected in NW Iberian mud belt

Table 4. Geological features evaluated by various studies. Only studies that evaluated geological features are included in the table.

Citation	*Surfacne and subsurface sediments*	*Biogenic depressions*	*Biogenic burrows*	*Bedforms*	*Scattered gravel*	*Gravel pavement*	*Piled gravel*	*Shell deposits*	*Geo-chemical*	*Geological impacts description*
Simboura et al 1998 (599)	x									Sediments better sorted, higher proportion of fines at S. Evvoikos than Petalioi. Not clear if these differences were related to fishing directly or to degree of enclosure of area.
Gilkinson et al 2015 (670)	x							x		Tracks only partially degraded after 5 years; after 10 yrs tracks were faint and had nearly disappeared over half their length; winter storm waves (height 11 m) major cause of degradation at this depth; scattered, small shell patches appeared after 5 yrs
Lindholm et al 2015 (671)		x	x	x						Scour marks from doors still visible after 1 yr; no signif impact to microtopographic complexity (one exception 6 mos after high intensity trawling), but never higher in trawled plots
Ragnarsson et al 2015 (681)	x									Surficial sediments in tracks smoother and more fluidized than controls throughout study period
Goldberg et al 2014 (683)									x	Results of biological analyses same as in study #682. Similarly, there were no significant differences between dredged and not dredged plots for any of the chemical parameters measured, only some differences related to shore position and/or sediment grain size.
Oberle et al 2015 (684)									x	Results show chronic trawling-induced sediment distrurbance: lower near surface clay content, lower mean porosity with no decrease with depth, and sub-surface sediment mixing

Table 5. Biological features evaluated by various studies. Seagrass was not carried forward into the matrices. Only studies that evaluated biological features are included in the table.

Citation	*Sponge*	*Bryozoan*	*Hydroid*	*Emergent anemone*	*Burrowing anemone*	*Soft corals*	*Hard corals*	*Sea pens*	*Tube worms*	*Bivalves*	*Brachiopods*	*Ascidians (tunicates)*	*Macroalgae*	*Sea grass*	*Impacts description*
Probert et al 1997 (541)						x	x	x							Difference betw invert macro caught in hills and flats, and also difference between hills
Hinz et al 2009 (658)															Epifauna includes fish, some species are prey, no structure-forming taxa (see paper (Table 6). Epifaunal abundance 81% lower from low to high trawling intensity, no effect on biomass; at indiv species level no sig linear relation between trawl intensity and abundance.
Lindholm et al 2015 (671)				x				x							No signif differences in densities of sessile inverts between control and trawled plots
Atkinson et al 2011 (672)															Marked differences in epifaunal assemblages between sites and between trawling treatments at all sites; abundance, number of species, and species diversity decreased with increasing trawling intensity
LeBlanc et al 2015 (674)	x			x	x					x					No signif short or long-term impacts on indiv taxa (ex starfish), no evidence for greater effects of first pass; signif site-wide changes in abundance unrelated to fishing (eg seasonal) much more prevalent than changes related to fishing intensity
Sciberras et al 2013 (675)		x	x			x				x		x			No differences in diversity or community composition between study areas, temporal changes driven by seasonal fluctuations and natural disturbance, not related to recovery
Cook et al 2013 (676)		x				x				x		x			*M. modiolus, Alcyonium digitatum, Ophiothrix fragilis, Ascidiella* sp., *Flustra foliacea, Pyura* sp., *Antedon bifida, Anomiidae.* Significant impacts on epifaunal community composition at both sites, 85% average dissimilarity inside and outside of trawl track, 31% inside/outside of dredge track; no evidence of recovery two years after otter trawl pass.
Hinz et al 2012 (677)						x									Significant percentage changes in total abundance and biomass not detected for any gear or the control; abundance and biomass of brittle star *O. ophiura* significantly decreased after fishing with all 3 gears, scavengers (eg starfish) increased
Buhl-Mortensen et al 2016 (678)	x	x		x		x	x	x		x	x	x			Five species most associated with low fishing intensity (FI) and low density of trawl marks = a hard coral, sea pen, sea urchin, polychaete, and a hydroid. An anemone + 4 sponges (discarded?) most typical of high FI areas, no encrusting organisms in locations with high FI. Invertebrate density and diversity was significantly lower in areas with higher FI in sandy and hard substrates, but not in mud. 79 of 97 most common taxa showed a negative trend with increased FI; of nine that were S, five were sponges.
Pitcher et al 2009 (679)	x	x	x	x		x	x			x		x			300 species or taxa collected in prawn trawl and dredge were analyzed. Only 6 taxa showed significant unambiguous impact effects; most differences were also affected by depth and/or season. Impacts evenly divided between + and -. Overall impact on total B = ca 3%, range 0-ca 20% for sensitive sessile species.
Pitcher et al 2016 (680)	x					x	x					x			Recovery rates varied from rapid (7-12% per yr) for some soft corals and ascidians to slow (<1-2%) for some sponges and gorgonians. 20-75% of ca 20 species analyzed recovered to ref levels in 5 yrs, others est to take up to several decades.

3.0 Estimating susceptibility and recovery for biological and geological features

This section describes updates to the matrix-based approach used to estimate vulnerability (i.e. susceptibility and recovery) of geological and biological habitat features to fishing gear impacts.

3.1 Methods: S-R matrices

The same as SASI, the FE model disaggregates fishing effort by gear type, and classifies habitat into six types based on five substrate types (mud, sand, granule-pebble, cobble, boulder). The FE model adds a steep and deep habitat type expected to contain deep-sea corals and other associated species. Geological and biological features are inferred to each of these habitat types, as specific in NEFMC 2011, with steep and deep features identified in the tables below. With respect to a feature-gear-substrate-energy combination, 'vulnerability' represents the extent to which the effects of fishing gear on a feature are adverse. 'Vulnerability' is defined as the combination of how susceptible the feature is to a gear effect and how quickly it can recover following the fishing impact. Specifically, susceptibility is defined as the percentage of total habitat features encountered by fishing gear during a hypothetical single pass fishing event that have their functional value reduced, and recovery is defined as the time in years that would be required for the functional value of that unit of habitat to be restored. Functional value is intended to indicate the usefulness of that feature in its intact form to a fish species requiring shelter. This relative usefulness as shelter can be extended to the prey of managed species as well, which provides indirect benefits to the managed species. However, because functional value is difficult to assess directly, and will vary for each managed species using the feature for shelter, feature removal or damage is used as a proxy for reduction in functional value. Results such as percent reduction of a geological or biological feature are common in the gear impacts literature. The definitions of vulnerability, susceptibility, and recovery are unchanged from SASI, but worth repeating here as the concepts are so central to the modeling framework.

In order to make the susceptibility and recovery information work as a set of model parameters, the susceptibility and recovery of each feature-gear-substrate-energy combination were scored on a 0-4 scale as described in Table 6. The additional recovery score of 4 (10-50 years) was added for the FE model to accommodate deepwater habitat types. The scaling process eliminated any differentiation in units (i.e. percent change for susceptibility vs. time for recovery). The scale is also intended to compare the magnitidue of susceptibility and recovery values, since susceptibility and recovery are closely related. Susceptibility and recovery scoring was done by the Habitat Plan Development Team during 2009-2010 to support development of SASI (methods and results are detailed in NEFMC 2011 and Grabowski et al. 2014). Briefly, susceptibility and recovery were scored based on information found in the scientific literature, to the extent possible, combined with professional judgment where research results are lacking or inconsistent. Quantitative susceptibility percentages in Table 6 indicate the proportion of features in the path of the gear likely to be modified to the point that they no longer provide the same functional value. Recovery does not necessarily mean a restoration of the exact same features, but that after recovery the habitat would have the same functional value.

Table 6. Susceptibility and recovery values. The score of 4 is only used in specific steep and deep/deep-sea coral areas.

Code	*Quantitative definition of susceptibility*	*Quantitative definition of recovery*
0	0–10%	< 1 year
1	>10%-25%	1-2 years
2	25-50%	2 – 5 years
3	>50%	> 5 years
4	n/a	10-50 years

The gear/habitat combinations evaluated are listed in Table 7. Each matrix includes the features present in that particular substrate and energy environment, gear effects related to that gear type and feature combination, susceptibility and recovery for each feature, and the literature deemed relevant to assigning S and R for a particular feature and gear combination.

Table 7. Matrices evaluated. Each substrate-type matrix included both energy environments and all associated features.

Gear type	*Mud*	*Sand*	*Granule-pebble*	*Cobble*	*Boulder*	*Steep and Deep*
All trawl gears	X	X	x	X	X	X (New)
Scallop dredge	X	X	X	X	X	
Hydraulic dredge	-	X	X	X (New)	X (New)	
Longline	X	X	X	X	X	X (New)
Gillnet	X	X	X	X	X	X (New)
Trap	X	X	X	X	X	X (New)

3.2 Results: S-R matrices

The following sections present the S-R matrices by gear type (otter trawl, scallop dredge, hydraulic dredge, longline, gillnet, and trap). To save space, justifications for the scores are presented separately.

3.2.1 Demersal otter trawls

Table 8 shows trawl gear S/R values, grouped by substrate and then by feature. Table 9 summarizes the justification for the susceptibility scores for trawl gear. Justifications for recovery scores for all gear types are combined into two tables at the conclusion of the matrix results section (Table 17, geological, Table 18, biological).

Table 8. Trawl gear matrices. Susceptibility (S) values are coded as follows: 0: 0-10%; 1: >10-25%; 2: >25-50%; 3: >50%. Recovery (R) values are coded as follows: 0: <1 year; 1: 1-2 years; 2: 2-5 years; 3: >5 years. The literature column indicates those studies identified during the literature review as corresponding to that combination of gear, feature, energy, and substrate. The studies referenced here were intended to be inclusive, so any particular study may or may not have directly informed the S or R score. Any literature used to estimate scores is referenced in Table 9 (Trawl S), Table 17 (Geo R), and Table 18 (Bio R).

Gear: Trawl					
Substrate: Mud					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Biogenic burrows (G)	filling, crushing	334, 408, 409	97, 101, 313, 333, 336, 407, 671	2	0
Biogenic depressions (G)	filling	236, 408, 409	101, 247, 336, 671	2	0

Sediments, surface/subsurface (G)	re-suspension of fine sediments, compression, geochemical, mixing	88, 92, 211, 236, 330, 334, 406, 408, 409, 599	88, 97, 211, 247, 277, 283, 313, 320, 333, 335, 336, 338, 372, 407, 414, 684	2	0
Amphipods, tube-dwelling (B) – see note	crushing	34, 113, 119, 211, 228, 292, 334, 408, 409, 599, 658	89, 80, 97, 113, 149, 320, 575	1	0
Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	none	none	2	2
Corals, sea pens (B)	breaking, crushing, dislodging, displacing	none	101, 164	2 (low energy only)	2 (low energy only)
Hydroids (B)	breaking, crushing, dislodging, displacing	408, 409, 679	368	1	1
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	21, 34, 368, 408, 409	89, 203, 360, 368, 678	1	3
Substrate: Sand					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Bedforms (G)	smoothing	11, 35, 225, 408, 409	671 (parameter not scored)	2 (high energy only)	0 (high energy only)
Biogenic burrows (G)	filling, crushing	225, 334, 355, 408, 409	97, 101, 128, 313, 325, 336, 355, 671	2	0
Biogenic depressions (G)	filling	11, 35, 225, 355, 408, 409	97, 101, 247, 325, 336, 355, 671	2	0
Sediments, surface/subsurface (G)	resuspension, geochemical, mixing and resorting	35, 92, 120, 225, 236, 330, 334, 408, 409, 599	97, 128, 214, 247, 313, 325, 336, 414	2	0
Shell deposits (G)	displacing, burying, crushing	11, 225	101, 325	1	1 (high), 2 (low)
Amphipods, tube-dwelling (B) – see note	crushing	113, 225	34, 97, 113, 119, 141, 194, 228, 292, 334, 408, 409, 599, 658	1	0
Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	228	None	2	2
Ascidians (B)	breaking, crushing, dislodging, displacing	11, 34, 38, 157, 238, 368, 676, 679, 680	203, 360, 368, 678	2	1
Corals, sea pens (B)	breaking, crushing, dislodging, displacing	228, 248	101, 247, 671	2 (low energy only)	2 (low energy only)
Hydroids (B)	breaking, crushing, dislodging, displacing	11, 34, 38, 69, 70, 71, 157, 184, 225, 228, 285, 368, 408, 409, 679	360	1	1
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	38, 69, 70, 71, 158, 194, 285, 355, 368, 408, 409, 679, 680	203, 214, 355, 360, 678	1	3
Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B) – see note	breaking, crushing	69, 70, 71, 158, 194, 355, 368, 408, 409, 676, 679, 680	203, 214, 355, 678	1	2
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 158	11, 336	2	2
Sponges (B)	breaking, crushing, dislodging, displacing	11, 34, 38, 70, 71, 157, 225, 228, 238, 248, 285, 368, 382, 387, 408, 409, 679, 680	336, 203, 360, 101, 247, 368, 678	2	2
Substrate: Granule-pebble					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**

Granule-pebble, pavement (G)	burial, mixing, homogenization	none	n/a	1 (high energy only)	0 (high energy only)
Granule-pebble, scattered, in sand (G)	burial, mixing	11	11, 110, 111, 247	1	0 (high), 2 (low)
Shell deposits (G)	burying, crushing, displacing	11, 225	11, 101	1	1 (high), 2 (low)
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	11, 38, 70, 71, 194, 225, 228, 368	11, 101, 111, 678	2	2
Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	70, 71, 194, 228, 404	none	2	2
Ascidians (B)	breaking, crushing, dislodging, displacing	11, 157, 194, 368	11, 678	2	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	194	247, 678	2	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	11, 38, 69, 70, 71, 157, 225, 228, 368, 404	11, 678	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	11, 38, 69, 70, 71, 157, 225, 228, 368, 404	11, 111	1	1
Macroalgae (B)	breaking, dislodging	none	n/a	1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	69, 70, 71, 158, 194, 368, 404	11, 678	2	3
Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B) – see note	breaking, crushing	69, 70, 71, 158, 194, 368, 404	11, 678	1	2
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 158, 404	11	2	2
Polychaetes, other tube-dwelling (B) – see note	crushing, dislodging	11, 69, 70, 71, 158, 404	11	2	1
Sponges (B)	breaking, dislodging, displacing	11, 38, 70, 71 ,157, 225, 228, 248, 368, 387, 404	11, 678	2	2
Substrate: Cobble					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Cobble, pavement (G)	burial, mixing, homogenization	11	n/a	1 (high energy only)	0 (high energy only)
Cobble, piled (G)	smoothing, displacement	none	101	3	3
Cobble, scattered in sand (G)	burial, mixing, displacement	none	11, 110, 111	1	0
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	11, 70, 71, 194	11, 101, 111, 678	2	2
Ascidians (B)	breaking, crushing, dislodging, displacing	11, 157, 194	11, 678	2	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	194	247, 678	2	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 157, 228, 404	11, 678	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 157, 158, 228, 404	11, 110	1	1
Macroalgae (B)	breaking, dislodging	none		1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 158, 194, 404	111, 214, 678	2	3

Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B) – see note	breaking, crushing	11, 69, 70, 71, 158, 194, 404	111, 214, 678	1	2
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	69, 70, 71, 158, 194, 404	none	2	2
Polychaetes, other tube-dwelling (B) – see note	crushing, dislodging	69, 70, 71, 158, 194, 404	none	2	1
Sponges (B)	breaking, dislodging, displacing	11, 70, 71, 157, 158, 228, 404	11, 101, 110, 111, 678	2	2
Substrate: Boulder					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Boulder, piled (G)	displacement	none	101, 111	2	3
Boulder, scattered, in sand (G)	displacement	none	110, 111	0	0
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	none	11, 111, 678	2	2
Ascidians (B)	breaking, crushing, dislodging, displacing	none	11, 678	2	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	194	247, 678	2	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	none	11, 678	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	none	11, 110	1	1
Macroalgae (B)	breaking, dislodging	none	n/a	1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	none	11, 111, 214, 678	2	3
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	none	none	2	2
Polychaetes, other tube-dwelling (B) – see note	crushing, dislodging	none	none	2	1
Sponges (B)	breaking, dislodging, displacing	none	11, 110, 111, 678	2	2
Habitat: Steep and Deep					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Biogenic burrows (G)	filling, crushing	n/a	None	2	0
Biogenic depressions (G)	filling	n/a	None	2	0
Boulder, piled (G)	Displacement	n/a	None	2	3
Boulder, scattered (G)	Displacement	n/a	None	0	0
Cobble, piled (G)	smoothing, displacement	n/a	None	3	3
Cobble, scattered in sand (G)	burial, mixing, displacement	n/a	None	1	0
Granule-pebble, scattered, in sand (G)	burial, mixing	n/a	None	1	2
Sediments, surface/subsurface (G)	re-suspension of fine sediments, compression, geochemical, mixing	n/a	None	2	0
Amphipods, tube-dwelling (B) – see note	Crushing	n/a	None	1	0
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	n/a	678	2	3
Anemones, tube dwelling (B)	breaking, crushing, dislodging, displacing	n/a	None	2	3

Ascidians (B)	breaking, crushing, dislodging, displacing	n/a	678	2	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	n/a	678	2	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	n/a	678	1	1
Corals, sea pens (B)	breaking, crushing, dislodging, displacing	n/a	541, 678	2	3
Hydroids (B)	breaking, crushing, dislodging, displacing	n/a	None	1	1
Polychaetes, other tube-dwelling (B)	breaking, crushing, dislodging, displacing	n/a	None	2	1
Sponges (B)	breaking, crushing, dislodging, displacing	n/a	678	2	3
Corals, soft or stony (B)	breaking, crushing, dislodging, displacing	n/a	541, 678	3	4

Note: Only reference 225 is specific to tube-dwelling amphipods, the rest are derived from entries in database coded as prey/amphipods. Similarly, references for epifaunal bivalves/ scallops and other tube-dwelling polychaetes are based on database entries for epifaunal bivalves/mussels and polychaetes/F. implexa.

Table 9. Trawl gear susceptibility summary for structural features.

Feature	*Substrates evaluated*	*Score*	*Notes*
Amphipods, tube-dwelling	Mud, sand, steep/deep	1	Tubes are pliable and only extend 2-2.5 cm above bottom, therefore susceptibility to single tows was assumed to be low. “Disruption” of amphipod tube mats on Fippennies Ledge (GOM) after commercial scallop dredging (217).
Anemones, actinarian	Granule-pebble, cobble, boulder, steep/deep	2	Anemones are able to retract tentacles, which may offer some protection. 50% reduction after single tows in a low energy area, but anemones remaining on seabed were undamaged (111). *Urticina* sp. on west coast ca 75% less abundant in heavily trawled area than in adjacent lightly trawled area at same depth (101)
Anemones, cerianthid burrowing	Mud, sand, granule-pebble, steep/deep	2	Anemones can retract into semi-rigid tubes. Tubes of largest species (Cerianthus borealis) extend 15 cm above sediment surface and are susceptible to trawls. E.g., the only large organism in study 194 that showed significant decline (> 50%) after trawling (12-14 tows) was *Cerianthus* sp. However, Shepard et al. (1986) surmised that because the tubes of larger cerianthids are deeply buried, shallow grab samples extending only 3-5 cm into the seabed would be unlikely to dislodge these specimens. A similar resistance to fishing gear that skims the sediment surface seems likely. However, this does not mean that the gear does not damage the tube, perhaps making the anemone more vulnerable to predation. It is important to note that tubes of another species (*Cerianthiopsis americanus*) do not extend above the sediment and the tentacle whorl is nearly flush with the sediment surface. William High, in a NMFS Northwest Center report, describes direct observations of trawl groundlines pinching cerianthids between rollers or bobbins or cookies and pulling them out of the bottom. Hence, they are not fully immune due to a retraction response. Andy Shepard also collected cerianthids using the grab sampler on the Johnson-Sea-Link submersible. He was able to collect specimens with a fast “grab”, also indicating they are not all that quick.
Ascidians	Sand, granule-pebble, cobble, boulder, steep/deep	2	>25% reductions 1 wk and 3 mo after 2 tows with prawn trawl (chain sweeps) in sand (360)
Bedforms	Sand	2	Smoothing of seafloor (see 97, 247, 325,336), assume that smaller ripples in mud and sand would be fully susceptible, larger sand waves in sand would be less

Feature	***Substrates evaluated***	***Score***	***Notes***
			susceptible, no data indicating degree of disturbance from a single tow, probably highly variable, assume 25-50% loss.
Biogenic burrows	Mud, sand, steep/deep	2	Major issue is smoothing of 'surface features' (97, 236, 247, 387, 408), also removal of 'mounds, tubes, and burrows' following trawling (325); no data indicating degree of disturbance from a single tow, assume 25-50% loss.
Biogenic depressions	Mud, sand, steep/deep	2	See above for biogenic burrows.
Boulder, piled	Boulder, steep/deep	2	Assume that displacement of piled boulders would be more likely than displacement of scattered boulders. Loss of deep crevice habitats, potentially greater effect than on piled cobbles, but boulders are more resistant to disturbance because of their size.
Boulder, scattered in sand	Boulder, steep/deep	0	Average 19% displacement of boulders by single tows in a deep, undisturbed environment (111), similar results in Gulf of Maine observational study (11), but no burial, so there is no loss of physical habitat. S scores are based on probability that cobble or boulder would be buried, or partially buried, by gear (higher S for cobble reflects a higher assumed likelihood of burial for smaller sediment sizes). It was assumed that if a cobble or boulder has a depression under it/beside it and it is rolled over or moved, that it is likely to have a new depression in its new location. Thus, its functional value as a habitat is the same. If the depressions under cobble/boulders are biogenic, it was assumed that the biogenic depression under the cobble or boulder is susceptible if the cobble or boulder is susceptible, thus scores of S=1 cobble, S=0 boulder.
Brachiopods	Granule-pebble, cobble, boulder, steep/deep	2	62% reduction in biomass after two years of experimental trawling on Scotian shelf (est 1-4 passes each year, see 194); thus a lower percentage reduction expected after single pass.
Bryozoans	Granule-pebble, cobble, boulder, steep/deep	1	Bushy bryozoans significantly more abundant at shallow and deep sites undisturbed by fishing on Georges Bank, emergent growth form makes them vulnerable to fishing gear, but not as much as sponges, which generally are taller (404), one of erect but flexible taxa attached to cobbles that likely passed under trawl and rockhoppers with only limited harm on Scotian shelf (157). S=1 based on best professional judgment.
Cobble, pavement	Cobble	1	Assume that largest impact would be from doors but that overall only 10-25% of feature would be lost (buried) due to size of cobbles
Cobble, piled	Cobble, steep/deep	3	Assume that displacement of piled cobbles would be more likely than displacement of scattered cobbles and would have greater impact because of reduced three-dimensional structure and fewer shelter-providing crevices
Cobble, scattered in sand	Cobble, steep/deep	1	S scores are based on probability that cobble or boulder would be buried, or partially buried, by gear (higher S for cobble reflects a higher assumed likelihood of burial for smaller sediment sizes). It was assumed that if a cobble or boulder has a depression under it/beside it and it is rolled over or moved, that it is likely to have a new depression in its new location. Thus, its functional value as a habitat is the same. If the depressions under cobble/boulders are biogenic, it was assumed that the biogenic depression under the cobble or boulder is susceptible if the cobble or boulder is susceptible, thus scores of S=1 cobble, S=0 boulder.
Corals, sea pens	Mud, sand, steep/deep	2	Significantly lower densities of sea pens (>100% *Ptilosarcus* sp., 80% *Stylatula* sp.) in heavily trawled area than in adjacent lightly trawled with same depth on west coast (101), no experimental before/after impact studies, S=2 based on their size (10 cm for *Pennatula aculeata*) and fact that they don't retract into bottom when disturbed (102)

Feature	***Substrates evaluated***	***Score***	***Notes***
Granule-pebble, pavement	Granule-pebble	1	Assume pavement broken up mostly by trawl doors and partially buried by sand stirred up by ground cables, sweep, and net, with "loss" of 10-25% of this feature after a single tow.
Granule-pebble, scattered in sand	Granule-pebble, steep/deep	1	Rock-hoppers left 1-8 cm deep furrows in low energy pebble bottom (111) - effects of smaller ground gear (e.g., rollers, chain sweeps) probably less severe; granules and pebbles are small and are susceptible to burial in sand, reducing amount of hard substrate available for growth of emergent epifauna
Hydroids	Mud, sand, granule-pebble, cobble, boulder, steep/deep	1	Significant decrease in hydroid biomass after trawling (12-14 tows) on Scotian shelf, erect but flexible morphology, low relief, reduces vulnerability to trawls and dredges (see bryozoans) (157); significantly more abundant at deep sites on George Bank undisturbed by trawls and scallop dredges, no difference at shallow sites where densities were lower (404); aggregations of *Corymorpha pendula* "absent" in trawl and scallop dredge paths in coarse sand on Stellwagen Bank (11).
Macroalgae	Granule-pebble, cobble, boulder	1	Flexible body morphology, relatively short height of many species (e.g., red algae in deeper water), assumed to limit removal/structural loss to 10-25% per tow. Although the larger kelps (*Laminaria* spp.) would likely be more susceptible, kelps are relatively rare in their distribution offshore, so the score is intended reflect the susceptibility of smaller algae.
Mollusks, epifaunal bivalve, *Modiolus modiolus*	Mud, sand Granule-pebble, cobble, boulder	1 2	80% reductions in abundance of epifaunal bivalve *Hiatella* sp. Barents Sea after 10 tows (214); >60% reduction in biomass of horse mussels in cobble on Scotian shelf after 2 years of repeated tows (1-4 each year), 8% mussels remaining on bottom were damaged after 1st year (194). *Pinna* sp. reduced >25% 1 wk and 3 mos after 2 tows in mud (360). Horse mussels sensitive to bottom fishing (long-lived, thin-shelled - see 404), partially buried in mud and sand, therefore assumed to be less vulnerable than in gravel substrates.
Mollusks, epifaunal bivalve, *Placopecten magellanicus*	Sand, granule-pebble, boulder	1	Trawls not as efficient as scallop dredges at removing scallops from bottom (S=2 for scallop dredges)
Polychaetes, *Filograna implexa*	Sand, granule-pebble, cobble, boulder	2	Significantly more at shallow sites disturbed by trawling and dredging on Georges Bank, fewer at deep disturbed sites, tubes heavily affected by bottom fishing because they can be easily crushed and require stable substrate (404), susceptibility based on data for *T. cincinnatus* (see below).
Polychaetes, other tube-dwelling	Granule-pebble, cobble, boulder, steep/deep	2	37% reduction in biomass of *Thelepus cincinnatus* on Scotian shelf after two years of experimental trawling (1-4 tows/yr), 9% on bottom damaged (194)
Sediments, surface/subsurface	Mud, sand, steep/deep	2	Doors create furrows up to 20 cm deep, 40 cm wide, with berms 10-20 cm high in mud (92, 97, 236, 320, 372, 88, 247, 164, 277, 406, 336, 313, 408), shallower furrows in sand (97, 120, 325), but effect is limited to doors. Ground rope and tickler chains also leave marks, mostly in fine sediment (247, 406). Major issue is re-suspension: trawling causes loss of fine surficial sediment (88, 236, 277, 325, 406); also removal of flocculent organic material (325). Little or no evidence that remaining sediments (mud or sand) are re-sorted (35, 325, 372, 408), some evidence that sand is compacted (336), but mud bottom is not "plowed" (236). Assume all fine surficial sediment in path of trawl is subject to re-suspension during a tow, but mud is more susceptible than sand because of its biogenic structure and because it is more easily re-suspended by turbulence. Scores based on professional judgment and comparison with hydraulic dredges which have much greater effects in sand, esp sub-surface sediments. Aside from door

Feature	***Substrates evaluated***	***Score***	***Notes***
			tracks, trawls primarily affect top few cm of sediment, reducing functional value of habitat for prey organisms. (Also see scallop dredges).
Shell deposits	Sand, granule-pebble	1	Assume that displacement is more likely than burying or crushing, and that the effects of a single tow are minor (mostly trawl doors) because shells are large and aggregated in a mud or sand matrix.
Sponges	Sand, granule-pebble, cobble, boulder, steep/deep	2	Variations in morphology likely to influence susceptibility; values given in literature are highly variable. In 382, 30-50% reduction in density after one tow (mostly barrel sponge, other spp not signif affected), with 32% damage to sponges remaining on bottom. In 111, 30% reduction in density, heavy damage to some types (67% for vase sponges), very little damage to others (14% "finger" sponges knocked over). In 387, net removed average 14% per tow (all sizes), but removed 40-70% sponges >50 cm - all large branched sponges that did not pass into net were either removed by footrope or crushed under it. In 248, all epifauna >20cm high reduced (average per tow) by 15% - 50% in 4 tows - but sponges are more susceptible. 10% video frames on Jeffreys Bank (GOM) before trawling with >25% cover (max 35%), no frame with >7% 6 yrs later, after area was trawled.
Deep-sea corals	Steep/deep	3	Assume a high degree of susceptibility based on physical attributes of deep-sea corals.

3.2.2 New Bedford-style scallop dredge

Table 10 shows scallop dredge gear S/R values, grouped by substrate and then by feature. Scores are the same for high and low energy unless otherwise noted. Table 11 summarizes the justifications for susceptibility scores for scallop dredge gear. Recovery scores for all gear types are combined into two tables at the conclusion of the matrix results section (Table 17, geological, Table 18, biological).

Table 10 . Scallop dredge matrices. Susceptibility (S) values are coded as follows: 0: 0-10%; 1: >10-25%; 2: >25-50%; 3: >50%. Recovery (R) values are coded as follows: 0: <1 year; 1: 1-2 years; 2: 2-5 years; 3: >5 years. The literature column indicates those studies identified during the literature review as corresponding to that combination of gear, feature, energy, and substrate. The studies referenced here were intended to be inclusive, so any particular study may or may not have directly informed the S or R score. Any literature used to estimate scores is referenced in Table 11 (Scallop dredge S), Table 17 (Geo R), and Table 18 (Bio R).

Gear: Scallop					
Substrate: Mud					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Biogenic burrows (G)	filling, crushing	none	none	2	0
Biogenic depressions (G)	filling	11	11	2	0
Sediments, surface/subsurface (G)	resuspension, compression, geochem, sorting, mixing	42, 236, 256, 391	none	2	0
Amphipods, tube-dwelling (B) – see note	crushing	228, 359	217	1	0
Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	228	217	2	2
Corals, sea pens (B)	breaking, crushing, dislodging, displacing	228	none	2 (low energy only)	2 (low energy only)
Hydroids (B)	breaking, crushing, dislodging, displacing	11, 228	11	1	1

Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	42, 43, 256	203, 217	1	3
Substrate: Sand					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Bedforms (G)	smoothing	11, 225, 236, 359	n/a	2 (high energy only)	0 (high energy only)
Biogenic burrows (G)	filling, crushing	225	none	2	0
Biogenic depressions (G)	filling	11, 225 ,359	11, 359	2	0
Sediments, surface/subsurface (G)	resuspension, compression, geochem, sorting/mixing	42, 119, 225, 236, 256, 352, 359, 391	none	2	0
Shell deposits (G)	displacing, burying, crushing	11, 225, 352	11	1	1 (high), 2 (low)
Amphipods, tube-dwelling (B) – see note	crushing	225, 228, 359	217	1	0
Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	70, 71, 228, 352, 674	217	2	2
Ascidians (B)	breaking, crushing, dislodging, displacing	11, 352, 675	203	2	1
Corals, sea pens (B)	breaking, crushing, dislodging, displacing	228	none	2 (low energy only)	2 (low energy only)
Hydroids (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 225, 228, 352	11	1	1
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	42, 43, 69, 70, 71, 158, 352	203, 217	1	3
Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B) – see note	breaking, crushing	42, 43, 69, 70, 71, 158, 352, 674, 675	203, 217	2	2
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 158, 352	11, 217	2	2
Sponges (B)	breaking, crushing, dislodging, displacing	11, 70, 71, 225, 228, 352, 674	203	2	2
Substrate: Granule-pebble					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Granule-pebble, pavement (G)	burial, mixing, homogenization	none		1 (high energy only)	0 (high energy only)
Granule-pebble, scattered, in sand (G)	burial, mixing	11, 43, 225, 352	11	1	0 (high), 2 (low)
Shell deposits (G)	burying, crushing, displacing	11, 225, 352	11	1	1 (high), 2 (low)
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	11, 70, 71, 203, 225, 228, 352, 674	none	2	2
Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	70, 71, 228, 352, 404, 674	217	2	2
Ascidians (B)	breaking, crushing, dislodging, displacing	352, 675	203	2	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	none	none	2	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 225, 228, 352, 404, 675	11	1	1

Hydroids (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 225, 228, 352, 404, 675	11	1	1
Macroalgae (B)	breaking, dislodging	none	n/a	1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	43, 69, 70, 71, 158, 352, 404	203, 217	2	3
Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B) – see note	breaking, crushing	43, 69, 70, 71, 158, 352, 404, 674, 675	203, 217	2	2
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 158, 352, 404	11, 217	2	2
Polychaetes, other tube-dwelling (B) – see note	crushing, dislodging	11, 69, 70, 71, 158, 352, 404	11, 217	2	1
Sponges (B)	breaking, dislodging, displacing	11, 70, 71, 225, 228, 352, 404	11, 203	2	2
Substrate: Cobble					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Cobble, pavement (G)	burial, mixing, homogenization	none	n/a	1 (high energy only)	0 (high energy only)
Cobble, piled (G)	smoothing, displacement	none	none	3	3
Cobble, scattered in sand (G)	burial, mixing, displacement	11, 43, 352	11	1	0
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	11, 70, 71, 228, 352, 674	none	2	2
Ascidians (B)	breaking, crushing, dislodging, displacing	11, 352, 675	11	2	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	None	none	2	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 228, 352, 404, 675	11	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 228, 352, 404, 675	11	1	1
Macroalgae (B)	breaking, dislodging	None	n/a	1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	43, 69, 70, 71, 158, 352, 404	217	2	3
Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B) – see note	breaking, crushing	43, 69, 70, 71, 158, 352, 404, 674, 675	217	2	2
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 158, 352, 404	11, 217	2	2
Polychaetes, other tube-dwelling (B) – see note	crushing, dislodging	11, 69, 70, 71, 158, 352, 404	11, 217	2	1
Sponges (B)	breaking, dislodging, displacing	11, 70, 71, 228, 352, 404	11	2	2
Substrate: Boulder					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Boulder, piled (G)	displacement	none	none	2	3
Boulder, scattered, in sand (G)	displacement	11, 43, 352	11	0	0
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	11, 352	none	2	2

Ascidians (B)	breaking, crushing, dislodging, displacing	11, 352	11	2	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	none	none	2	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	11, 352	11	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	11, 352	11	1	1
Macroalgae (B)	breaking, dislodging	none	n/a	1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	43, 352	217	2	3
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	11, 352	11, 217	2	2
Polychaetes, other tube-dwelling (B) – see note	crushing, dislodging	11, 352	11, 217	2	1
Sponges (B)	breaking, dislodging, displacing	11, 352	11, 217	2	2

Note: Only references 217 and 225 are specific to tube-dwelling amphipods, the rest are derived from entries in database coded as prey/amphipods. Similarly, references for epifaunal bivalves/ scallops and other tube-dwelling polychaetes are based on database entries for epifaunal bivalves/mussels and polychaetes/F. implexa.

Table 11. Scallop dredge susceptibility summary for structural features.

Feature	***Substrates evaluated***	***Score***	***Notes***
Amphipods, tube-dwelling	Mud, sand	1	See trawls
Anemones, actinarian	Granule-pebble, cobble, boulder	2	See trawls
Anemones, cerianthid burrowing	Mud, sand, granule-pebble	2	See trawls
Ascidians	Sand, granule-pebble, cobble, boulder	2	*Molgula arenata* removed from sand in linear patterns by scallop dredges on Stellwagen Bank (11), degree of impact assumed to be same as trawls
Bedforms	Sand	2	Multiple tows reduced frequency of sand waves in treatment areas compared to control areas (359), no information for single tows.
Biogenic burrows	Mud, sand	2	Multiple tows reduced frequency of amphipod tube mats in treatment areas compared to control areas (359), no information for single tows.
Biogenic depressions	Mud, sand	2	Multiple tows reduced frequency of biogenic depressions in treatment areas compared to control areas (359), no information for single tows.
Boulder, piled	Boulder	2	No information, see trawls.
Boulder, scattered in sand	Boulder	0	Single tows plowed boulders (43), but probability of burial is assumed to be low (see trawls).
Brachiopods	Granule-pebble, cobble, boulder	2	See trawls
Bryozoans	Granule-pebble,	1	See trawls

Feature	***Substrates evaluated***	***Score***	***Notes***
	cobble, boulder		
Cobble, pavement	Cobble	1	Single tows dislodged cobbles (43)
Cobble, piled	Cobble	3	
Cobble, scattered in sand	Cobble	1	See trawls
Corals, sea pens	Mud, sand	2	See trawls
Granule-pebble, pavement	Granule-pebble	1	
Granule pebble, scattered in sand	Granule-pebble	1	Single tows overturned and buried gravel fragments (43)
Hydroids	Mud, sand, granule-pebble, cobble, boulder	1	See trawls
Macroalgae	Granule-pebble, cobble, boulder	1	See trawls
Mollusks, epifaunal bivalve, *Modiolus modiolus*	Mud, sand	1	See trawls
	Granule-pebble, cobble, boulder	2	
Mollusks, epifaunal bivalve*,* *Placopecten magellanicus*	Sand, granule-pebble, cobble	2	Scallop dredge efficiency estimated to be 54% per tow (Gedamke et al. 2005), approximately 30% of scallops slightly buried after passage of 8 m dredge (42). Even if removal rates per tow are high (>50%), shucked shells returned to bottom still provide habitat value, so loss of functional value was assumed to be 25-50%.
Polychaetes, *Filograna implexa*	Sand, granule-pebble, cobble, boulder	2	See trawls
Polychaetes, other tube-dwelling	Granule-pebble, cobble, boulder	2	See trawls
Sediments, surface and subsurface	Mud, sand	2	Single tow lowered mud sediment surface 2 cm, mixed finer sediment to 5-9 cm, increasing mean grain size in upper 5 cm (236). Skids left furrows 2 cm deep in mixed mud/sand bottom, depression from tow bar, marks made by rings in chain belly of dredge (42, 43). Multiple tows in mud/muddy sand caused loss of fine sediments and reduced food value in top few cm (391). In sand, single tows re-suspended sand (43), multiple tows re-worked top 2-6 cm of sediments (359). Effects expected to be especially consequential in mud due to presence of biogenic matrix and because mud is more easily re-suspended by turbulence than sand (see trawls).
Shell deposits	Sand, granule-pebble	1	Individual dredge tows dispersed shell fragments in troughs between sand waves (11), degree of impact assumed to be same as trawls.

Feature	***Substrates evaluated***	***Score***	***Notes***
Sponges	Sand, granule-pebble, cobble, boulder	2	Significantly more sponges at shallow sites undisturbed by trawls and scallop dredges on Georges Bank two years after area was closed, but not at deeper sites (404); for before/after impact experiments, see trawls.

3.2.3 Hydraulic clam dredges

Table 12 shows hydraulic dredge gear S/R values, grouped by substrate and then by feature. Scores are the same for high and low energy unless otherwise noted. Table 13 summarizes the justifications for susceptibility scores for hydraulic dredge gear. Recovery scores for all gear types are combined into two tables at the conclusion of the matrix results section (Table 17, geological, Table 18, biological). Cobble and boulder substrates were scored for this update of the model based on Council discussions that occurred after the development of the original model regarding where the gear is fished in relation to the distribution of these sediment types.

Table 12. Hydraulic clam dredge matrices. Susceptibility (S) values are coded as follows: 0: 0-10%; 1: >10-25%; 2: >25-50%; 3: >50%. Recovery (R) values are coded as follows: 0: <1 year; 1: 1-2 years; 2: 2-5 years; 3: >5 years. The literature column indicates those studies idenfied during the literature review as corresponding to that combination of gear, feature, energy, and substrate. The studies referenced here were intended to be inclusive, so any particular study may or may not have directly informed the S or R score. Any literature used to estimate scores is referenced in Table 13 (Hydraulic clam dredge S), Table 17 (Geo R), and Table 18 (Bio R).

Gear: Hydraulic					
Substrate: Sands					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Bedforms (G)	smoothing	none	n/a	3 (high energy only)	0 (high energy only)
Biogenic burrows (G)	filling, crushing	none	121	3	1 (high), 2 (low)
Biogenic depressions (G)	filling	none	none	3	0
Sediments, surface/subsurface (G)	resuspension, compression, geochem, fluidization and resorting	140, 232, 373, 681, 683	121, 670	3	1 (high), 2 (low)
Shell deposits (G)	burying, crushing, displacing	none	121, 670	2	1 (high), 2 (low)
Amphipods, tube-dwelling (B) – see note	crushing	140, 373	122	3	0
Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	none	none	3	3
Ascidians (B)	breaking, crushing, dislodging, displacing	none	none	3	1
Corals, sea pens (B)	breaking, crushing, dislodging, displacing	none	671	3 (low energy only)	2 (low energy only)
Hydroids (B)	breaking, crushing, dislodging, displacing	none	none	3	1
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	287	none	2	3
Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B) – see note	breaking, crushing	287	none	1	2
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	none	none	3	2
Sponges (B)	breaking, crushing, dislodging, displacing	none	none	3	2

Substrate: Granule-pebble

Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Granule-pebble, pavement (G)	burial, mixing, homogenization	none	none	3 (high energy only)	2 (high energy only)
Granule-pebble, scattered, in sand (G)	burial, mixing	none	None	3	1 (high), 2 (low)
Shell deposits (G)	burying, crushing, displacing	none	none	2	1 (high), 2 (low)
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	none	none	3	2
Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	none	none	3	3
Ascidians (B)	breaking, crushing, dislodging, displacing	none	none	3	1 (high), 2 (low)
Brachiopods (B)	breaking, crushing, dislodging, displacing	none	none	3	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	none	none	3	1 (high), 2 (low)
Hydroids (B)	breaking, crushing, dislodging, displacing	none	none	3	1 (high), 2 (low)
Macroalgae (B)	breaking, dislodging	none	none	3 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	none	none	3	3
Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B) – see note	breaking, crushing	none	none	1	2
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	none	none	3	2
Polychaetes, other tube-dwelling (B)	crushing, dislodging	none	none	3	1 (high), 2 (low)
Sponges (B)	breaking, dislodging, displacing	none	none	3	2

Substrate: Cobble

Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Cobble, pavement (G)	burial, mixing, homogenization	none	n/a	1 (high energy only)	0 (high energy only)
Cobble, piled (G)	smoothing, displacement	none	none	3	3
Cobble, scattered in sand (G)	burial, mixing, displacement	11, 43, 352	11	1	0
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	11, 70, 71, 228, 352	none	2	2
Ascidians (B)	breaking, crushing, dislodging, displacing	11, 352	11	2	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	none	none	2	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 228, 352, 404	11	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 228, 352, 404	11	1	1
Macroalgae (B)	breaking, dislodging	none	n/a	1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	43, 69, 70, 71, 158, 352, 404	217	2	3
Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B) – see note	breaking, crushing	43, 69, 70, 71, 158, 352, 404	217	2	2

Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	11, 69, 70, 71, 158, 352, 404	11, 217	2	2
Polychaetes, other tube-dwelling (B) – see note	crushing, dislodging	11, 69, 70, 71, 158, 352, 404	11, 217	2	1
Sponges (B)	breaking, dislodging, displacing	11, 70, 71, 228, 352, 404	11	2	2
Substrate: Boulder					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Boulder, piled (G)	displacement	none	none	2	3
Boulder, scattered, in sand (G)	displacement	11, 43, 352	11	0	0
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	11, 352	none	2	2
Ascidians (B)	breaking, crushing, dislodging, displacing	11, 352	11	2	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	none	none	2	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	11, 352	11	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	11, 352	11	1	1
Macroalgae (B)	breaking, dislodging	none	n/a	1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	43, 352	217	2	3
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	11, 352	11, 217	2	2
Polychaetes, other tube-dwelling (B) – see note	crushing, dislodging	11, 352	11, 217	2	1
Sponges (B)	breaking, dislodging, displacing	11, 352	11, 217	2	2

Note: All references for tube-dwelling amphipods are derived from entries in database coded as prey/amphipods. Similarly, references for epifaunal bivalves/ scallops are based on database entries for epifaunal bivalves/mussels.

Table 13. Hydraulic dredge gear susceptibility summary for structural features.

Feature	*Substrates evaluated*	*Score*	*Notes*
Amphipods, tube-dwelling	Sand	3	Assume pulverizing effect of water pressure would cause 100% destruction of tubes which are soft and attached to bottom, releasing animals into water column where they would be highly susceptible to predation
Anemones, actinarian	Granule-pebble	3	Anemones would be removed from substrate, some might re-attach and survive
Anemones, cerianthid burrowing	Sand, granule-pebble	3	Would expect that most anemones (and tubes) in the path of the dredge would be uprooted due to the depth that pressurized water penetrates into the seabed. Impact could be considerable for uprooted anemones since they are soft bodied and cannot re-bury.
Ascidians	Sand, granule-pebble	3	Tunicates presumed to be highly susceptible to downward effects of water pressure because they are soft-bodied.
Bedforms	Sand	3	Assume that due to fluidizing action of the gear, any smaller bedforms would be completely smoothed. Although larger sand waves might only partially damaged, > 50% susceptibility of feature still expected.
Biogenic burrows	Sand	3	Density of burrows reduced by up to 90%, smoothing of seafloor, after 12 overlapping tows (not 100% replicated) (121)
Biogenic depressions	Sand	3	Any depressions in path of gear would be filled in as sand is fluidized and re-settles in dredge path (see surface sediments)

Feature	***Substrates evaluated***	***Score***	***Notes***
Boulder, piled	Boulder	2	Dredge would knock over boulder piles, reducing number of interstices between boulders
Boulder, scattered in sand	Boulder	2	Depending on their size and position in dredge track, some boulders would be moved to side of dredge track, some picked up in dredge and returned to the bottom from the vessel, and others totally or partially buried in sand kicked up by dredge
Cobble, pavement	Cobble	2	Dredge would re-arrange cobbles and partially bury them
Cobble, piled	Cobble	3	Cobble piles would be more susceptible to dispersal and burial than larger boulders
Cobble, scattered in sand	Cobble	3	Because they are smaller than boulders, the same effects described for boulders, but probability of burial is increased (assume >50%)
Granule-pebble, pavement	Granule-pebble	3	This substrate type only exists in high energy environments; dredge would destroy pebble pavement and replace it temporarily with sand
Granule pebble, scattered in sand	Granule-pebble	3	Re-sorting of sediment in dredge track would cause larger, heavier gravel to be >50% buried by sand (232)
Brachiopods	Granule-pebble	3	Assume that brachiopods attached to gravel in path of dredge would be removed from substrate.
Bryozoans	Granule-pebble	3	See brachiopods.
Corals, sea pens	Sand	3	Assume nearly complete up-rooting of sea pens in dredge path, some of which could re-bury and survive (102)
Granule-pebble, pavement	Granule-pebble	3	Assume that granule-pebble pavement would be affected similarly to scattered granule-pebble.
Granule-pebble, scattered, in sand	Granule-pebble	3	Assume that most granule-pebble in path of dredge would be buried due to re-sorting of sediment (see sub-surface sediment).
Hydroids	Sand, granule-pebble	3	Hydroids are very susceptible to effects of this gear (delicate, soft-bodied)
Macroalgae	Granule-pebble	3	Algae in dredge path would be buried or dislodged from substrate with high mortalities.
Mollusks, epifaunal bivalve, *Modiolus modiolus*	Sand Granule-pebble	2 3	Some mussels dislodged from bottom might re-settle and survive outside dredge paths if they can attach to other mussels or to granule-pebble substrate, but available hard substrate in dredge path would be buried under sand.
Mollusks, epifaunal bivalve, *Placopecten magellanicus*	Sand, granule-pebble	1	Assume most scallops caught in clam dredges are discarded, undamaged, and return to bottom
Polychaetes, *Filograna implexa*	Granule-pebble	3	Assume that *F. implexa* are highly susceptible to breakage/crushing action of water pressure.
Polychaetes, other tube-dwelling	Granule-pebble	3	Assume that most granule-pebble in path of dredge that could be used as substrate would be buried due to re-sorting of sediment (see sub-surface sediment).

Feature	***Substrates evaluated***	***Score***	***Notes***
Sediments, surface and subsurface	Sand	3	Action of this gear fluidizes sediment to depth of 30 cm in bottom of trench and 15 cm in sides (373), compromising functional value of sedimentary habitat for infauna. In addition, resorting of sediments was observed in dredge path – coarser sediments at bottom (232). Dredges create steep-sided trenches 8-30 cm deep with sediment mounds along edges (140, 244, 245, 256, 287, 373). In path of dredge, assume that nearly all of finer surface sediments will be suspended and re-settle outside dredge path, thus functional value will be compromised substantially.
Shell deposits	Sand	2	Shell deposits in path of dredge would likely be somewhat susceptible to burial in dredge paths and by sand that is re-suspended and settles outside of dredge path, but lighter shell fragments re-settle on top of trench (232), so impact may be <50%.
Sponges	Sand, granule-pebble	3	Assume that most granule-pebble in path of dredge that could be used as substrate would be buried due to re-sorting of sediment (see sub-surface sediment).

3.2.4 Fixed gears

Table 14 shows demersal longline and sink gillnet S/R values, grouped by substrate and then by feature. Table 15 shows trap gear S/R values, grouped by substrate and then by feature. Table 16 summarizes the rationale behind the structural feature susceptibility values for all the fixed gears. Recovery scores for all gear types are combined into two tables at the conclusion of the matrix results section (Table 17, geological, Table 18, biological).

Table 14. Demersal longline and sink gillnet matrices. Susceptibility (S) values are coded as follows: 0: 0-10%; 1: >10-25%; 2: >25-50%; 3: >50%. Recovery (R) values are coded as follows: 0: <1 year; 1: 1-2 years; 2: 2-5 years; 3: >5 years. The literature column indicates those studies idenfied during the literature review as corresponding to that combination of gear, feature, energy, and substrate. The studies referenced here were intended to be inclusive, so any particular study may or may not have directly informed the S or R score. Any literature used to estimate scores is referenced in Table 16 (Fixed gear S), Table 17 (Geo R), and Table 18 (Bio R).

Gear: Longline/Gillnet					
Substrate: Mud					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Biogenic burrows (G)	filling, crushing	none	none	1	0
Biogenic depressions (G)	filling	none	none	0	0
Sediments, surface/subsurface (G)	resuspension, compression, geochem, mixing, sorting	none	none	0	0
Amphipods, tube-dwelling (B)	crushing	none	none	1	0
Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	none	none	1	2
Corals, sea pens (B)	breaking, crushing, dislodging, displacing	none	none	1 (low energy only)	0 (low energy only)
Hydroids (B)	breaking, crushing, dislodging, displacing	none	none	1	1
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	none	678	0	0
Substrate: Sand					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Bedforms (G)	smoothing	none	n/a	0 (high energy only)	0 (high energy only)
Biogenic burrows (G)	filling, crushing	none	none	1	0
Biogenic depressions (G)	filling	none	none	1	0

Sediments, surface/subsurface (G)	resuspension, compression, geochem, mixing, sorting	none	none	0	0
Shell deposits (G)	displacing, burying, crushing	none	none	0	0
Amphipods, tube-dwelling (B)	crushing	none	none	1	0
Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	none	none	1	2
Ascidians (B)	breaking, crushing, dislodging, displacing	none	678	1	1
Corals, sea pens (B)	breaking, crushing, dislodging, displacing	none	none	1 (low energy only)	0 (low energy only)
Hydroids (B)	breaking, crushing, dislodging, displacing	none	none	1	1
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	none	678	0	0
Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B)	breaking, crushing	none	678	0	0
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	none	none	1	2
Sponges (B)	breaking, crushing, dislodging, displacing	none	678	0	1
Substrate: Granule-pebble					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Granule-pebble, pavement (G)	burial, mixing, homogenization	none	n/a	0 (high energy only)	0 (high energy only)
Granule-pebble, scattered, in sand (G)	burial, mixing	none	none	0	0
Shell deposits (G)	burying, crushing, displacing	none	none	0	0
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	none	678	1	2
Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	none	none	1	2
Ascidians (B)	breaking, crushing, dislodging, displacing	none	678	1	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	none	678	1	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	none	678	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	none	none	1	1
Macroalgae (B)	breaking, dislodging	none	n/a	1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	none	678	0	0
Mollusks, epifaunal bivalve, P*lacopecten magellanicus* (B)	breaking, crushing	none	678	0	0
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	none	none	1	2
Polychaetes, other tube-dwelling (B)	crushing, dislodging	none	none	1	1
Sponges (B)	breaking, dislodging, displacing	none	678	1	1
Substrate: Cobble					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Cobble, pavement (G)	burial, mixing, homogenization	none	n/a	0 (high energy only)	0 (high energy only)
Cobble, piled (G)	smoothing, displacement	none	none	1	3
Cobble, scattered in sand (G)	burial, mixing, displacement	none	none	0	0

Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	none	678	1	2
Ascidians (B)	breaking, crushing, dislodging, displacing	none	678	1	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	none	678	1	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	none	678	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	none	none	1	1
Macroalgae (B)	breaking, dislodging	none	n/a	1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	none	678	0	0
Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B)	breaking, crushing	none	678	0	0
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	none	none	1	2
Polychaetes, other tube-dwelling (B)	crushing, dislodging	none	none	1	1
Sponges (B)	breaking, dislodging, displacing	none	678	1	1
Substrate: Boulder					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Boulder, piled (G)	displacement	none	none	0	3
Boulder, scattered, in sand (G)	displacement	none	none	0	0
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	none	678	1	2
Ascidians (B)	breaking, crushing, dislodging, displacing	none	678	1	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	none	678	1	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	none	678	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	none	none	1	1
Macroalgae (B)	breaking, crushing, dislodging, displacing	none	n/a	1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	none	678	0	0
Polychaetes, *Filograna implexa* (B)	crushing, dislodging	none	none	1	2
Polychaetes, other tube-dwelling (B)	breaking, dislodging, displacing	none	none	1	1
Sponges (B)	breaking, crushing, dislodging, displacing	none	678	1	1
Habitat: Steep and Deep					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Biogenic burrows (G)	filling, crushing	n/a	None	1	0
Biogenic depressions (G)	filling	n/a	None	1	0
Boulder, piled (G)	Displacement	n/a	None	0	3
Boulder, scattered (G)	Displacement	n/a	None	0	0
Cobble, piled (G)	smoothing, displacement	n/a	None	1	3
Cobble, scattered in sand (G)	burial, mixing, displacement	n/a	None	0	0
Granule-pebble, scattered, in sand (G)	burial, mixing	n/a	None	0	0
Sediments, surface/subsurface (G)	re-suspension of fine sediments, compression, geochemical, mixing	n/a	None	0	0

Amphipods, tube-dwelling (B) – see note	Crushing	n/a	None	1	1
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	n/a	678	1	3
Anemones, tube dwelling (B)	breaking, crushing, dislodging, displacing	n/a	None	1	3
Ascidians (B)	breaking, crushing, dislodging, displacing	n/a	678	1	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	n/a	678	1	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	n/a	678	1	1
Corals, sea pens (B)	breaking, crushing, dislodging, displacing	n/a	678	1	4
Hydroids (B)	breaking, crushing, dislodging, displacing	n/a	None	1	1
Polychaetes, other tube-dwelling (B)	breaking, crushing, dislodging, displacing	n/a	None	1	1
Sponges (B)	breaking, crushing, dislodging, displacing	n/a	678	1	4
Corals, soft or stony (B)	breaking, crushing, dislodging, displacing	n/a	678	4	4

Table 15. Lobster and deep-sea red crab trap matrices. Susceptibility (S) values are coded as follows: 0: 0-10%; 1: >10-25%; 2: >25-50%; 3: >50%. Recovery (R) values are coded as follows: 0: <1 year; 1: 1-2 years; 2: 2-5 years; 3: >5 years. The literature column indicates those studies idenfied during the literature review as corresponding to that combination of gear, feature, energy, and substrate. The studies referenced here were intended to be inclusive, so any particular study may or may not have directly informed the S or R score. Any literature used to estimate scores is referenced in Table 16 (Fixed gear S), Table 17 (Geo R), and Table 18 (Bio R).

Gear: Trap					
Substrate: Mud					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Biogenic burrows (G)	filling, crushing	none	none	1	0
Biogenic depressions (G)	filling	none	none	1	0
Sediments, surface/subsurface (G)	resuspension, compression, geochem, mixing, sorting	none	none	1	0
Amphipods, tube-dwelling (B)	crushing	none	none	1	0
Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	none	none	1	2
Corals, sea pens (B)	breaking, crushing, dislodging, displacing	102	102	1 (low energy only)	0 (low energy only)
Hydroids (B)	breaking, crushing, dislodging, displacing	none	none	1	1
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	none	none	0	0
Substrate: Sand					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Bedforms (G)	smoothing	none	none	0 (high energy only)	0 (high energy only)
Biogenic burrows (G)	filling, crushing	none	none	1	0
Biogenic depressions (G)	filling	none	none	1	0
Sediments, surface/subsurface (G)	resuspension, compression, geochem, mixing, sorting	none	none	1	0
Shell deposits (G)	crushing	none	none	0	0
Amphipods, tube-dwelling (B)	crushing	none	none	1	0

Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	184	none	1	2
Ascidians (B)	breaking, crushing, dislodging, displacing	none	none	1	1
Corals, sea pens (B)	breaking, crushing, dislodging, displacing	none	none	1 (low energy only)	0 (low energy only)
Hydroids (B)	breaking, crushing, dislodging, displacing	none	none	1	1
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	none	none	0	0
Mollusks, epifaunal bivalve*, Placopecten magellanicus* (B)	breaking, crushing	none	none	0	0
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	none	none	1	2
Sponge (B)	breaking, crushing, dislodging, displacing	none	none	0	1
Substrate: Granule-pebble					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Granule-pebble, pavement (G)	burial, mixing, homogenization	none	n/a	0 (high energy only)	0 (high energy only)
Granule-pebble, scattered, in sand (G)	burial, mixing	none	none	0	0
Shell deposits (G)	burying, crushing, displacing	none	none	0	0
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	none	none	1	2
Anemones, cerianthid burrowing (B)	breaking, crushing, dislodging, displacing	none	none	1	2
Ascidians (B)	breaking, crushing, dislodging, displacing	102	102	1	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	none	none	1	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	102	102	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	none	none	1	1
Macroalgae (B)	breaking, dislodging	none	n/a	1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	none	none	1	0
Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B)	breaking, crushing	none	none	0	0
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	102	102	1	2
Polychaetes, other tube-dwelling (B)	crushing, dislodging	102	102	1	1
Sponges (B)	breaking, dislodging, displacing	102	102	1	1
Substrate: Cobble					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Cobble, pavement (G)	burial, mixing, homogenization	none	n/a	0 (high energy only)	0 (high energy only)
Cobble, piled (G)	smoothing, displacement	none	none	1	3
Cobble, scattered in sand (G)	burial, mixing, displacement	none	none	0	0
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	none	none	1	2
Ascidians (B)	breaking, crushing, dislodging, displacing	102	102	1	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	none	none	1	2

Bryozoans (B)	breaking, crushing, dislodging, displacing	102	102	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	none	none	1	1
Macroalgae (B)	breaking, dislodging	none	n/a	1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	none	none	1	0
Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B)	breaking, crushing	none	none	0	0
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	102	102	1	2
Polychaetes, other tube-dwelling (B)	crushing, dislodging	102	102	1	1
Sponges (B)	breaking, dislodging, displacing	102	102	1	1
Substrate: Boulder					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Boulder, piled (G)	displacement	None	None	0	3
Boulder, scattered, in sand (G)	displacement	None	None	0	0
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	None	None	1	2
Ascidians (B)	breaking, crushing, dislodging, displacing	102	102	1	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	None	None	1	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	102	102	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	None	None	1	1
Macroalgae (B)	breaking, dislodging	None	n/a	1 (high energy only)	1 (high energy only)
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	None	None	1	0
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	102	102	1	2
Polychaetes, other tube-dwelling (B)	crushing, dislodging	102	102	1	1
Sponges (B)	breaking, dislodging, displacing	102	102	1	1
Habitat: Steep and deep					
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**Literature high**	**Literature low**	**S**	**R**
Biogenic burrows (G)	filling, crushing	n/a	None	1	0
Biogenic depressions (G)	filling	n/a	None	1	0
Boulder, piled (G)	Displacement	n/a	None	0	3
Boulder, scattered (G)	Displacement	n/a	None	0	0
Cobble, piled (G)	smoothing, displacement	n/a	None	1	3
Cobble, scattered in sand (G)	burial, mixing, displacement	n/a	None	0	0
Granule-pebble, scattered, in sand (G)	burial, mixing	n/a	None	0	0
Sediments, surface/subsurface (G)	re-suspension of fine sediments, compression, geochemical, mixing	n/a	None	1	0
Amphipods, tube-dwelling (B) – see note	Crushing	n/a	None	1	1
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	n/a	None	1	3
Anemones, tube dwelling (B)	breaking, crushing, dislodging, displacing	n/a	None	1	3

Ascidians (B)	breaking, crushing, dislodging, displacing	n/a	None	1	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	n/a	None	1	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	n/a	None	1	1
Corals, sea pens (B)	breaking, crushing, dislodging, displacing	n/a	None	1	4
Hydroids (B)	breaking, crushing, dislodging, displacing	n/a	None	1	1
Polychaetes, other tube-dwelling (B)	breaking, crushing, dislodging, displacing	n/a	None	1	1
Sponges (B)	breaking, crushing, dislodging, displacing	n/a	None	1	4
Corals, soft or stony (B)	breaking, crushing, dislodging, displacing	n/a	None	3	4

Table 16. Fixed gears susceptibility summary for all structural features. When applicable, reasons for differences in values between gear types and/or substrates are summarized.

Feature	*Substrates evaluated*	*Score*	*Susceptibility*
Amphipods, tube-dwelling	Mud, sand, steep/deep	1	The percentage of amphipods impacted by fixed gear is likely very low except for direct contact with the trap or anchors. It is unlikely that much damage will occur within 1 m of the groundline/net, though some abrasion could occur.
Anemones, actinarian	Granule-pebble, cobble, boulder, steep/deep	1	The percentage of anemones impacted by fixed gear is likely very low except for direct contact with the trap or anchors. It is unlikely that much damage will occur within 1 m of the groundline/net, though some abrasion could occur.
Anemones, cerianthid burrowing	Mud, sand, granule-pebble, steep/deep	1	The percentage of burrowing anemones impacted by fixed gear is likely very low except for direct contact with the trap or anchors. It is unlikely that much damage will occur within 1 m of the groundline/net, though some abrasion could occur.
Ascidians	Sand, granule-pebble, cobble, boulder, steep/deep	1	The percentage of tunicates impacted by fixed gear is likely very low except for direct contact with the trap or anchors. It is unlikely that much damage will occur within 1 m of the groundline/net, though some abrasion could occur. Study 102 found evidence of tunicate detachment likely from setting and hauling back traps.
Bedforms	Mud, sand	0	Currently there is no evidence that any fixed gears will alter bed forms. Gear will sit atop bedforms.
Biogenic burrows	Mud, sand, steep/deep	1	All three gears can collapse a burrow, especially the anchor for longline and gillnet gears. However, unlikely that the longline, gillnet or trap bottom lines will cause significant damage within 1 meter of the line/net.
Biogenic depressions	Mud, sand, steep/deep	0 (mud), 1 (sand)	All three gears can cause damage to biogenic depressions, especially the anchor (gillnet/longlines). However, unlikely that the longline or gillnet will cause significant damage within 1 meter of the line/net.
Boulder, piled	Boulder, steep/deep	0	Fixed gears do not impact this geological feature.
Boulders, scattered in sand	Boulder, steep/deep	0	Fixed gears do not impact this geological feature.
Brachiopods	Granule-pebble, cobble, boulder, steep/deep	1	The percentage of brachiopds impacted by fixed gear is likely very low except for direct contact with the trap or anchors. It is unlikely that much damage will occur within 1 m of the groundline/net, though some abrasion could occur.

Feature	***Substrates evaluated***	***Score***	***Susceptibility***
Bryozoans	Granule-pebble, cobble, boulder, steep/deep	1	The percentage of erect bryozoans impacted by fixed gear is likely very low except for direct contact with the trap or anchors. It is unlikely that much damage will occur within 1 m of the groundline/net, though some abrasion could occur. Study 102 found some damage to large individuals of the ross coral, *Pentapora foliacea* likely caused by hauling traps.
Cobble, pavement	Cobble	0	Fixed gears do not impact this geological feature.
Cobble, piled	Cobble, steep/deep	1	Fixed gear could dislodge piled cobbles if dragged across them.
Cobble, scattered in sand	Cobble, steep/deep	0	Fixed gears do not impact this geological feature.
Corals, sea pens	Mud, sand, steep/deep	1	The percentage of sea pens impacted by fixed gear is likely very low except for direct contact with the trap or anchors. It is unlikely that much damage will occur within 1 m of the groundline/net, though some abrasion could occur. Study 102 found that sea pens off the coast of Great Britain bent but did not break under the weight of crustacean traps. However, traps used in NE US are much heavier and likely would cause at least some damage.
Granule-pebble, pavement	Granule-pebble	0	Fixed gears do not impact this geological feature.
Granule-pebble, scattered in sand	Granule-pebble, steep/deep	0	Fixed gears do not impact this geological feature.
Hydroids	Mud, sand, granule-pebble, cobble, boulder, steep/deep	1	The percentage of hydroids impacted by fixed gear is likely very low except for direct contact with the trap or anchors. It is unlikely that much damage will occur within 1 m of the groundline/net, though some abrasion could occur. Study 184 found lower hydroid biomass in areas that were fished heavily.
Macroalgae	Granule-pebble, cobble, boulde	1	Fixed gear impacts on macroalgae are likely very low except for direct contact with the trap or anchors. It is unlikely that much damage will occur within 1 m of the groundline/net, though some abrasion could occur.
Mollusks, epifaunal bivalve	Mud, sand, granule-pebble, cobble, boulder	0	Long-line and gillnet gears likely do not impact this biological feature. Traps are likely to crush some bivalves that exist on hard substrates such as mussels.
Polychaetes, *Filograna implexa*	Sand, granule-pebble, cobble, boulder	1	Colonial tube worms are very fragile, and consequently are susceptible to damage via contact with anchors, gillnets, bottom lines, and traps. However, it is unlikely that more than 25% of colonial tube worm aggregations would be removed within the 1 m swath of potential impact adjacent to a gillnet, long-line, or trap bottom line.
Polychaetes, other tube-dwelling	Granule-pebble, cobble, boulder, steep/deep	1	Colonial tube worms are very fragile, and consequently are susceptible to damage via contact with anchors, gillnets, bottom lines, and traps. However, it is unlikely that more than 25% of colonial tube worm aggregations would be removed within the 1 m swath of potential impact adjacent to a gillnet, long-line, or trap bottom line.
Sediments, surface and subsurface	Mud, sand, steep/deep	0, 1 (traps)	Sediment impacts expected to be limited; some compression due to traps, so score of 1
Shell deposits	Mud, sand, granule-pebble, cobble, boulder	0	Fixed gears do not impact this geological feature.

Feature	*Substrates evaluated*	*Score*	*Susceptibility*
Sponges	Mud, sand, granule-pebble, cobble, boulder, steep/deep	0	The percentage of sponges impacted by fixed gear is likely very low except for direct contact with the trap or anchors. It is unlikely that much damage will occur within 1 m of the groundline/net, though some abrasion could occur. Study 102 found evidence of sponge detachment likely from setting and hauling back traps.
Deep-sea corals	Steep and deep habitat type	3	Assume a high degree of susceptibility based on physical attributes of deep-sea corals.

3.2.5 Recovery– all gear types

Table 17. Recovery summary for all geological features, by, substrate, gear type, and energy.

Feature	*Substrate**	*Gear type**	*Recovery score high energy*	*Recovery summary high energy*	*Recovery score low energy*	*Recovery summary low energy*
Bedforms	Sand	Trawls, scallop dredges	0	Sand ripples re-formed by tidal currents within hrs/days, sand waves by storms that occur at least once a year	n/a	This feature was assumed not to occur in a low energy environment.
Bedforms	Sand	Hydraulic dredges	0	Dredge tracks still visible after 2 mos (287), no longer visible after 11 wks (373), nearly indistinct after 24 hrs (245), complete recovery of physical features after 40 days (140)	n/a	This feature was assumed not to occur in a low energy environment.
Bedforms	Sand	Fixed gears	0	Bedforms estimated to have very low susceptibility to fixed gears, so recovery is not really required	n/a	This feature was assumed not to occur in a low energy environment.
Biogenic burrows	Mud, sand	Trawls, scallop dredges	0	Assume recovery <1 yr because organisms creating depressions are mobile, will move quickly into trawl/dredge path	0	Same as high energy: depends on number/activity of organisms, no reason to think it will vary by energy level
Biogenic burrows	Sand, granule pebble	Hydraulic dredge	1	Slower re-colonization by organisms (clams?) that live deeper in sediment?	2	No recovery after 3 yrs due to high mortality of organisms (clams) that make burrows (121)
Bedforms	Mud, sand	Fixed gears	0	Burrows estimated to have very low susceptibility to fixed gears, so recovery is not really required	0	Burrows estimated to have very low susceptibility to fixed gears, so recovery is not really required

Feature	***Substrate****	***Gear type****	***Recovery score high energy***	***Recovery summary high energy***	***Recovery score low energy***	***Recovery summary low energy***
Biogenic depressions	Mud, sand	All	0	Assume recovery <1 yr because organisms creating depressions are mobile, will move quickly into trawl/dredge path	0	Same as high energy: depends on number/activity of organisms, no reason to think it will vary by energy level
Boulder, piled	Boulder	Trawls, scallop dredges, hydraulic dredges, fixed gears	3	Assume any disturbance would be permanent	3	Assume any disturbance would be permanent
Boulders, scattered in sand	Boulder	Trawls, scallop dredges, fixed gears	0	If the cobble/boulder is rolled over or buried, the depression underneath it would need to be recreated, but we estimated the time required for this would be under one year (R=0). This is consistent with the recovery times estimated for the burrow and depression features in the mud and sand substrates.	0	If the cobble/boulder is rolled over or buried, the depression underneath it would need to be recreated, but we estimated the time required for this would be under one year (R=0). This is consistent with the recovery times estimated for the burrow and depression features in the mud and sand substrates.
Boulders, scattered in sand	Boulder	Hydraulic dredges	1	Because of their size, partially or totally buried boulders could take 1-2 yrs to be exposed even in high energy environments	2	Assume exposure would take longer than 2 yrs
Cobble, pavement	Cobble	Trawls, scallop dredges, hydraulic dredges, fixed gears	0	Assume pavement re-forms quickly as overlying sand is removed by currents, wave action	n/a	This feature was assumed not to occur in a low energy environment.
Cobble, piled	Cobble	Trawls, scallop dredges, hydraulic dredges, fixed gears	3	Assume any disturbance would be permanent	3	Assume any disturbance would be permanent
Cobble, scattered in sand	Cobble	Trawls, scallop dredges, fixed gears	0	Similar to boulder, if cobble is rolled or dragged, it does not change its ability to provide structure, so recovery doesn’t really apply and thus was set to zero.	0	Similar to boulder, if cobble is rolled or dragged, it does not change its ability to provide structure, so recovery doesn’t really apply and thus was set to zero.

Feature	***Substrate****	***Gear type****	***Recovery score high energy***	***Recovery summary high energy***	***Recovery score low energy***	***Recovery summary low energy***
Cobble, scattered in sand	Cobble	Hydraulic dredges	0	Because they are smaller than boulders, assume fully or partially buried cobbles would be re-exposed in <1 yr	2	Similar to boulders
Granule-pebble, pavement	Granule-pebble	Trawls, scallop dredges, fixed gears	0	Assume pavement re-forms quickly as overlying sand is removed by currents, wave action	n/a	This feature was assumed not to occur in a low energy environment.
Granule-pebble, pavement	Granule-pebble	Hydraulic dredges	2	Sediments homogenized, coarser sediments end up deeper in trenches (232); pavement might never reform?	n/a	This feature was assumed not to occur in a low energy environment.
Granule pebble, scattered in sand	Granule-pebble	Trawls, scallop dredges	0	Assume primary action of both gears is displacement, not burial. Assume any buried granules/pebbles would be uncovered quickly by currents, wave action.	2	Storms are less frequent in deeper water; furrows left in pebble bottom by rockhoppers still prominent a year later (111, but 200-300 m deep)
Granule pebble, scattered in sand	Granule-pebble	Fixed gears	0	Scattered granule-pebble estimated to have very low susceptibility to fixed gears, so recovery is not really required	0	Scattered granule-pebble estimated to have very low susceptibility to fixed gears, so recovery is not really required
Granule pebble, scattered in sand	Granule-pebble	Hydraulic dredges	1	Coarser sediments end up deeper in trenches (232); slower recovery than trawls and scallop dredges since granules-pebbles would be buried deeper by a hydraulic dredge.	2	Storms that would re-expose granules/pebbles are less frequent in deeper water
Sediments, surface and subsurface	Mud	Trawls	0	No data, assume faster recovery in high energy. Although resuspended sediment may be transported away in high energy, it is assumed that the sediment would be replaced by transport from elsewhere.	0	Recovery of bottom roughness in 6 mos (372), all geochemical sediment properties recovered within 3.5 mos (338). Recovery of door tracks takes 1-2 yrs in low energy (372,277), but door impacts less important because such a small proportion of area swept by trawl gear. Resuspension would have limited effects, because resuspended sediment will remain in area.

Feature	***Substrate****	***Gear type****	***Recovery score high energy***	***Recovery summary high energy***	***Recovery score low energy***	***Recovery summary low energy***
Sediments, surface and subsurface	Mud	Scallop dredges	0	No recovery of fine sediments 6 mos after dredging (391-multiple tows, recovery not checked after 1 yr)	0	No data, so assume same recovery as trawls
Sediments, surface and subsurface	Mud, Sand	Fixed gears	0	Estimated to have very low susceptibility to fixed gears, so recovery is not really required	0	Estimated to have very low susceptibility to fixed gears, so recovery is not really required
Sediments, surface and subsurface	Sand	Trawls	0	Lost fine sediments replaced very quickly (within hours or days) by bottom currents, or less than a year by turbulence from wave action	0	Door tracks not visible or faintly visible in SS sonar records, recovery of seafloor topography within a year (325), compacted sediments recovered within 5 mos (336)
Sediments, surface and subsurface	Sand	Scallop dredges	0	Same as trawls	0	Recovery of food value of sediments within 6 mos, but no recovery of lost fine sediments (391)
Sediments, surface and subsurface	Sand	Hydraulic dredge	1	Trenches no longer visible a day to three months after dredging (245, 246, 287, 373), also see trawls. Top 20 cm of sand in trenches still fluidized after 11 wks, but not examined after that (373).	2	Trenches no longer visible after 1 yr (121), but replacement of lost fine sediment would take longer in low energy environments. Acoustic reflectance of trenches still different than surrounding seabed after 3 yrs (121)
Shell deposits	Sand, granule-pebble, cobble	Trawls, scallop dredges	1	Shells are much heavier than sand, so if they are dispersed it could take 1-2 yrs for storms to re-aggregate them.	2	Assume it would take 2-5 yrs in low energy because storms would have to be more severe to produce bottom turbulence in deeper water.
Shell deposits	Sand, gr-pebble	Hydraulic dredges	1	Assume shells buried in trench would remain buried, but new ones would “recruit” to sediment surface within 1-2 yrs	2	Over time, empty shells collect in dredge tracks (121). Similar to trawls, s dredges, assume it would take 2-5 yrs in low energy because storms would have to be more severe to produce bottom turbulence in deeper water.
Shell deposits	Sand, granule-pebble, cobble	Fixed gears	0	Gear would not completely remove or crush shells, so deposit would remain largely intact and recovery would not be required	0	Gear would not completely remove or crush shells, so deposit would remain largely intact and recovery would not be required

Table 18. Recovery summary for all biological features, by, substrate and gear type.

Feature	*Substrate*	*Gear type*	*Recovery score*	*Recovery summary (same scoresfor low and high energy, except as noted)*
Amphipods, tube-dwelling	Mud, sand	Trawls, scallop dredges	0	*A. abdita* are short-lived, highly seasonal occurrence (several times a year), tube mats re-form within months following benthic recruitment of juveniles (MacKenzie et al 2006)
Amphipods, tube-dwelling	Sand	Hydraulic dredges	0	See above
Amphipods, tube-dwelling	Mud, sand	Fixed gears	0	See above
Anemones, actinarian	Granule-pebble, cobble, boulder	Trawls, scallop dredges	2	Recovery could take >7 yr (see Witman 1998, referenced in 404), colonized cobble in settlement trays on GB within 2.5 yrs (Collie et al 2009)
Anemones, actinarian	Granule-pebble	Hydraulic clam dredge	2	See above
Anemones, actinarian	Granule-pebble, cobble, boulder	Fixed gears	2	See above
Anemones, cerianthid burrowing	Mud, sand, granule-pebble	Trawls, scallop dredges	2	Apparently long-lived (>10 yrs?), but If animal is still alive, assume damaged tube can be repaired/replaced fairly quickly; recovery score is a “compromise” between 1-2 yrs for tube repair and 5-10 yrs (?) to replace animal.
Anemones, cerianthid burrowing	Sand, granule-pebble	Hydraulic clam dredge	3	Assume impact is removal of animal, not damage to tube, so recovery time is longer than for other gears (see above)
Anemones, cerianthid burrowing	Mud, sand, granule-pebble	Fixed gears	2	See trawls, scallop dredges
Ascidians	Sand, granule-pebble, cobble, boulder	Trawls, scallop dredges	1	Later colonizers than bryozoans, accounted for 6% of patch space 15 mos after all organisms were removed from rock surface (30m, Cashes Ledge in GOM, Witman 1998). *Molgula arenata* removed in linear patterns by scallop dredges on Stellwagen Bank (sand), widely distributed over bottom a year later (11), but not known whether they had returned to pre-disturbance densities. Assume recovery would be mostly complete within 1-2 years
Ascidians	Sand, granule-pebble	Hydraulic clam dredge	1, except 2 in low energy granule-pebble	See above, except that longer recovery in low energy granule pebble because substrate on which organisms settle (granules, pebbles) highly susceptible also
Ascidians	Sand, granule-pebble, cobble, boulder	Fixed gears	1	See above
Brachiopods	Granule-pebble, cobble, boulder	Trawls, scallop dredges	2	*Terebratulina septentrionalis* is relatively short-lived (1-5 ys), so “lost” individuals would be replaced in 2-5 years.
Brachiopods	Granule-pebble	Hydraulic clam dredge	2	See above
Brachiopods	Granule-pebble, cobble, boulder	Fixed gears	2	See above

Feature	***Substrate***	***Gear type***	***Recovery score***	***Recovery summary (same scoresfor low and high energy, except as noted)***
Bryozoans	Granule-pebble, cobble, boulder	Trawls, scallop dredges	1	Recovered within 2 yrs after CAII (eastern George Bank) was closed, grow/recolonize rapidly, life spans typically <1 yr (see #404). Two species were first colonizers of rocky substrate on Cashes Ledge, accounting for most of patch space after 15 mos (Witman 1998). At 50m site on Cashes Ledge, bryozoans covered >50% rock substrate within a year and approached 100% by second year (Sebens et al 1988).
Bryozoans	Granule-pebble	Hydraulic clam dredge	1, except 2 in low energy granule-pebble	See above, except that longer recovery in low energy granule pebble because substrate on which organisms settle (granules, pebbles) highly susceptible also
Bryozoans	Granule-pebble, cobble, boulder	Fixed gears	1	See above
Corals, sea pens	Mud, sand	Trawls, scallop dredges, hydraulic clam dredges (sand only)	2 (high energy only)	Sea pens (Stylatula spp) in mud (180-360m) on west coast are sessile, slow-growing, long-lived (up to 50 yrs) species that are likely to recover slowly from physical disturbance (164), but sea pens are sometimes able to "re-root" if removed from bottom (see below).
Corals, sea pens	Mud, sand	Fixed gears	0 (high energy only)	Full recovery from bending, smothering, some from uprooting, from pot fishing (in mud) within days, don't retract when pots drop on them (102); however, little known about lifespan, growth rates
Hydroids	Mud, sand, granule-pebble, cobble, boulder	Trawls, scallop dredges	1	Life histories similar to bryozoans (live 10 days-1 yr), some species are perennial but exhibit seasonal regression, spatial extent of recovery restricted by limited larval dispersal, or absence of pelagic medusa stage (404). On Stellwagen Bank (coarse sand), no recovery of hydroid (*Corymorpha pendula)* a year after removal by trawls and scallop dredges (11)
Hydroids	Sand, granule-pebble	Hydraulic clam dredge	1, except 2 in low energy granule-pebble	See above, except that longer recovery in low energy granule pebble because substrate on which organisms settle (granules, pebbles) highly susceptible also
Hydroids	Mud, sand, granule-pebble, cobble, boulder	Fixed gears	1	See above
Macroalgae	Granule-pebble, cobble, boulder	Trawls, scallop dredges	1	All macroalgae in NE region are perennials, so some re-growth and replacement of lost plants occurs within a year, but assume that full growth and recovery of lost structure would take 1-2 years, maybe longer for large laminarians.
Macroalgae	Granule-pebble	Hydraulic clam dredge	1	See above
Macroalgae	Granule-pebble, cobble, boulder	Fixed gears	1	See above
Mollusks, epifaunal bivalve, *Modiolus modiolus*	Mud, sand, granule-pebble, cobble, boulder	Trawls, scallop dredges	3	*Mytilus edulis* can reach full growth within a year in optimum conditions, but otherwise 2-5 years are needed, *Modiolus* is a long-lived species (some individuals live 25 years or more) and inhabits colder water, presumably with slower growth rate.

Feature	***Substrate***	***Gear type***	***Recovery score***	***Recovery summary (same scoresfor low and high energy, except as noted)***
				Recovery of mussel beds – which have greater habitat value – may be longer than for individuals.
Mollusks, epifaunal bivalve , *Modiolus modiolus*	Sand, granule-pebble	Hydraulic clam dredge	3	See above
Mollusks, epifaunal bivalve , *Modiolus modiolus*	Mud, sand, granule-pebble, cobble, boulder	Fixed gears	0	Minimal susceptibility to disturbance, therefore recovery was assumed to be complete within a year.
Mollusks, epifaunal bivalve , *Placopecten magellanicus*	Sand, granule-pebble, cobble, boulder	Trawls, scallop dredges	2	Scallop biomass increased 200x in prime, gravel pavement habitat in closed area on Georges Bank 7 years after area was closed to fishing, much higher than 9-14x increase for all GB closed areas combined (157)
Mollusks, epifaunal bivalve , *Placopecten magellanicus*	Sand, granule-pebble	Hydraulic clam dredge	2	
Mollusks, epifaunal bivalve , *Placopecten magellanicus*	Sand, granule-pebble, cobble, boulder	Fixed gears	0	Scallops not susceptible to fixed gears, therefore R=0
Polychaetes, *Filograna implexa*	Sand, granule-pebble, cobble, boulder	Trawls, scallop dredges	2	*Filograna* colonized cobble in settlement trays on GB within 2.5 yrs (Collie et al 2009), on pebble pavement (eastern GB) full recovery within 5 yrs following closure of area (71)
Polychaetes, *Filograna implexa*	Granule-pebble	Hydraulic clam dredges	2	See above
Polychaetes, *Filograna implexa*	Granule-pebble, cobble, boulder	Fixed gears	2	See above
Polychaetes, other tube-dwelling	Granule-pebble, cobble, boulder	Trawls, scallop dredges	1	Because tubes are less fragile than *Filograna* tubes, assume they are less susceptible to damage from these two gears and therefore recover more quickly.
Polychaetes, other tube-dwelling	Granule-pebble	Hydraulic clam dredges	1, except 2 in low energy granule-pebble	See above, except that longer recovery in low energy granule pebble because substrate on which organisms settle (granules, pebbles) highly susceptible also
Polychaetes, other tube-dwelling	Granule-pebble, cobble, boulder	Fixed gears	1	Slower recovery time based on lower susceptibility to fixed gears
Sponges	Sand, granule-pebble, cobble, boulder	Trawls, scallop dredges	2	With one exception, value is consistent with literature. On eastern GB, recovery in closed area (CAII) within 5 yrs (esp *Polymastia, Isodictya*), colonization of gravel 2.5 yrs after closure with increase in sponge cover after 4.5 yrs (71) . Significantly

Feature	***Substrate***	***Gear type***	***Recovery score***	***Recovery summary (same scoresfor low and high energy, except as noted)***
				higher incidence of sponge (*S. ficus*)/shell fragment microhabitats inside S part of CAII after 4.5 yrs (225). No recovery from single tows after a year in Gulf of Alaska (111). Aperiodoc recruitment and perennial life cycles, life spans >5 yrs account for relatively slow recovery times (404). Exception is study 382 (shallow water in Georgia) which reports full recovery of large sponges from damage and return to pre-trawl densities (single tows) within a year.
Sponges	Sand, granule-pebble	Hydraulic clam dredge	2	See above
Sponges	Sand granule-pebble, cobble, boulder	Fixed gears	1	Slower recovery time based on lower susceptibility to fixed gears, higher probability that disturbance would damage or remove parts of sponge rather than remove whole animal.
Corals, soft and stony	Steep/deep habitat type	Trawls, fixed gears	4	Assume a long duration of recovery based on the biology of deep-sea corals.

4.0 Estimating contact-adjusted area swept

In order to quantify fishing effort in like terms and compare the relative effects of different fishing gears, fishing effort inputs to the Fishing Effects model (e.g. number of trips, tows, sets) are converted to area swept in km^2, regardless of gear type. Because the trip is the reporting unit for vessel trip reports used in the Northeast region, the swept area estimates are calculated at the trip level. Tow and set level data are not available for most trips, so the workflow described below includes various assumptions to estimate the number of fishing events that occur during trip. These assumptions are based on at-sea observer data, and other sources, and in many cases these assumptions change over time. Once tables of area swept values from individual trips were generated, they were joined with spatial data products that estimate the footprint of each trip, and area swept was distributed over this footprint. These trip-level footprints were developed using modeling approach that is routinely used for various fisheries management applications in the northeast region (DePiper 2014, Benjamin *et al.* 2018). Spatial datasets in raster format were prepared by overlaying the swept area footprints for a specific gear type and month, based on the date sailed of each trip. Finally, these monthly gear-specific rasters were joined to the 5x5 grid in order to serve as inputs to the Fishing Effects model.

4.1 Area swept estimation

Simple quantitative models convert fishing effort data to area swept. These models provide an estimate of contact-adjusted area swept, measured in km^2 and are unchanged from the original SASI model. Appendix A provides the code used to pull fishing effort data from NEFMC databases, apply any annual and gear-specific assumptions about gear dimensions, tow lengths, and number of tows, and generate the swept area tables.

Regardless of gear type, the area swept models have three requirements:

- total distance towed, or, in the case of fixed gears, total length of the gear;
- width of the individual gear components; and
- contact indices for the various gear components.

The contact index is a key feature because it allows the model to ‘reward’ gears that are modified to reduce seabed contact. Contact indices do not vary by substrate.

4.1.1 Demersal otter trawl

A demersal trawl has four components that potentially contribute to seabed impact: the otter boards, the ground cables, the sweep, and the net. Because the net follows directly behind the sweep, it is not included in the effective gear width calculation. Thus, the SASI model for a demersal trawl simplifies to

$$A_{trawl}(km^2) = d_t\left[\left(2 \cdot w_o \cdot c_o\right) + \left(2 \cdot w_c \cdot c_c\right) + \left(w_s \cdot c_s\right)\right],$$

where:

d_t = distance towed in one tow (km)
w_o = effective width of an otter board (m), which equals otter board length (km)·sin (α_o), where α_o = angle of attack

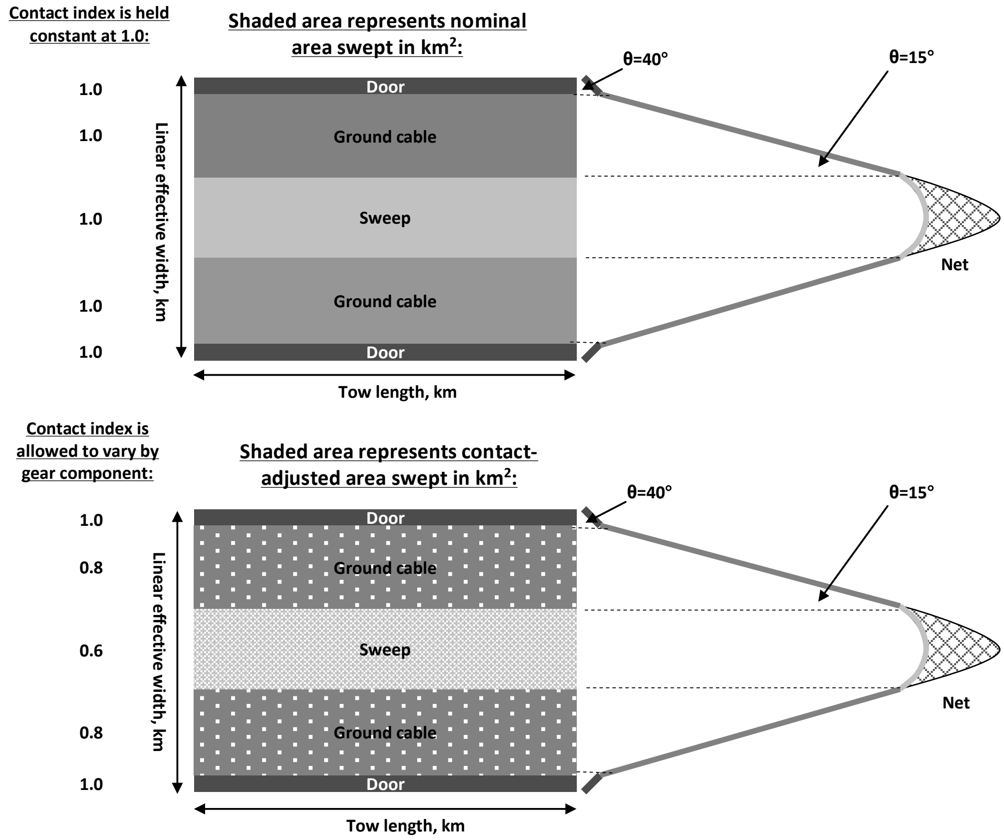
c_o = contact index, otter board
w_c = effective width of a ground cable (km), which equals ground cable length (km)·sin(α_c), where α_c = angle of attack
c_c = contact index, ground cables
w_s = effective width of sweep (km)
c_s = contact index, sweep

The demersal otter trawl SASI model assumes the following:

- Seabed contact does not change within a tow
- Otter board angle of attack is constant during a tow
- Ground cables are straight along their entire length
- The effect of towing speed on seabed contact is accommodated by d_t

Effective width of a trawl tow includes the three gear components: otter boards, ground cables and sweep. Gear geometry assumptions are discussed in more detail in the original SASI document (NEFMC 2011). The otter board angle of attack (α) was set at 40° and the angle of attack of the ground cables was set at 15°. Effective sweep width was assumed to be 43% of the nominal width. Nominal and contact adjusted area swept are represented graphically below (Figure 1).

Figure 1. Area swept schematic (top down view). The upper portion shows nominal area swept, and the lower portion shows contact adjusted area swept. Contact indices will vary according to Table 19; the figure below is for illustrative purposes only.



The area swept for an individual tow is summed across all tows in a trip. Thus, to calculate *A* for a single trip, the data required include: gear width for each of the three components (w_o, w_c, w_s), distance towed (d_t), and tows per trip. For mobile gears including otter trawls, tow length is always a derived value that combines tow speed (km/hour) and tow duration (hours).

The parameter w_o , the effective width of an otter board (m), is modeled as otter board length (m) times sin (α_o), where α_o = angle of attack (assumed to be 40^{o}). Otter board weight data is collected through the observer program, but dimensions are not. Using commercially available data on the size and weight of otter boards for two different door designs (Thyboron Type II and Bison, both distributed by Trawlworks, Inc of Narragansett RI), a linear relationship between otter board weight and otter board length was established (NEFMC 2011). The type and brand of otter boards used in the fishery are not reported, and it is not known if this sample is representative of the gear used on observed trips, or in the fishery as a whole. This relationship provides an estimate of otter board length for each observed trip, as follows:

Otter board width (inches) = 1223.7 + (0.8 * otter board weight in pounds)

This relationship is applied to fishing trips by constructing a relationship between reported door weight and a variable or variables common between both observer and VTR datasets. Several relationships are investigated. A significant and relatively strong linear relationship exists between door weight and a combination of gross tonnage and horsepower (NEFMC 2011). Thus, door weight for a particular trip is calculated as:

Door weight (tons) = 70.8 + (1.8 * Vessel tonnage) + (0.5 * Vessel horsepower)

Applying this relationship to all VTR-reported trips provides an estimate of door weights. Finally, applying the modeled relationship between otter board weight and otter board length, and correcting for angle of attack, provides an estimate of the effective linear width of otter boards used for each trip.

The parameter w_c , the effective width of a ground cable (km), equals ground cable length (m) multiplied by $\sin(\alpha_c)$, where α_c = angle of attack (assumed to be 15^o). Ground cable length data are collected directly through the observer program. Relationships between ground cable length and independent variable common between both observer and VTR datasets was investigated, and significant but weak linear relationship exists between ground cable length and vessel length (NEFMC 2011). Based on this investigation, ground cable length for a particular trip is calculated as:

Ground cable length (km) = 23.3 + (0.4* Vessel length (m)) * 0.001 m/km * 2 cables/trawl

Applying this relationship to all VTR-reported trips using otter trawls provides an estimate of ground cable length, and correcting for angle of attack provides an estimate of the effective linear width of ground cables used for each trip.

Tow duration is specified in the observer data. Tow duration and speed are combined to generate tow lengths in kilometers. Based on the similarity in tow speeds between years, the same speed was assumed for all tows in all years. Tow duration was by multiplying number of hauls taken directly from the VTR database by soak time, which was set at a fixed value depending on the year and gear type as indicated in Appendix A.

Finally, contact indices are specified separately for the four trawl gear types, by gear component (Table 19). This required distinguishing between the different types of trawls, which is done at the trip level by examining the VTR data (Table 20).

Table 19. Contact indices for trawl gear components

Gear type	*Component*	*Contact index*
Generic otter trawl	Doors	1.00
Generic otter trawl	Ground cable	0.95
Generic otter trawl	Sweep	0.90
Squid trawl	Doors	1.00
Squid trawl	Ground cable	0.95
Squid trawl	Sweep	0.50

Gear type	*Component*	*Contact index*
Shrimp trawl	Doors	1.00
Shrimp trawl	Ground cable	0.90
Shrimp trawl	Sweep	0.95
Raised footrope trawl	Doors	1.00
Raised footrope trawl	Ground cable	0.95
Raised footrope trawl	Sweep	0.05

Table 20. Distinguishing between trawl gear types

Trawl type	***Thresholds***
Generic otter trawl	All trawl trips not included in other categories including gear codes 050 (fish), 057 (haddock separator), 052 (scallop), 053 (twin trawl)
Squid trawl	75% of catch, by weight, was either *Illex* squid or *Loligo* squid; gear code 050
Shrimp trawl	Any trip with the gear type coded as shrimp gear (058)
Raised footrope trawl	Trip must have occurred during or after 2003, in statistical area with exemptions, during months fishery was open, and have greater than 50% whiting (silver hake) in catch, by weight

4.1.2 New Bedford-style scallop dredge

A scallop dredge has five key components that potentially contribute to seabed impact. They are: the contact shoes; the dredge bale arm including cutting bar; the bale arm rollers; the chain sweep; and the ring bag and club stick. However, additional dredge components do not add width to the area swept because they follow one behind the other as the gear is towed. Therefore, the dredge model shown below does not consider the potential impact of individual components of a dredge, but groups them together.

Given these simplifying assumptions, the scallop dredge SASI model is

$$A_{scallop}(km^2) = d_t\left(w \cdot c\right),$$

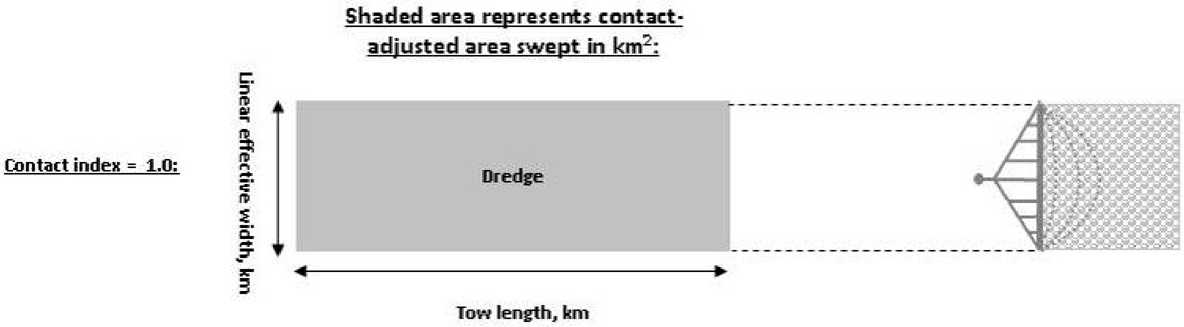
where:

d_t = distance towed in one tow (km)
w = effective width of widest dredge component (km)
c = contact index, all dredge components

Similar to the otter trawl model, the scallop dredge SASI calculation assumes that seabed contact does not change within a tow, and that the effect of towing speed on seabed contact is accommodated by d_t.

If two dredges are used simultaneously, the effective width is the sum of the individual dredge widths. The contact index is set to 1.0, which means that nominal area swept and contact-adjusted area swept are equal. A diagrammatic representation of area swept for scallop dredges is provided below (Figure 2).

Figure 2. Area swept schematic for scallop dredge gear (top down view). Since the contact index is 1.0, nominal area swept and contact-adjusted area swept are equivalent.



For scallop dredges, number of hauls, gear size, and gear quantity were taken directly from the VTR database, with some default parameters in cases of null values. Soak time and towing speed were hardcoded (varying by year) based on parameter estimates developed using observer data. Hours fished was estimated by multiplying soak time by the number of hauls, and the distance swept by multiplying hours fished by tow speed. This trip distance is then multiplied by gear size and gear quantity to generate swept area.

4.1.3 Hydraulic clam dredge

Similar to the scallop dredge model, the hydraulic clam dredge model shown below does not consider the potential impact of individual components of a dredge, but groups them together. The area swept model for hydraulic clam dredge is

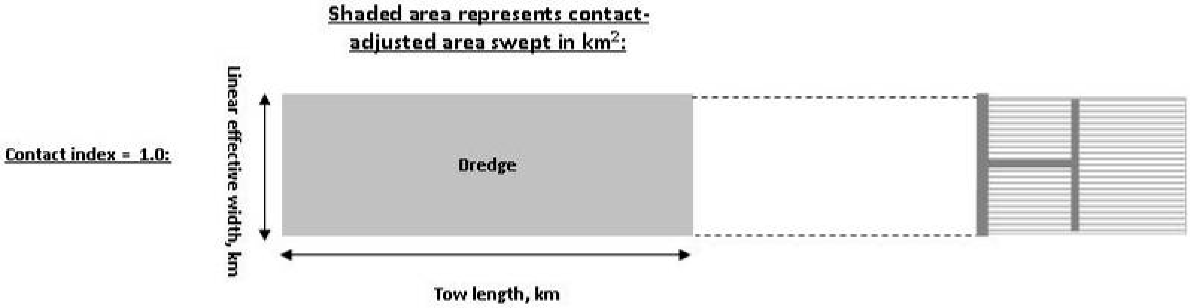
$$A_{hydraulic}(km^2) = d_t(w \cdot c),$$

where:

d_t = distance towed in one tow (km)
w = effective width of widest dredge component (km)
c = contact index, all dredge components

The hydraulic dredge area swept calculation assumes that seabed contact does not change within a tow, and that the effect of towing speed on seabed contact is accommodated by d_t. The contact index is set to 1.0, which means that nominal area swept and contact-adjusted area swept are equal. Nominal and contact adjusted area swept are represented graphically below (Figure 3).

Figure 3. Area swept schematic for hydraulic dredge gear (top down view). Since the contact index is 1.0, nominal area swept and contact-adjusted area swept are equivalent.



For clam dredges tow speed was set at a fixed value of 2 knots, and gear size (width) was also set at fixed values, derived from observer data and varying by year. Hours fished is calculated using soak time from the logbooks times the number of hauls, and distance towed is the hours fished times the tow speed. Gear width is set at fixed values, varying annually. Distance towed times gear width generates swept area at the trip level.

4.1.4 Demersal longline and sink gillnet

A demersal longline or gillnet has two key components that potentially contribute to seabed impact: the weights and either the mainline (longline) or the footline (gillnets). For longline gear, any impacts of the gangions and hooks are ignored.

The area swept model for a demersal longline or gillnet is

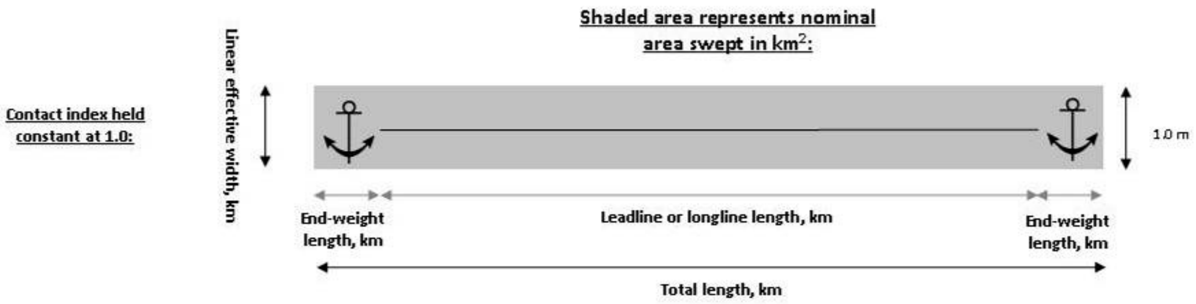
$$A_{longline/gillnet}(km^2) = 2(d_w \cdot l_w \cdot c_w) + (d_l \cdot l_l \cdot c_l),$$

where:

d_w = distance end-weight moves over the seabed (km)
w_w = length of end-weight (km)
c_s = contact index, end-weight
d_l = distance longline or leadline moves over the seabed (km)
l_l = length of longline or leadline (km)
c_l = contact index, longline or leadline

The distance that each gear component moves is a function of movements over the seabed both while the gear is fishing (soaking) and during the setting and hauling processes, although the extent of these movements is unknown. The d_w and d_l parameters are intended to capture both types of movement (i.e. lateral and perpendicular to the long axis of the gear). For both the end weights and the longlines/leadlines, this distance is assumed to be one meter (i.e. d_w and d_l are specified as 0.001 km (1.0 m)), and is assumed to be sufficient to capture any movement both laterally and perpendicular to the mainline. Seabed contact is assumed to be 1.0 for all gear components. Nominal and contact adjusted area swept are represented graphically below (Figure 4).

Figure 4. Area swept schematic for longline or gillnet gear (top down view). Since the contact index is 1.0, nominal area swept and contact-adjusted area swept are equivalent.



For longline and gillnet, tow distance was estimated by multiplying number of hauls by gear length. Details are in Appendix A. Linear effective width was estimated to be one meter for both gear types and all trips.

4.1.5 Traps

The area swept model for a line or trawl of *n* traps, accounting for each individual trap and ground line between traps is

$$A_{trap}(km^2) = \sum_{1}^{n}\left[d_{tn} \cdot l_{tn} \cdot c_{tn}\right] + \sum_{1}^{n-1}\left[d_{gn} \cdot l_{gn} \cdot c_{gn}\right],$$

where:

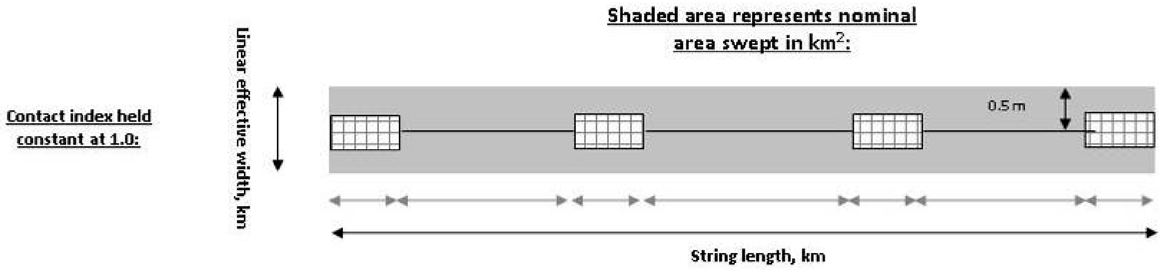
n = Number of traps
$n-1$ = Number of groundlines between traps
d_{tn} = lateral distance *n*th trap moves over the seabed (km)
l_{tn} = length of *n*th trap (km)
c_{tn} = contact index, *n*th trap
d_{gn} = lateral distance the *n*th ground line moves over the seabed (km)
l_{gn} = length of *n*th ground line (km)
c_{gn} = contact index, *n*th groundline

Similar to longlines and gillnets, the distance that each gear component moves is a function of movements over the seabed both while the gear is fishing (soaking) and during the setting and hauling processes, although the extent of these movements is unknown. The d_{tn} and d_{gn} parameters are intended to capture both types of movement (i.e. lateral and perpendicular to the long axis of the gear). For both the traps and the groundlines, these distances are assumed to be one meter. If d_{tn} and d_{gn} are specified as 0.001 km (1.0 m), and all traps and segments of groundline are assumed to be the same length, the equation simplifies to

$$A_{trap}(km^2) = (0.001 \cdot n \cdot l_{tn} \cdot c_{tn}) + (0.001 \cdot (n-1) \cdot l_{gn} \cdot c_{gn}).$$

Nominal and contact adjusted area swept are represented graphically below (Figure 5). The seabed contact index is assumed to be 1.0 for lines and traps.

Figure 5. Area swept schematic for trap gear (top down view). Since the contact index is 1.0, nominal area swept and contact-adjusted area swept are equivalent.



For traps, tow distance was estimated by multiplying number of hauls by gear length, with number of hauls from the VTR and gear length set at a fixed value of one mile for all trips. Details are in Appendix A. Linear effective width was estimated to be one meter for traps.

4.2 Assigning effort spatially

Fishing activity in the northeast region is documented using various methods, including vessel trip reports (often referred to as logbooks), satellite-based vessel monitoring systems, and at-sea observations by scientific personnel. The particulars of these datasets are discussed extensively elsewhere and beyond the scope of this report. Pertinent to the assembly of swept area data, the decision was made early on in the development of the SASI model to use vessel trip report (VTR) or the similar clam logbooks as the basis for swept area datasets. VTR/logbook data are available over the longest time series and for the largest fraction of trips and trip types, and compared to VMS data, which has limited temporal coverage and is not required for all fleets, and observer data, which covers a minority of trips.

Unfortunately from a spatial analysis standpoint, VTR/logbook are the least resolved of these three data types, with only a single position (latitude/longitude) reported for each subtrip, referred to as a GEARID in the VTRs[1]. Therefore, to support various fisheries management efforts, trip footprints are estimated using auxillary (primarily observer) data, in order to more accurately represent overall effort distributions in relation to a gear type, target species, or fishery management plan. The methods used for this spatial assignment are explained in DePiper (2014) and Benjamin *et al.* (2018). Briefly, as summarized in Bejamin *et al.*:

> "DePiper (2014) constructs the great circle (haversine) distance between the VTR coordinate and all observed hauls on that trip. A duration model is then estimated to explain distance from the self-reported VTR to observed fishing locations as a function of VTR characteristics, and finds that gear, trip length, and broad ocean area explain this distance. The model results can be used to construct c-confidence intervals, defined as the smallest

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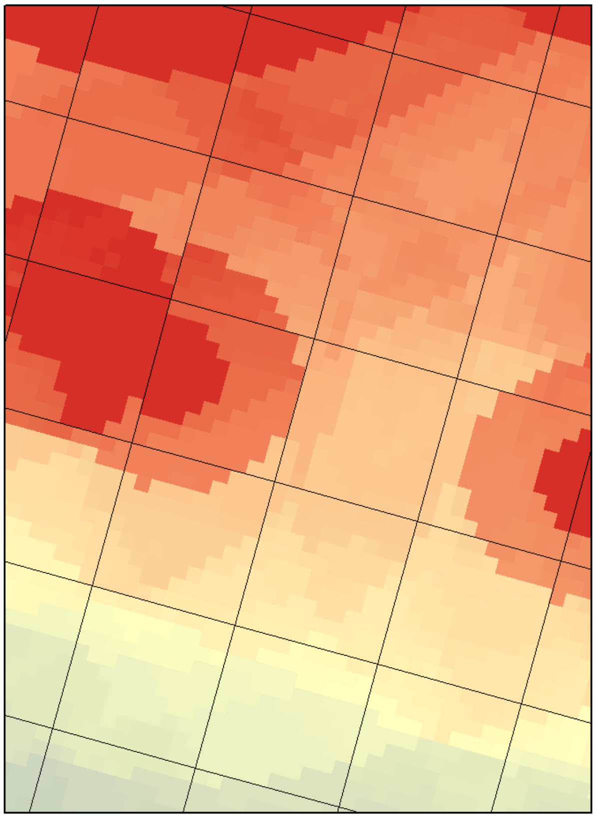
[1] A new gear ID is supposed to be used when the vessel switches gears or statistical areas during a trip.

> distance in which we expect to find c% of observed hauls around a VTR point can be constructed."

Area swept estimated at the subtrip (GEARID) level using the methods summarized in section 4.1 is assigned to these circular confidence intervals. Individual GEARID footprints are then combined by gear (trawl, scallop dredge, clam dredge, longline, gillnet, trap) and month. The final step, which is part of the model implementation, is reading these monthly raster datasets into R and assigning swept area to 5x5 km grids. The circular confidence interval rasters use a grid resolution of 250 m x 250 m, which is nested within the 5 km x 5 km grids (Figure 6).

Figure 6. Swept area raster data (blue to red coloration) as compared to FE model grid (black lines).



5.0 Base grid

5.1 Spatial distribution of sediment

A map of sediment-based habitat categories was developed in order to apply habitat vulnerabilities across the Northeast region. Six sediment types were used to classify habitat: mud, sand, gravel, cobble, boulder, and steep/deep. The steep/deep category was included to account for corals found at depth that are highly susceptible to impact and require long recovery times. A sediment profile was constructed for 5 km grid cells across the Northeast region that represented the proportional contribution of each sediment type found in the grid cell.

The sediment profiles were produced from a compilation of seven disparate data sources. Three were provided as GIS databases with point spatial geometry; four were provided with polygonal spatial geometry. The most substantial sediment database included in this analysis was optical assessments from camera surveys provided by the Marine Fisheries Field Research Group at University of Massachusetts Dartmouth School for Marine Science and Technology, which included over 187,000 sediment points distributed primarily throughout Georges Bank and the Mid-Atlantic. To improve the spatial coverage of sediment data, additional sediment points were downloaded from U.S. Geological Survey databases (https://cmgds.marine.usgs.gov/publications/of2005-1001/htmldocs/datacatalog.htm). Points representing known locations of corals were also compiled and provided by the NEFMC. Polygonal sediment data was limited to coastal regions along Maine and Massachusetts, Narragansett Bay, and deep/rocky regions beyond 200 m depth.

Each of the data source used a different sediment classification system. To standardize these classifications, the original sediment classifications were converted to a presence/absence representation of each of the six sediment types used in this analysis. Table 21 provides metadata for each data sources and a description of how the original sediment classifications were mapped to the six sediment types.

Despite a wide variability in the spatial distribution of sediment information support, sediment profiles were estimated on a consistent 5 km grid. The goal was to ensure the sediment data aligned with the resolution of the fishing data. To accommodate this varying spatial resolution of the sediment data, three different methods were used to convert presence/absence sediment data to sediment profiles depending on the geometry and/or density of points within a grid cell (Map 1). In grid cells with polygonal sediment data, a modified area-weighted approach was used to calculate the proportion of each sediment within a grid cell:

$$\varphi_{i,s} = \frac{\sum_{j=1}^{n} \pi_{i,s,j}}{\sum_{s=1}^{6} \sum_{j=1}^{n} \pi_{i,s,j}} \qquad (5.1),$$

where $\varphi_{i,s}$ is the proportion of sediment, s, in grid cell, i; and $\pi_{i,s,j}$ is the area of the jth polygon of n total polygons within a grid cell. Note that if no single polygon represented multiple sediments, the denominator would simply be equal to the area of the grid cell and be a straightforward area-weighted calculation.

In grid cells with eight or more sediment points, a similar method was used, except instead of using an area-weighted approach, a count of points with sediments present was used to calculate $\varphi_{i,s}$. *Eq. 5.1* was still the basis for the calculation, where *j* was an index of *n* total sediment points, and $\pi_{i,s,j}$ takes the value of 0 or 1 if sediment is absent or present, respectively.

In grid cells with less than eight points, an Ordinary Kriging spatial interpolation was first applied to the full domain to estimate the probability that each sediment was present at the center of a 2.5 km grid cells nested within the 5 km grid. This approach produced four estimations of sediment probabilities within each 5 km grid cell. Again, *Eq. 5.1* was used to calculate $\varphi_{i,s}$ in these grid cells, where $\pi_{i,s,j}$ was the estimated probability of presence for sediment s, and $n = 4$ was fixed, which corresponded to the four 2.5 km grid center points within each 5 km grid cell. The Kriging analysis was conducted in R (ver. 3.4.3) using the *gstat* package (Gräler *et al.*, 2016).

Table 21. Metadata for sediment GIS databases compiled for sediment distribution maps.

Source	Spatial geometry	Size	Presence/absence mapping process
Bethony & Stokesbury, 2018	Point	187,720 points	Data was coded as presence/absence. We used 'silt' to denote mud habitat; 'sand' and 'sandRipple' to denote sand habitat; 'gravel' to denote gravel habitat; 'cobble' to denote cobble habitat; and 'rock' to denote boulder habitat.
U.S. Geological Survey, 2014	Point	27,784 points	'Clay', 'silt', 'sand', and 'gravel' are coded as proportions. We used 'clay' and 'silt' together to denote mud category. If proportions were greater than zero, the sediment was assumed present. These data points were excluded from the cobble and boulder interpolations.
NEFMC, 2016[2]	Point	136 points	These points are known locations of corals. They were used to represent locations where boulder habitat was present. They were excluded from interpolations of the other sediment types.
Barnhardt *et al.*, 1998	Polygon	10,312 sq. km	Polygons were coded with a capital and lowercase letter for dominant and subordinate substrate, respectively. If a habitat category was coded by either the dominate or subordinate substrate, it was assumed present. 'M' was used to denote mud habitat; 'S' for sand habitat; 'G' for gravel habitat; and 'R' was used to denote boulder habitat. In this dataset 'R' corresponds to rock outcrops which are different from boulder habitats occurring elsewhere in the domain.
Massachusetts Office of Coastal	Polygon	9,572 sq. km	Polygons were coded with a capital and lowercase letter for dominant and subordinate substrate, respectively.

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[2] Compiled by NEFMC from data provided by the NOAA Deep-Sea Coral Research and Technology Program. Observations include towed camera, remotely operated vehicle, and autonomous underwater vehicle dive locations. Fieldwork was conducted from 2012 to 2017.

Zone Management			If a habitat category was coded by either the dominate or subordinate substrate, it was assumed present. 'M' was used to denote mud habitat; 'S' for sand habitat; 'G' for gravel habitat; and 'R' was used to denote boulder habitat. The data set used here was updated by the Regional Sediment Resource Management Workgroup in 2014.
Narragansett Bay Estuary Program, 2017	Polygon	2,191 sq. km	Polygons annotated by 'mud', 'sand', and 'gravel' denote the presence of each. 'Gravel mixes' denote gravel, and 'Muddy sand' denotes presence of both mud and sand.
ACUMEN, 2012[3]	Polygon	165 sq. km	Boundaries of all polygons indicate presence of deep/rocky category. ACUMEN is a 25 m^2 resolution digital elevation model. To develop this data product, a slope dataset was derived from the DEM, and then cells with values equal to or greater than 30 degrees were selected and dissolved into polygons. These areas with steep slopes tend to have rocky outcrops suitable for attached sessile fauna, and were shown to contain corals almost all the time when observed with remotely operated vehicles or towed cameras.

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[3] Polygons represent areas where the slope is greater than 30 degrees based on a 25 m resolution digital elevation model for the northeast U.S. canyon and slope region. Data come from a series of Atlantic Canyons Undersea Mapping Expeditions (ACUMEN) on NOAA's research vessels Hassler, Bigelow, and Okeanos Explorer. These mapping expeditions took place from February 2012 through August 2012.

Map 1. Sediment data support within 5 km grid cells. Pink areas show regions where an area weighted approach with polygon sediment data was used to calculate sediment profiles. Brown indicates grid cells with eight or more sediment points where a point aggregation approach was used to calculate sediment profiles. Light to dark blue shows grid cells with 0 – 7 sediment points per cell where a Kriging approach was used to estimate sediment profiles.

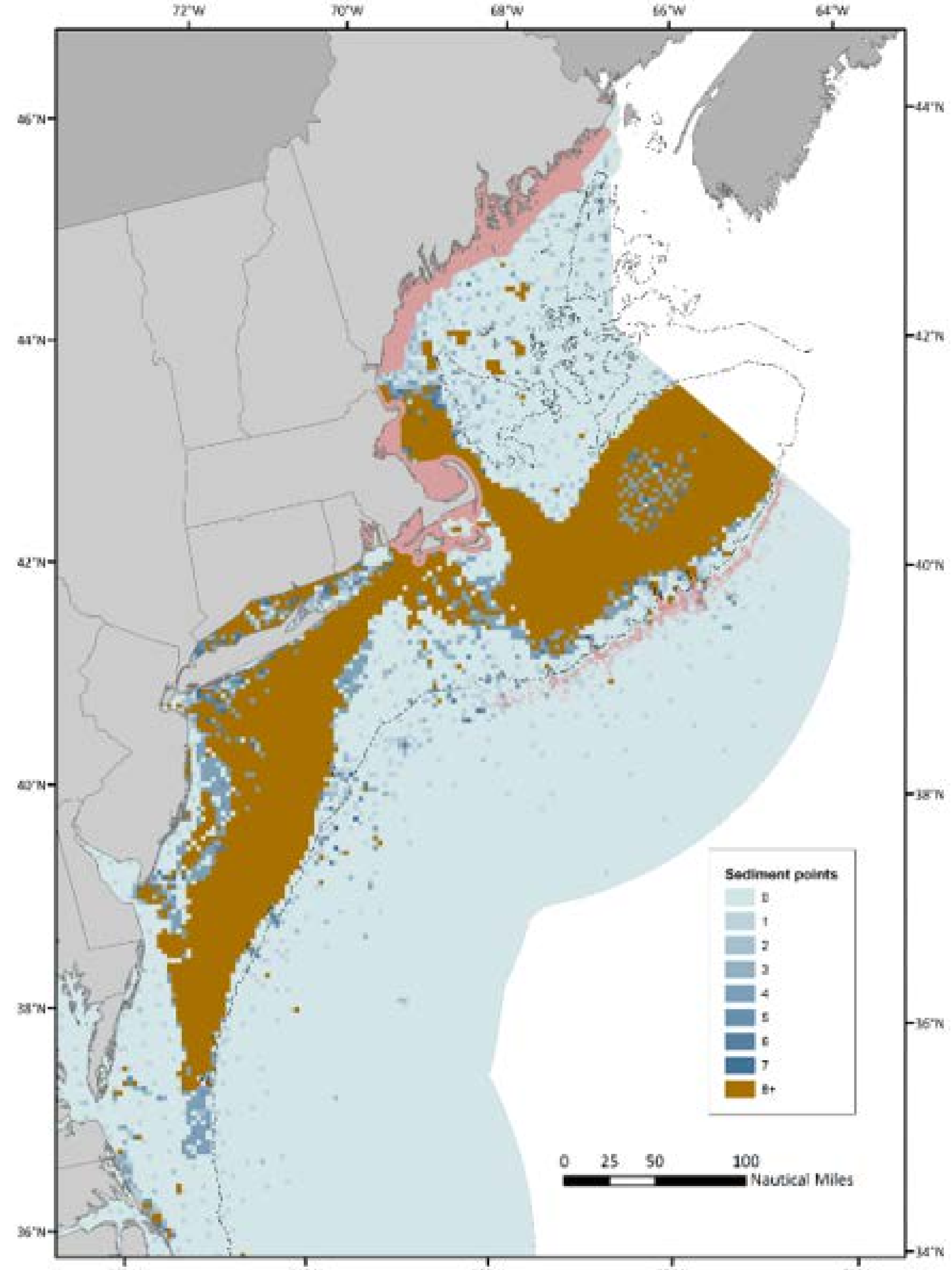


Figure 7. Variogram for mud sediments

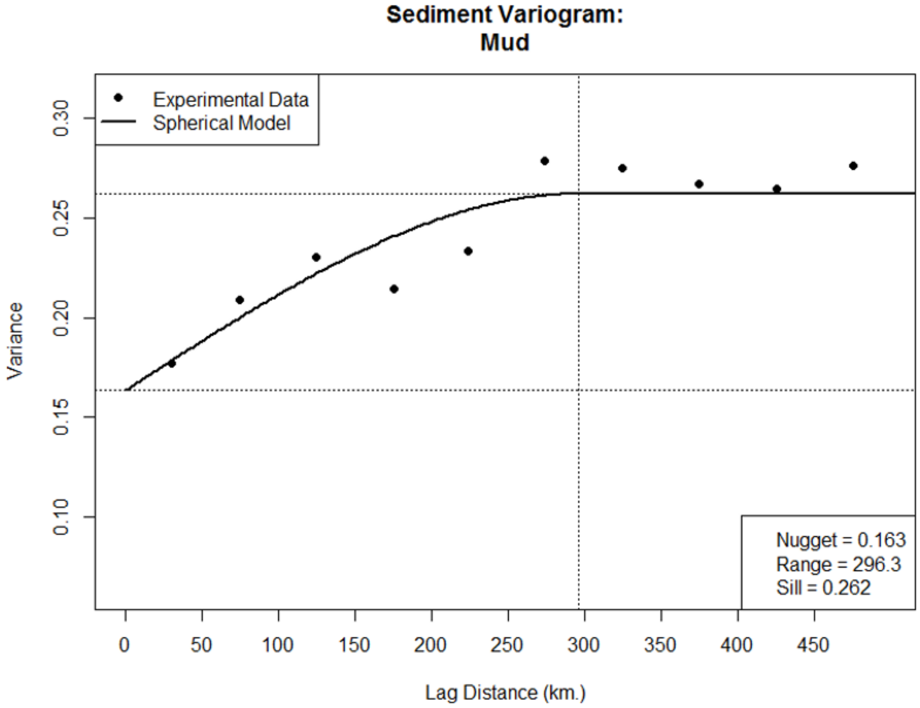


Figure 8. Variogram for sand sediments

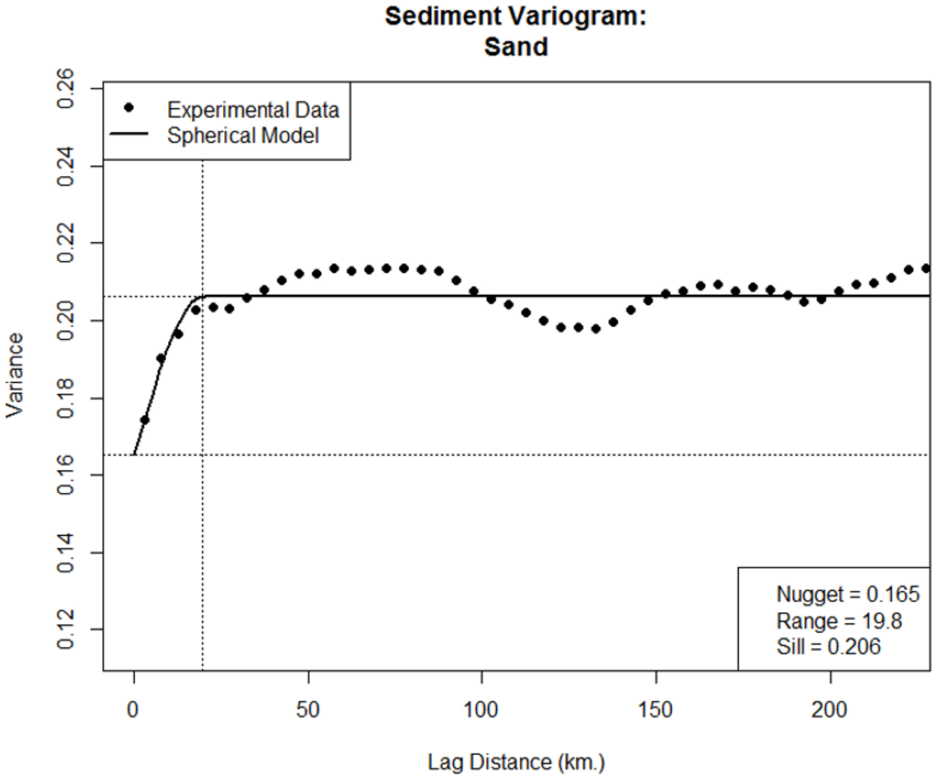


Figure 9. Variogram for gravel sediments

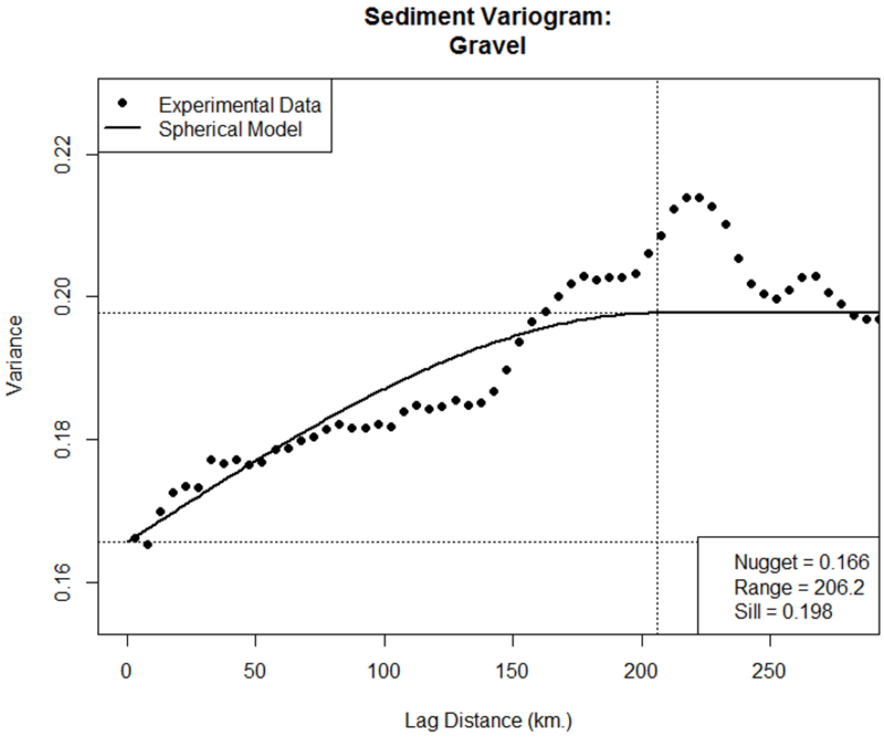


Figure 10. Variogram for cobble sediments

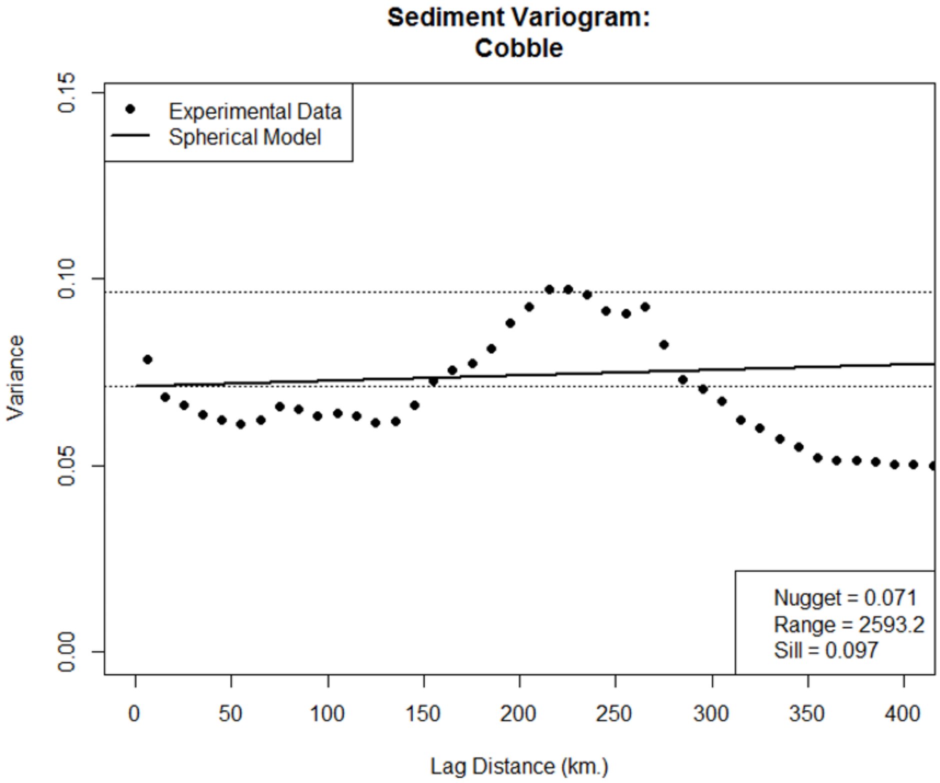
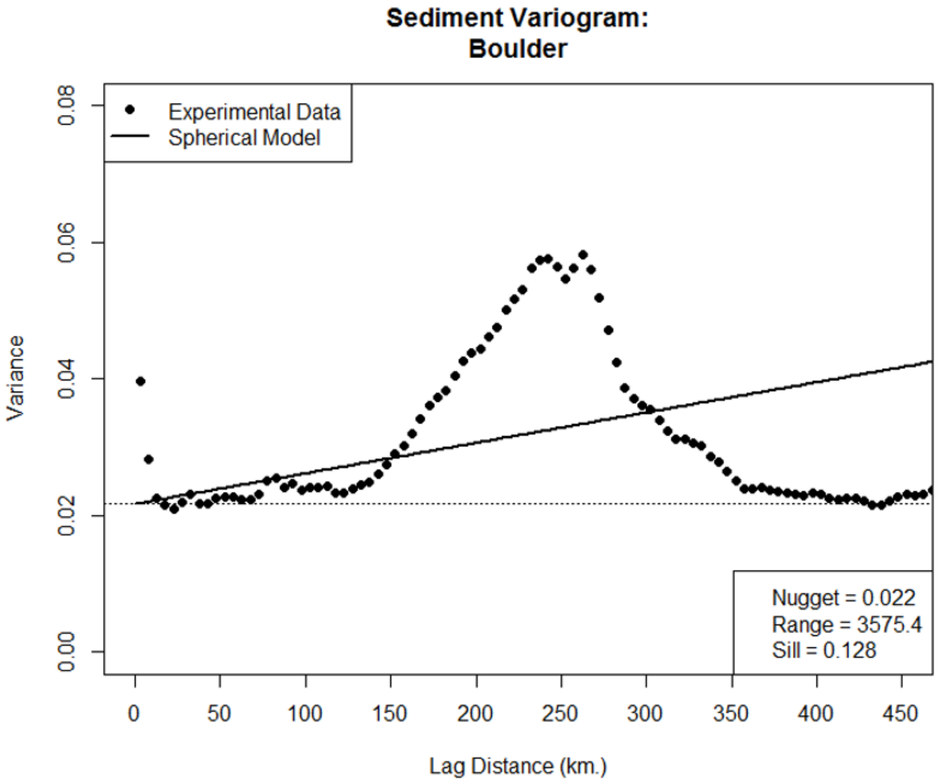
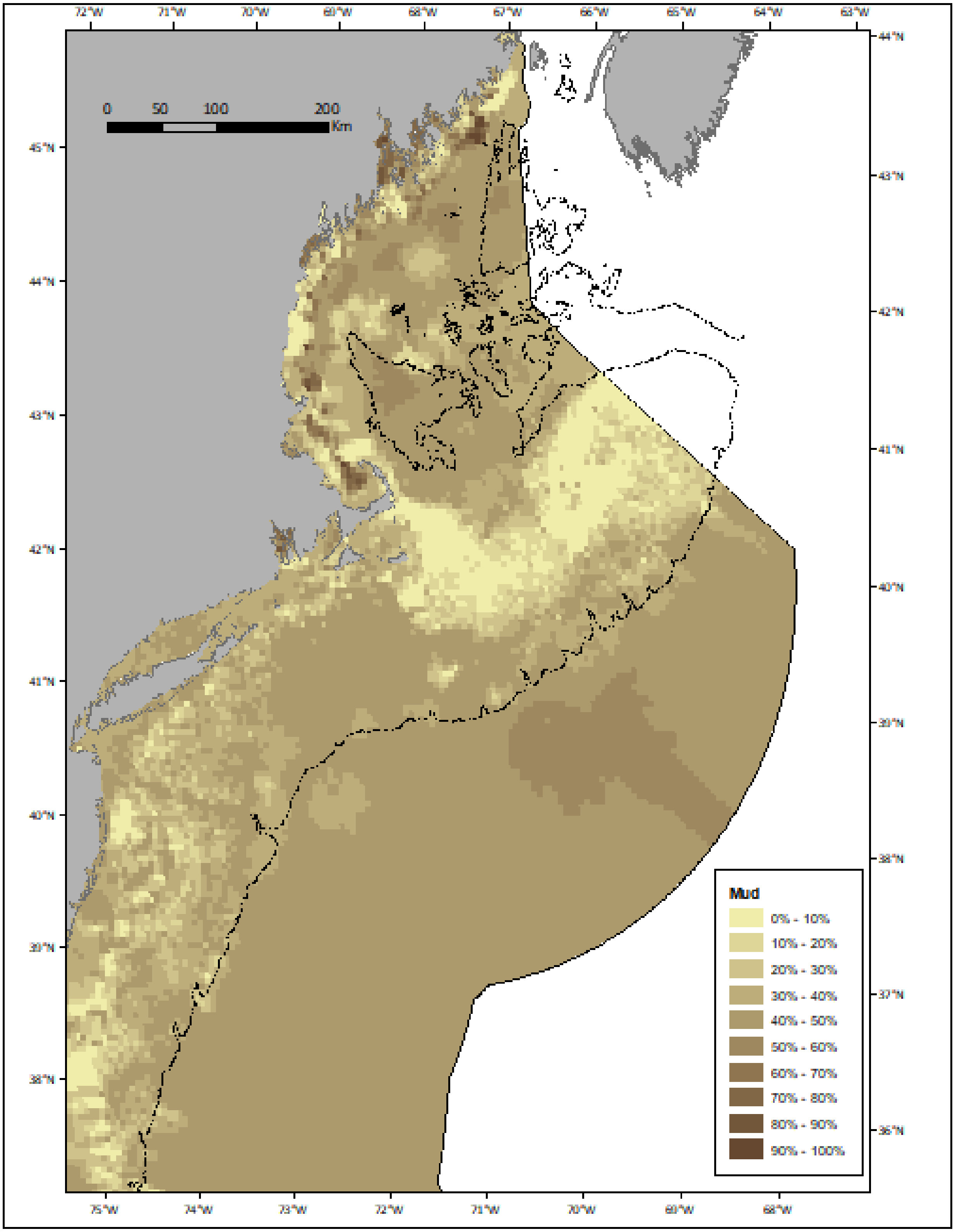


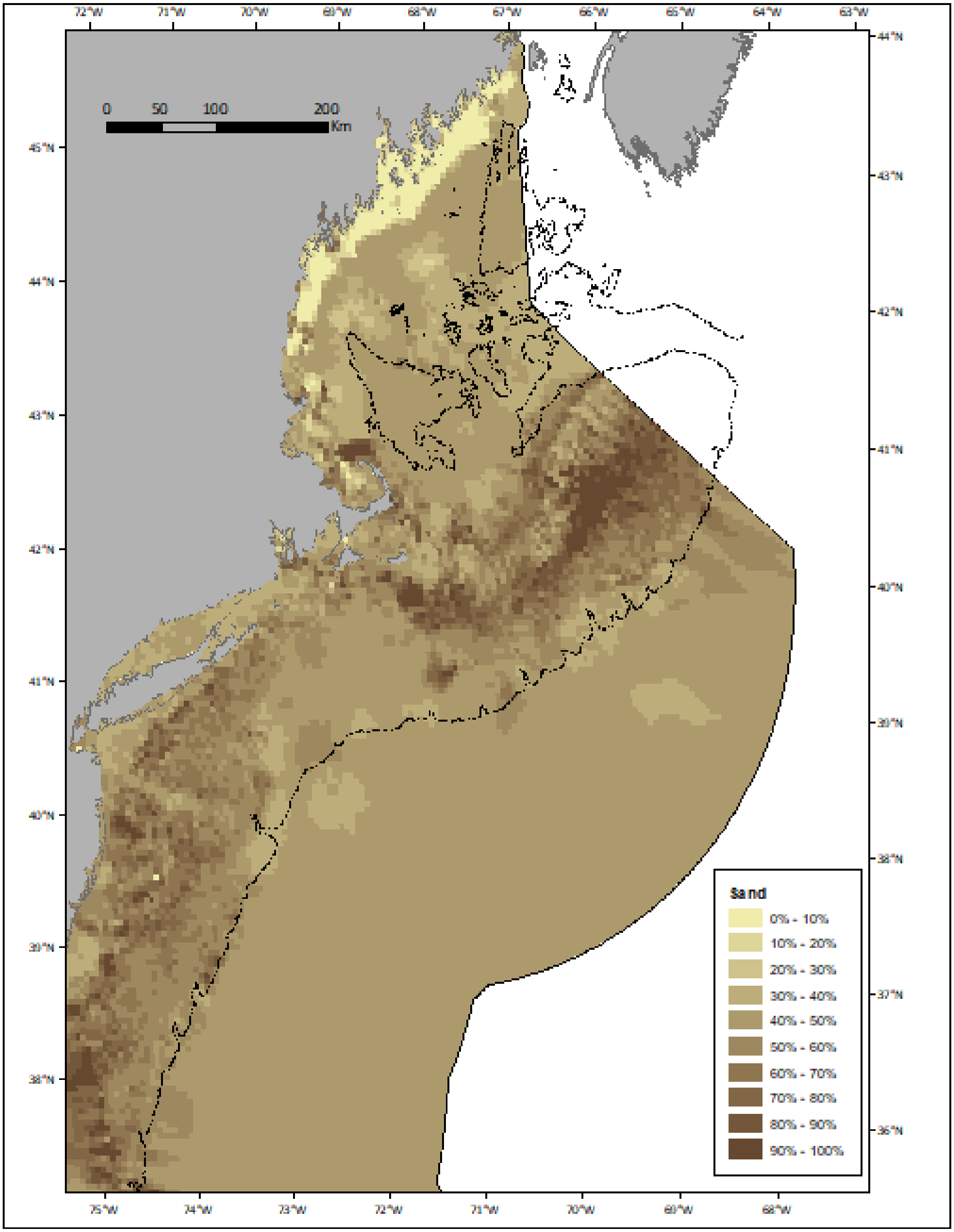
Figure 11. Variogram for boulder sediments



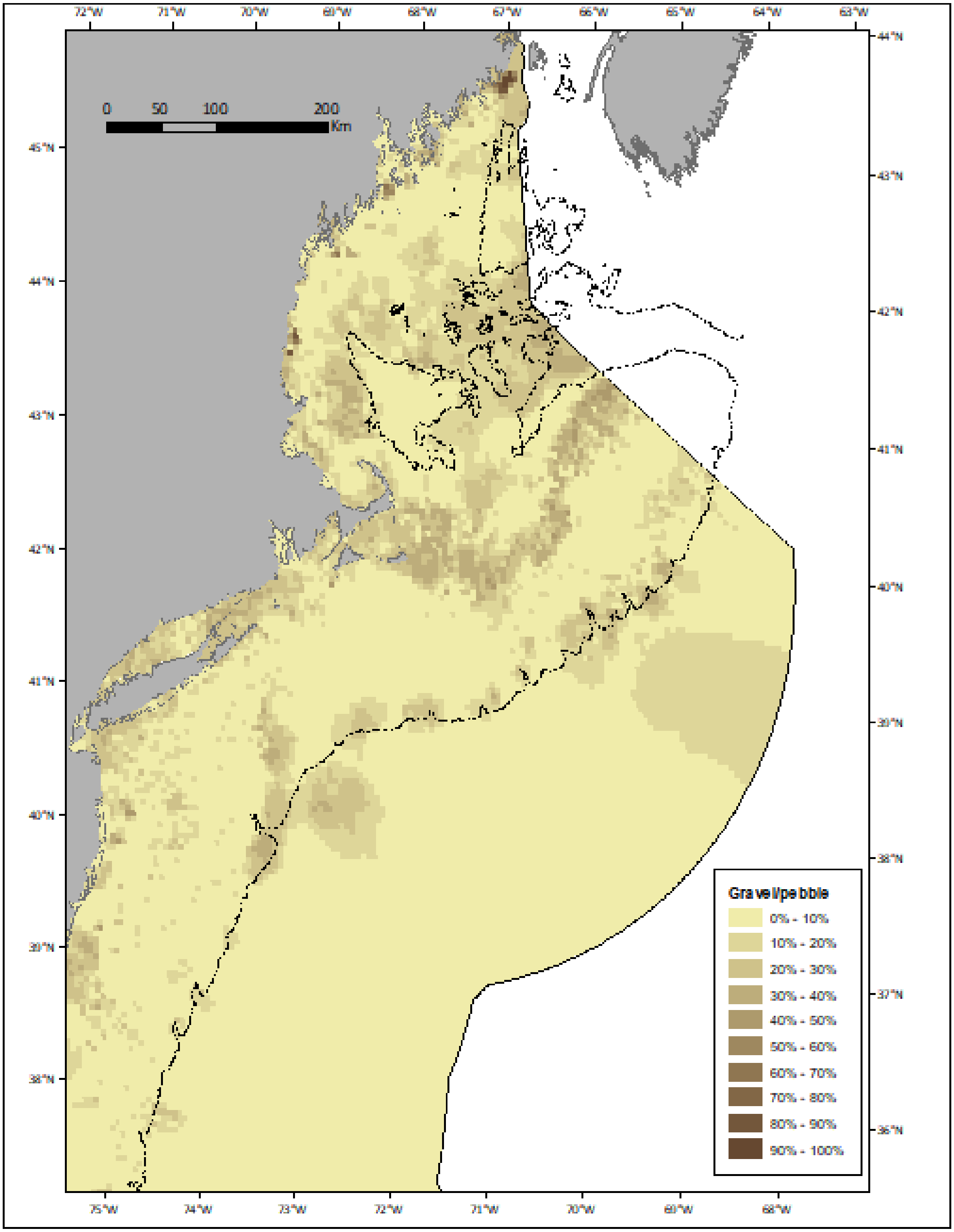
Map 2. Percent mud by 5 km grid cell.



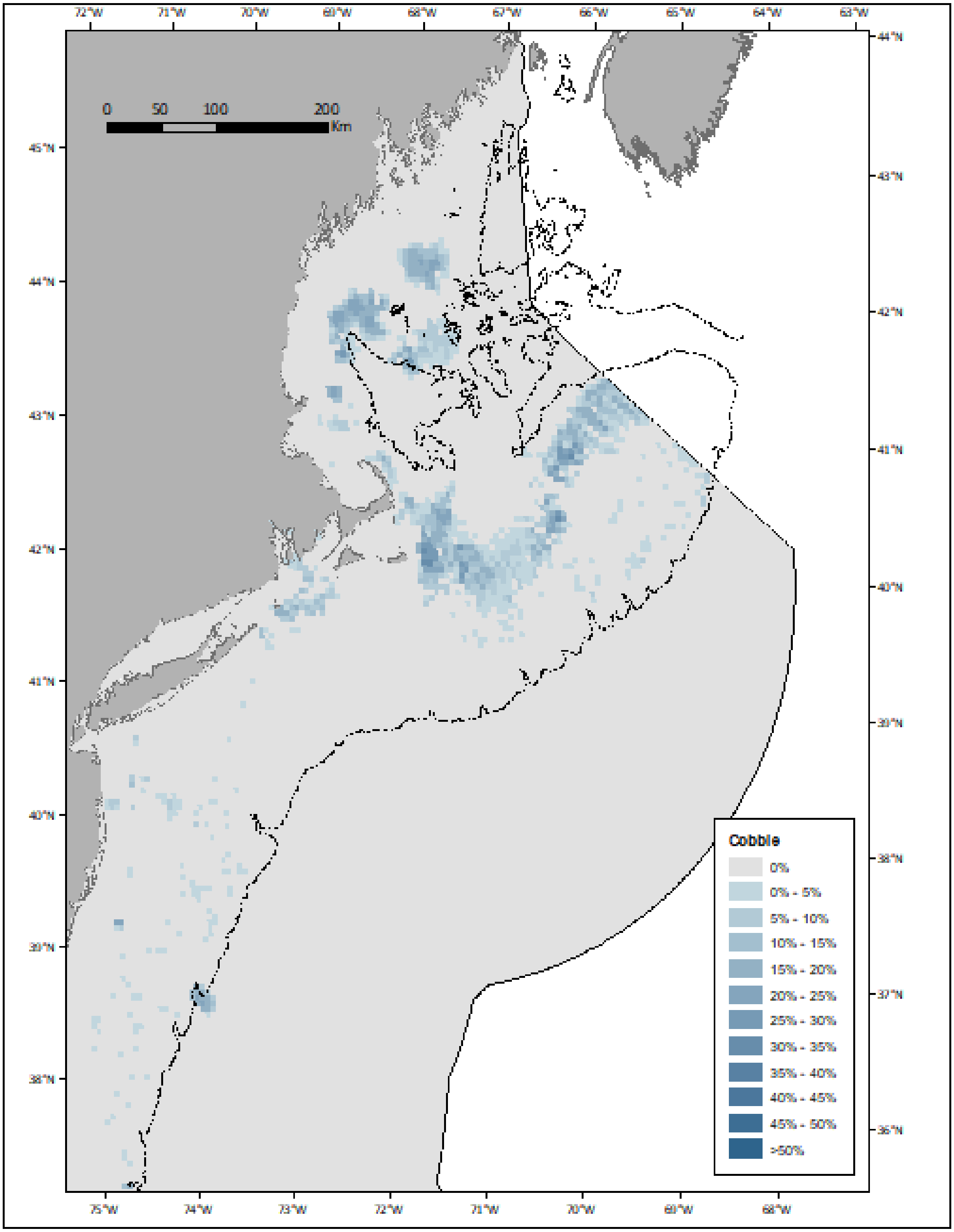
Map 3. Percent sand by 5 km grid cell.



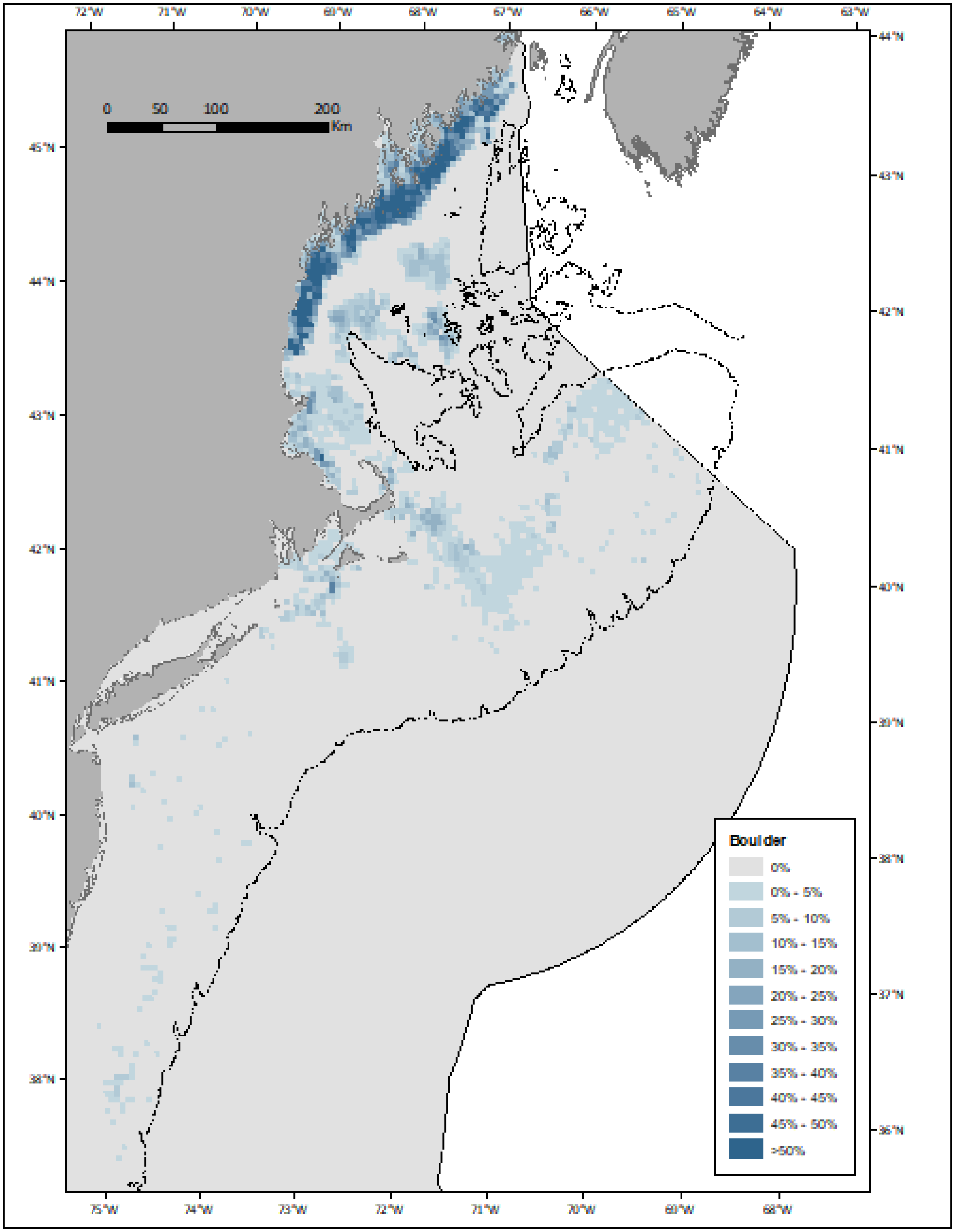
Map 4. Percent gravel by 5 km grid cell.



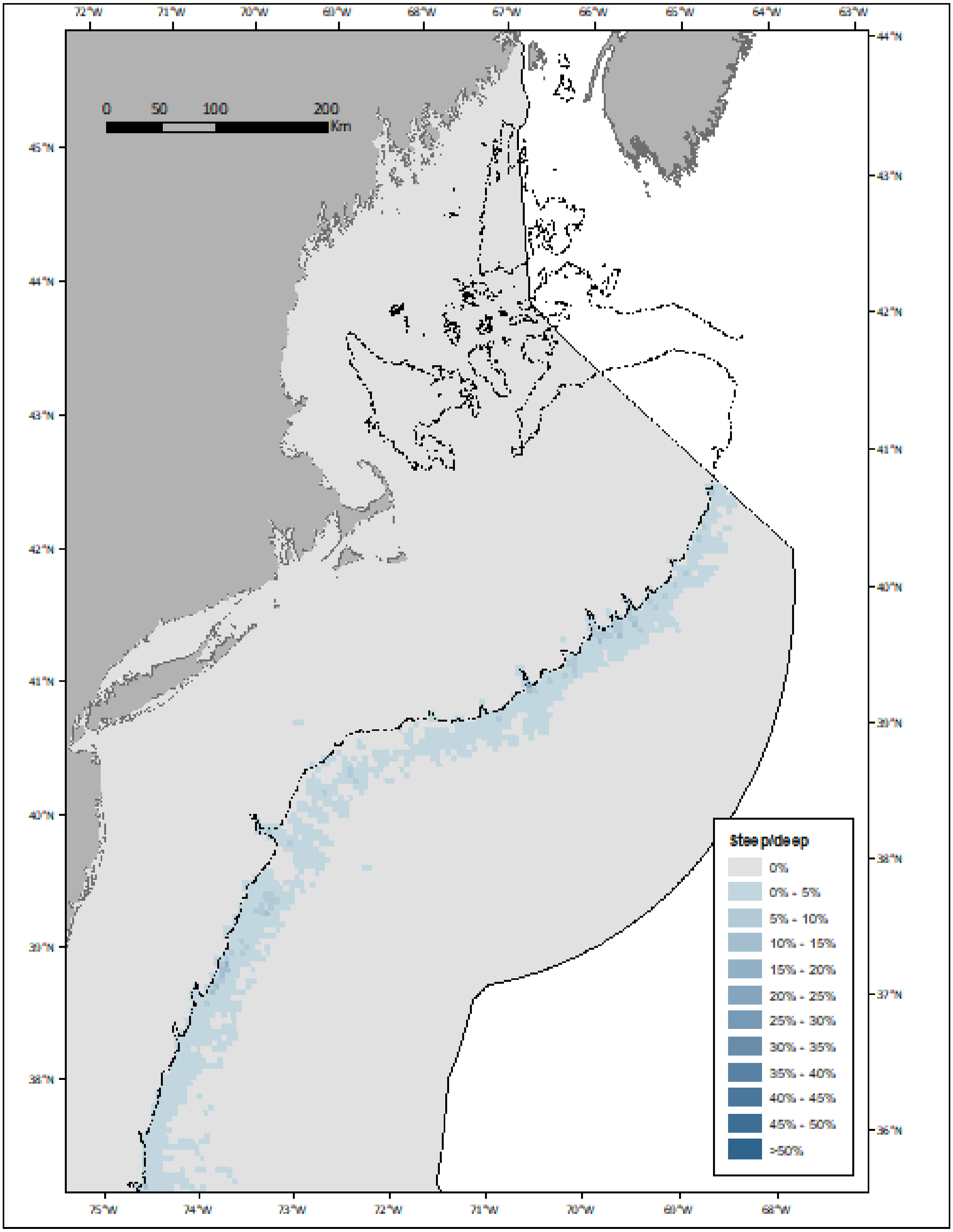
Map 5. Percent cobble by 5 km grid cell.



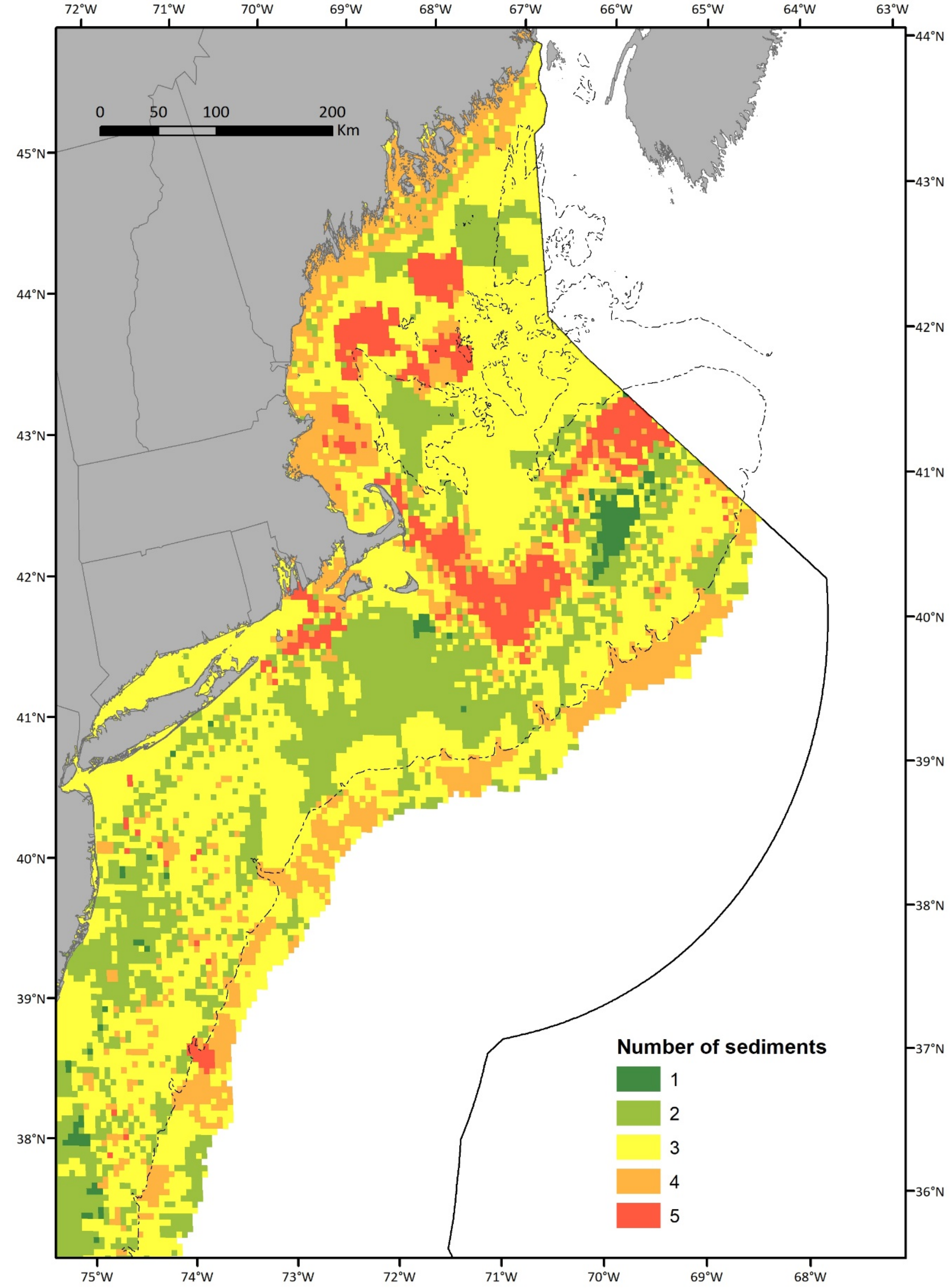
Map 6. Percent boulder by 5 km grid cell.



Map 7. Percent steep and deep habitat by 5 km grid cell.



Map 8. Number of sediment types present within each grid cell.



5.2 Setting the model domain

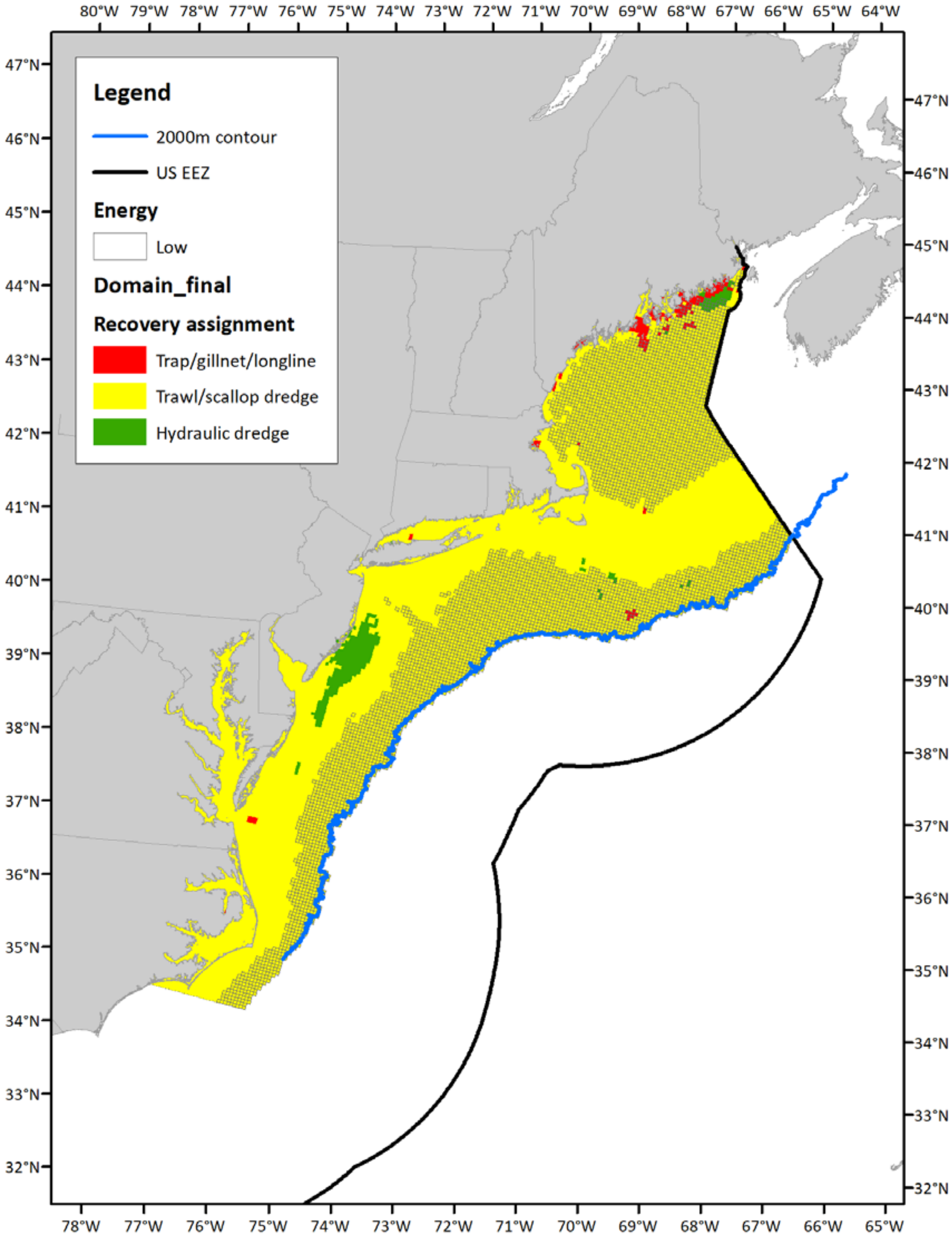
Generally the FE model domain extends north to south from the U.S./Canadian border to the N.C./S.C. border, and inshore to offshore from the coastline to the Exclusive Economic Zone boundary. The sediment basemap was developed for this entire domain. However, because model outputs can be expressed in terms of percent disturbance over the domain, total domain size becomes important. Thus, the team agreed it would be useful to truncate the domain to encompass just the area where fishing effort has occurred, and run the model and report the results over that subset of the region. In addition, the team determined that for combined model runs, where all types of fishing effort are overlaid, it would be useful to reference recovery values according to the predominant gear type used in each grid cell.

A depth of 2,000 m was selected to define the edge of the model domain along the shelf break. Between 2016 and 2018 to support development of its Deep Sea Coral Amendment, the Council convened extensive discussions about footprints of fishing effort along the edge of the shelf. Collectively, Council stakeholders indicated that effort with bottom-tending gears occurs to depths of around 650 meters, which is the depth at which deep-sea red crab traps are set. Depth contours are closely spaced along the shelf break, which is very steep, and fishing effort locations are not particularly precise. Considering these two factors, the 2000 meter contour was used as the edge of the domain to provide a buffer of around one 5 km grid cell beyond the depth actually fished. A digital elevation model developed by the Nature Conservancy and largely based on NOAA's Coastal Relief Model was used to create the 2000 m contour line used in this analysis.

In order to determine the dominant gear type in each grid cell, fishing effort data sets expressed in common area swept units were overlaid spatially, and the area swept values were compared across gears. Because the recovery values are similar across scallop dredges/trawls, vs. gillnets/longlines/traps, vs. hydraulic dredges, effort was summed into these three categories first, and then low effort cells (outliers) were dropped. Next the quantitative swept area values were compared across these three categories and the dominant grouping was identified. If the values were equal across categories and clam dredge effort was present in the grid, clam dredge was assigned. If values were equal across categories but only trawl/scallop dredge and fixed gears were present, or if these values were equal but greater than the clam dredge value, trawl/scallop dredge was assigned. These rules result in larger R values/longer recovery time parameter application in cases where equal amounts of swept area were present across gear categories. Cells outside any of the three footprints were assigned as trawl/scallop dredge. Detailed methods for assigning dominant gear type are provided in Appendix C.

High/low energy values were assigned as for the SASI model (NEFMC 2011) on the basis of benthic boundary shear stress estimates, or depth, where shear stress estimates were unavailable. R values are applied based on these high low energy values. The final domain with dominant gear type and energy assignment is shown in Map 8.

Map 8. Model domain, dominant gear type assignment, and energy assignment.



6.0 Model implementation

6.1 Overview of the Fishing Effects model

Habitat disturbance from commercial fishing activities in the Northeast region was estimated using the Fishing Effects model, a tool developed to support management of essential fish habitat (Smeltz *et al*. 2019). The model estimates functionally intact and disturbed habitat for proportional areas of 5 km x 5 km grid cells (25 km^2) on monthly time steps. The key dynamic of the model tracks habitat impacts and recovery during each time step to account for the proportion of habitat that transitions between disturbed and functionally intact states (Figure 12).

Impacts are defined as the proportion of intact habitat that is disturbed during each time step and are calculated from a series of steps that rely on information about fishing locations, fishing intensity, gear characteristics, and how susceptible the habitat is to fishing gear at that location. For the implementation of the Fishing Effects model in the Northeast region, spatially explicit contact-adjusted swept area (represented as proportional to a 25 km^2 grid cell) was first estimated using model-based estimates derived from vessel trip report (logbook) data and gear contact adjustment information (see Section 4.0 for details). Impacts from an individual fishing event were calculated as the product of bottom contact and habitat susceptibility for each grid cell and monthly time step. Susceptibility is defined as the proportion of habitat disturbed by contact with fishing gear and is specific to each gear-habitat combination. Tables of susceptibility values are provided in Section 3.2. All habitat impacts were summed within a grid cell and time step and adjusted to account for spatial overlap using the assumption that fishing effort is randomly distributed within a grid cell which was demonstrated to be adequate in 25 sq. km grid cells (Smeltz *et al.* 2019).

Recovery is defined as the proportional amount of habitat that transitions from disturbed back to a functionally intact state in each grid cell and time step. It is calculated using the mean time required for a habitat to return to an intact state. The recovery parameter is specific to each habitat type and is calculated as the average recovery time of all habitat features (both geological and biological features) associated with a habitat type.

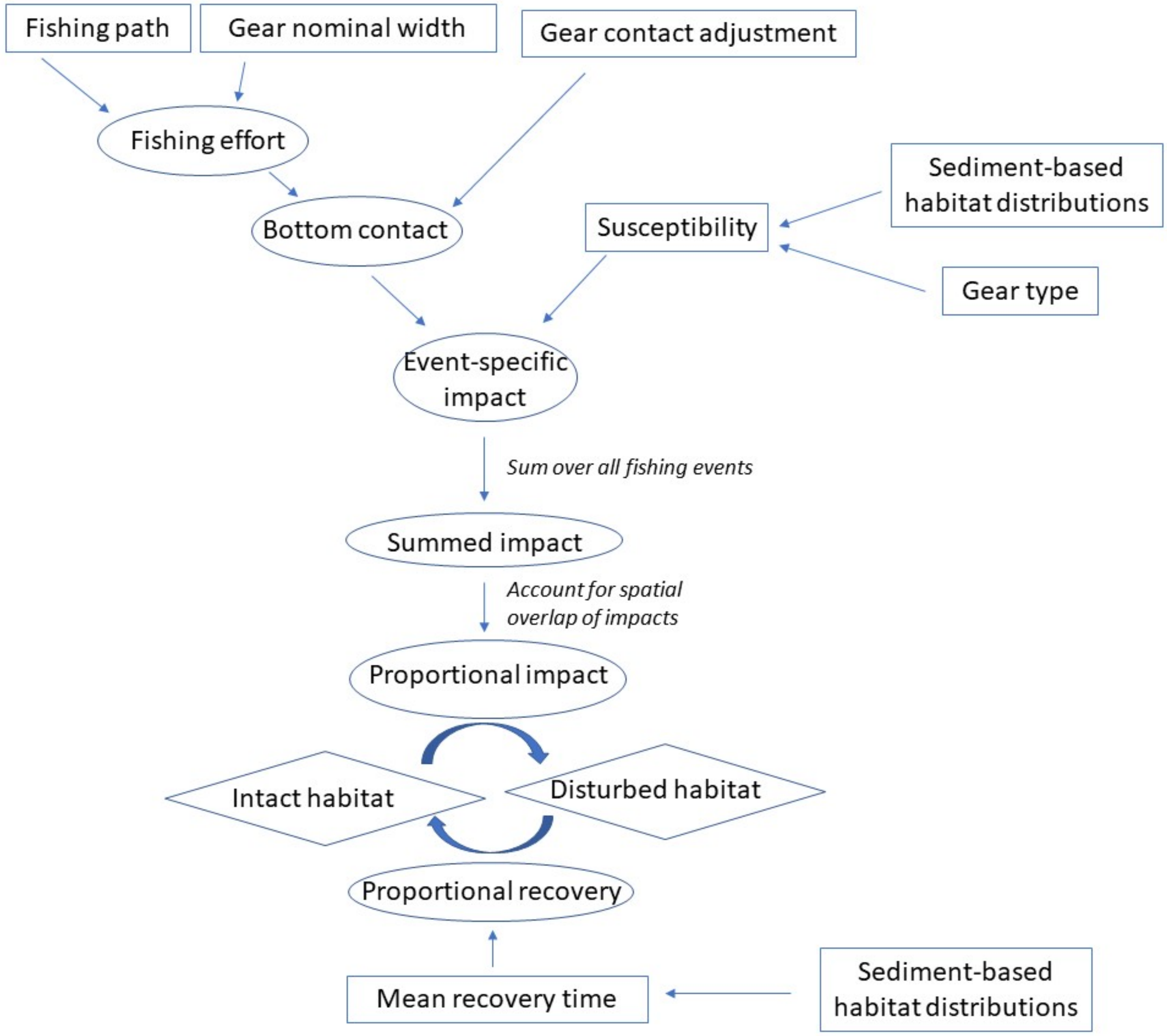
The Fishing Effects model was run using fishing data from 1996 to 2017 using the model domain defined in Section 5.2. Because habitat disturbance in each time step of the model is calculated based on the disturbed and intact habitat from the previous time step, a set of initial conditions is required to begin the model run and ideally reflect fishing patterns prior to 1996. To create a reasonable set of initial conditions, and model run using only fishing data from 1996-1998 looped ten times was used. This essentially runs the model for 30 years allowing the habitat disturbance to reach an equilibrium and assumes that fishing prior to 1996 was similar to fishing from 1996-1998.

6.2 Comparison to the Swept Area Seabed Impact model

The FE model was developed from the SASI model previously used by the Council to estimate habitat impacts from fishing. Both models use a discrete time impacts/recovery dynamic. The framework to calculate fishing impacts from fishing effort, nominal swept area, contact adjustment, and habitat susceptibility is the same in both models. The key difference between the two models is how the impacts and recovery are used to estimate fishing effect. In the original

SASI model, all impacts were summed, estimating fishing effects in units of swept area that could exceed the size of the grid cell. Recovery in the SASI model was treated as a linear process. The Fishing Effects model sums all impacts, but accounts for potentially overlapping fishing effort. Additionally, the Fishing Effects model uses an asymptotic recovery trajectory which better reflects the recovery dynamics of space-limited sessile habitat features. This produces an output from the Fishing Effects model that is constrained between 0% and 100% and can be interpreted as percent habitat disturbance.

Figure 12. Flow chart of the Fishing Effects model framework. These series of calculations are made for each grid cell and monthly time step. Square boxes show model inputs, ovals show calculated quantities, and diamonds are primary model outputs.



6.3 Mathematical description of the Fishing Effects model

The Fishing Effects model defines two habitat states, disturbed, $h_{i,t}$, and intact, $H_{i,t}$ for each grid cell and monthly time step, t, that together sum to unity:

$$H_{i,t} + h_{i,t} = 1 \qquad \text{(A1).}$$

Impact, $\tilde{I}_{i,t}$, is the proportion of $H_{i,t}$ that transition to $h_{i,t+1}$ and recovery, $\tilde{\rho}_{i,t}$, is a proportion that governs the transition of $h_{i,t}$ to $H_{i,t+1}$:

$$H_{i,t+1} = H_{i,t}\left(1 - \tilde{I}_{i,t}\right) + h_{i,t}\tilde{\rho}_{i,t} \qquad \text{(A2).}$$

The $\tilde{I}_t$ impact parameter is a strict proportion that accounts for spatial overlap of individual fishing events, j, from n total fishing events within a time step, and is calculated from the summation of individual impacts:

$$\tilde{I}_{i,t} = 1 - \exp(-\sum_{j=1}^{n} I_{i,t,j}) \qquad \text{(A3),}$$

where $I_{i,t,j}$ is the impact from an individual fishing event in a grid cell and time step. The assumption underlying *Eq. 3* is that the fishing effort is spatially random within a grid cell. Individual impacts are decomposed into the product of nominal swept area, $A_{t,i,j(g)}$, contact adjustment, $c_{t,j(g)}$, and habitat susceptibility, $q_{s,g}$:

$$I_{t,i,j} = A_{t,i,j(g)} c_{t,j(g)} q_{s,g} \qquad \text{(A4).}$$

Here, $A_{t,i,j(g)}$ is measured as an area proportional to the area of a grid cell by a fishing event with a specific gear type, g; $c_{t,g}$ is a strict proportion representing the portion of the swept area actually in contact with the seafloor by a gear; and q_s is a strict proportion representing the proportion of habitat features, s, disturbed if contacted by a gear.

Recovery, $\tilde{\rho}_t$, is calculated as a discretized proportion of an exponential distribution with a mean time to recovery (in months), τ_s:

$$\tilde{\rho}_s = 1 - \exp(-\frac{1}{\tau_s}) \qquad \text{(A5).}$$

7.0 Results and sensitivity analyses

7.1 Base model runs

Total habitat disturbance from all gears combined declined steadily from an initial condition of 35% to 20% by the terminal month of the model run (Dec. 2017, Figure 13). Of the total domain, approximately 1.7% of the grid cell had no fishing effort. Of the fished areas, habitat disturbance from all gears combined was only marginally less (19%) compared to the full domain. Thirty percent of the fished grid cell were estimated to have low habitat disturbance (<5%), and 8% of the grid cells were predicted to have high habitat disturbance (>50%).

When individual gears were considered in isolation, bottom trawls accounted for about 90% of the total habitat disturbance, with their disturbance trajectory largely driving the trend in total habitat disturbance. Habitat disturbance from bottom trawls decreased from an initial condition of 34% to a terminal estimate of 17%, largely reflecting the reduction in bottom trawl fishing effort over this time period. Bottom trawl fishing effort was estimated on 97% of the grid cell throughout the domain, with a predicted habitat disturbance of 18% in these fished grid cells. About 35% of the grid cells had low habitat disturbance and 7% had high habitat disturbance from bottom trawls.

Scallop dredges contributed the second most to total habitat disturbance. When considered in isolation, predicted habitat disturbance from scallop dredges showed marginal decrease in habitat disturbance from an initial condition of 3.6% to 2.5% by December 2017. About 91% of the grid cells had scallop dredge fishing activity with a predicted habitat disturbance of 2.8% in these fished cells. About 85% of the cells fished with scallop dredges had low habitat disturbance from and none had high habitat disturbance.

Habitat disturbance from hydraulic dredges, traps, longlines, and gillnets was substantially lower than bottom trawls or scallop dredges, with each respective gear causing <1% habitat disturbance. Hydraulic dredges led to an increase in habitat disturbance, from an initial condition of about 0.22% in January 2003 to 0.34% by December 2017 (data for hydraulic dredges was not available prior to 2003). Hydraulic dredge activity occurred on 64% of the grid cells, with 0.53% habitat disturbance on these fished cells. Nearly all of these fished cells (98%) had low habitat disturbance from hydraulic dredges.

Trap gears showed a declining trend in habitat disturbance from an initial condition of 0.24% to 0.10% by the end of the model run, with strong seasonal fluctuations. Trap fishing occurred on nearly all grid cells (97%), with an estimated habitat disturbance of 0.11% on these fished cells. Nearly all fished cells had low habitat disturbance from traps.

Habitat disturbance from longline also decreased over the time span from 0.09% to nearly zero (<0.01%). Longline fishing occurred on 88% of the grid cells, all with low habitat disturbance.

Habitat disturbance from gillnets was also exceptionally low, declining from remaining 0.02% to nearly zero (<0.01%) by December 2017. Gillnet fishing occurred on 94% of the grid cells, all of which had low habitat disturbance.

Figure 13. Time series of habitat disturbance (%) throughout total domain. Left panel shows all gear combined (black line) with individual gears that alone contribute >1% to habitat disturbance. Right panel shows individual gears that alone contribute <1% to habitat disturbance.

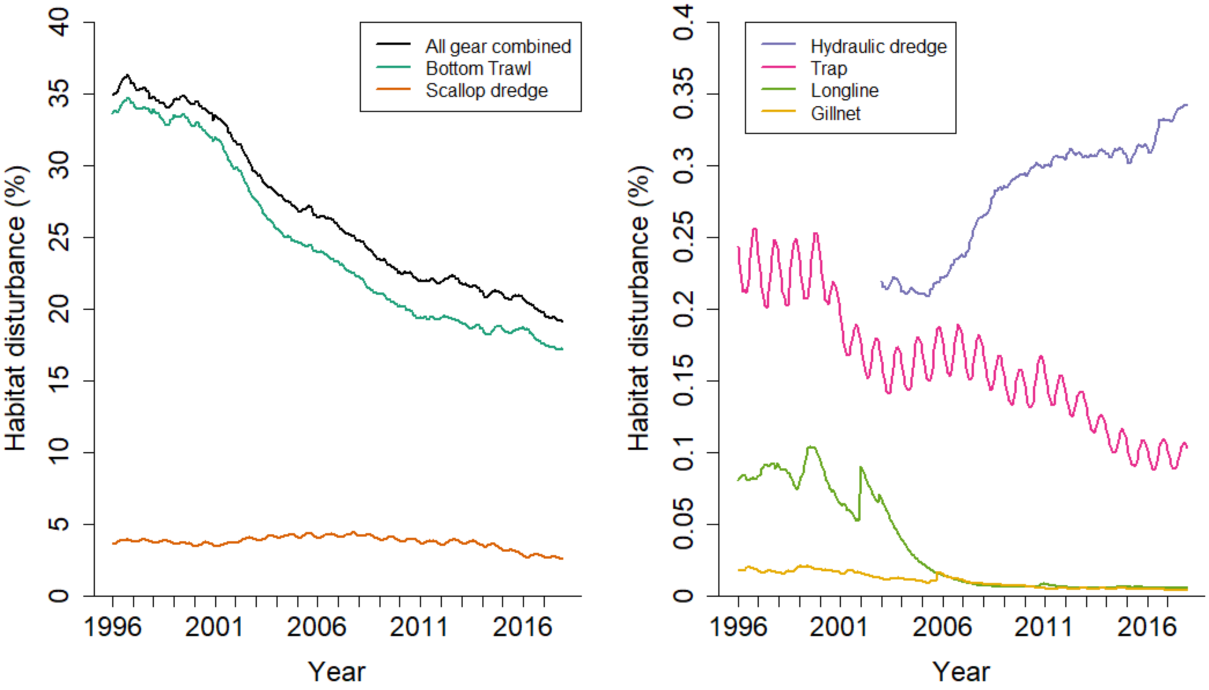
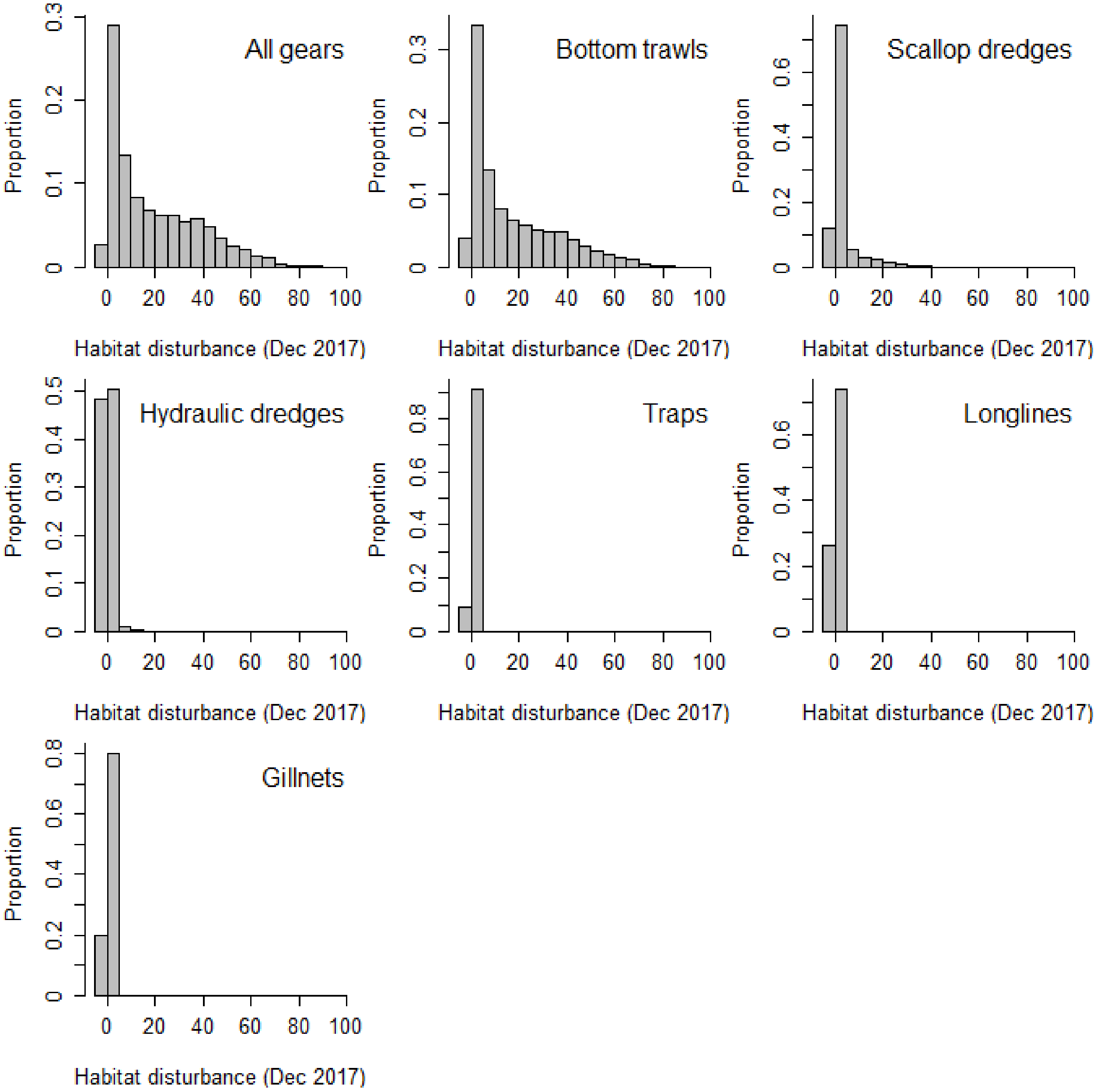
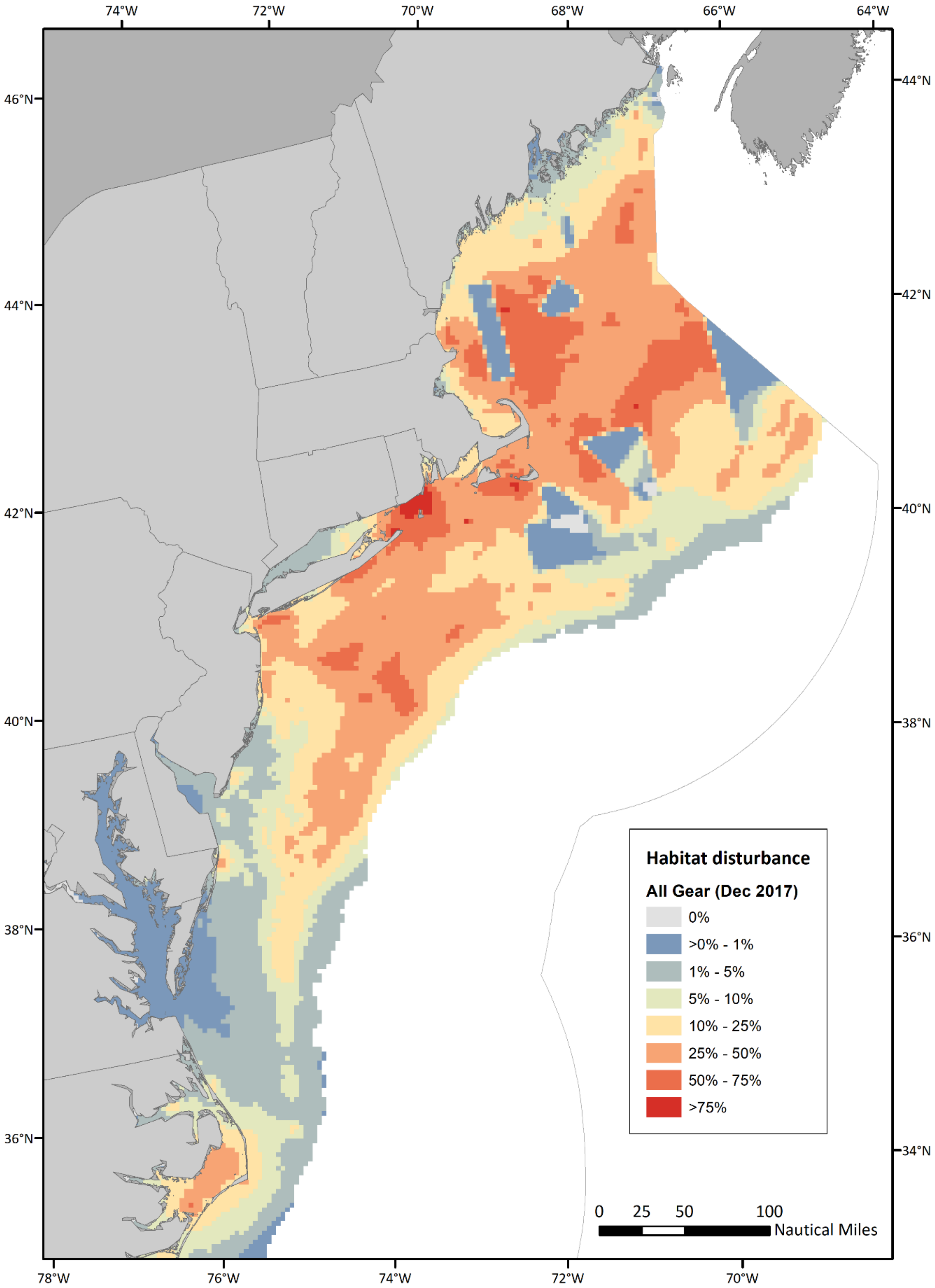


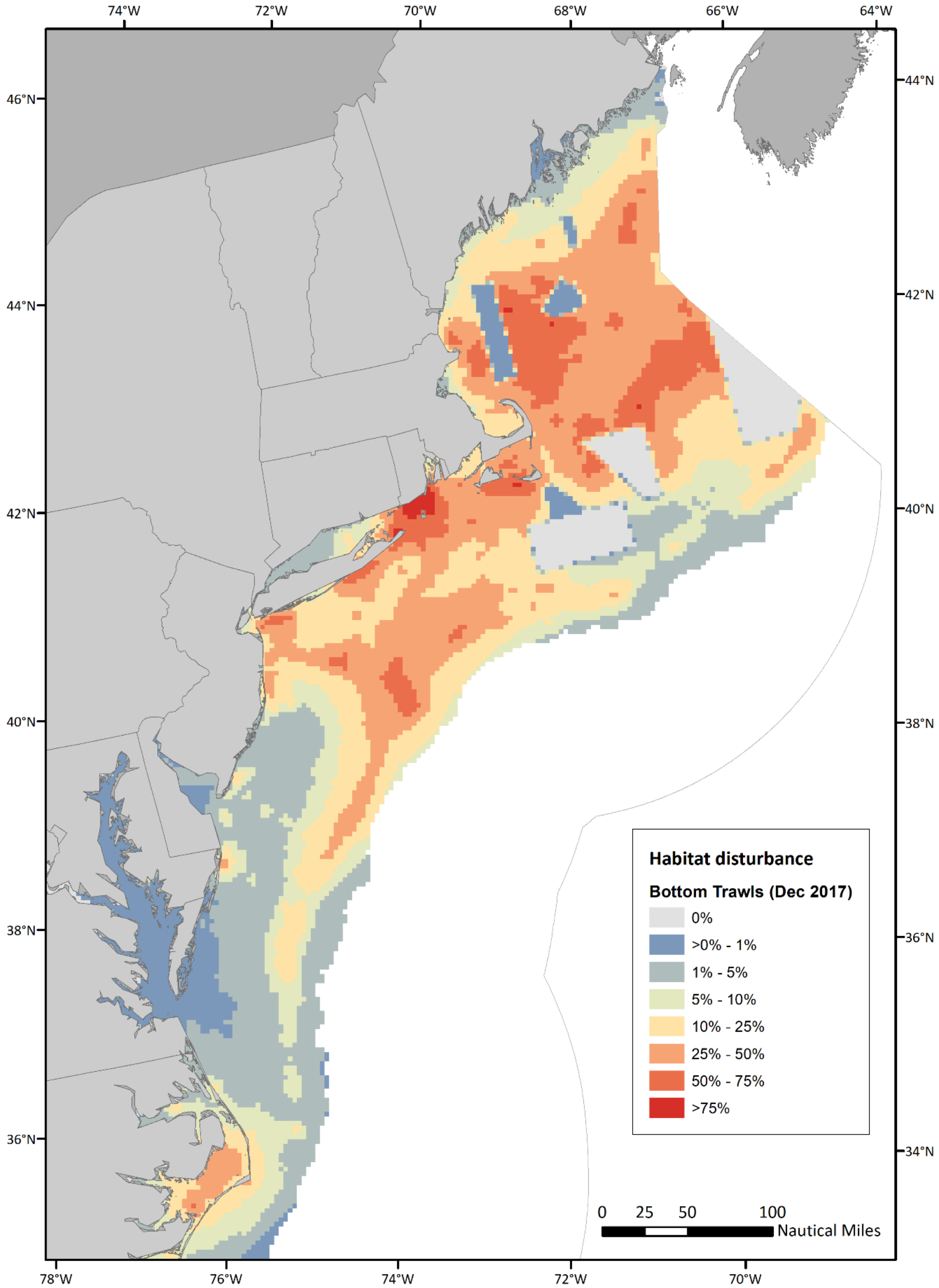
Figure 14. Histograms of habitat disturbance (December 2017) per grid cell by gear type. Bars to the left of the zero mark show proportion of true zeros (unfished grid cells).



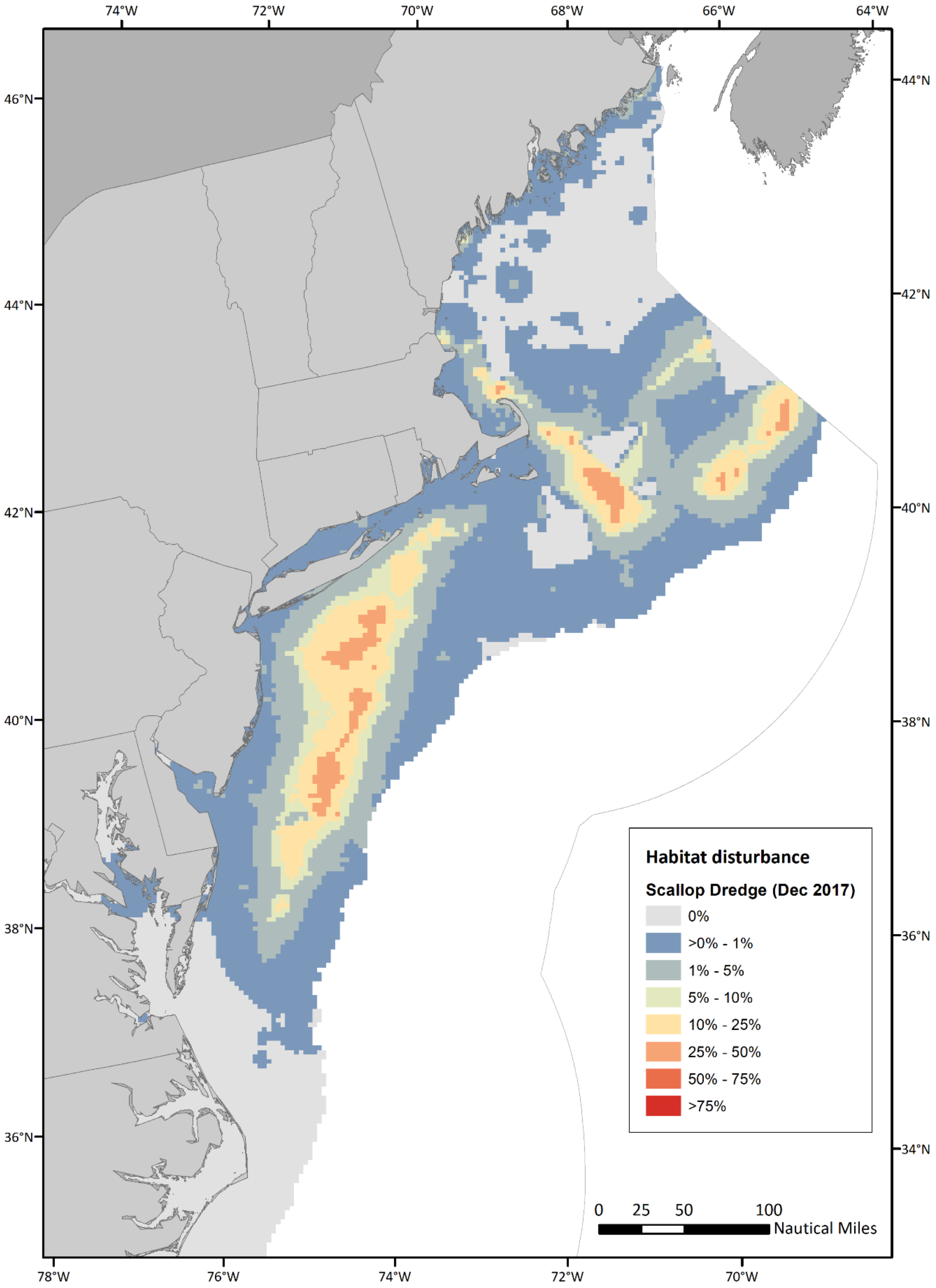
Map 9. Percent habitat disturbance, all gears combined.



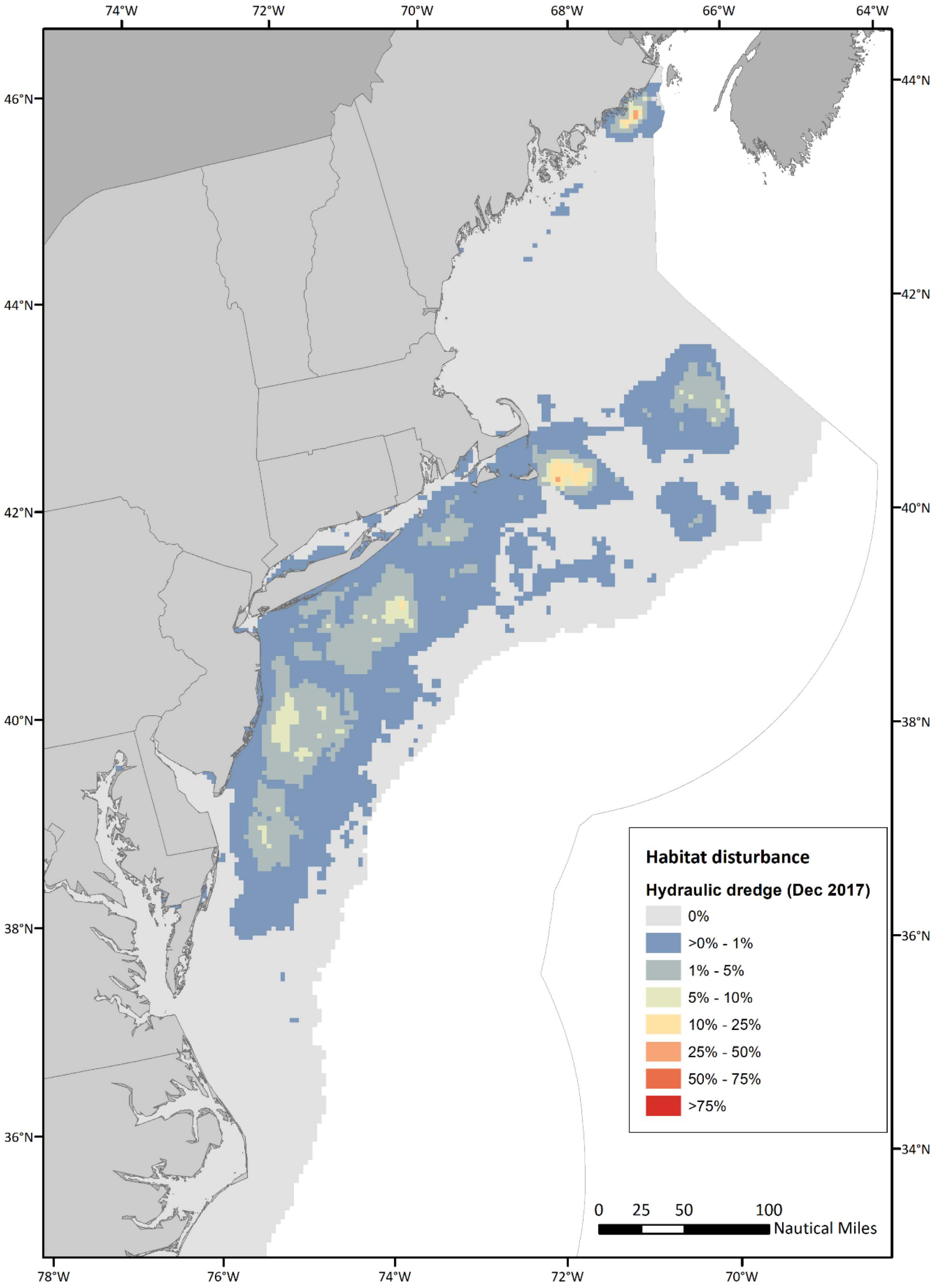
Map 10. Percent habitat disturbance, bottom trawl gear.



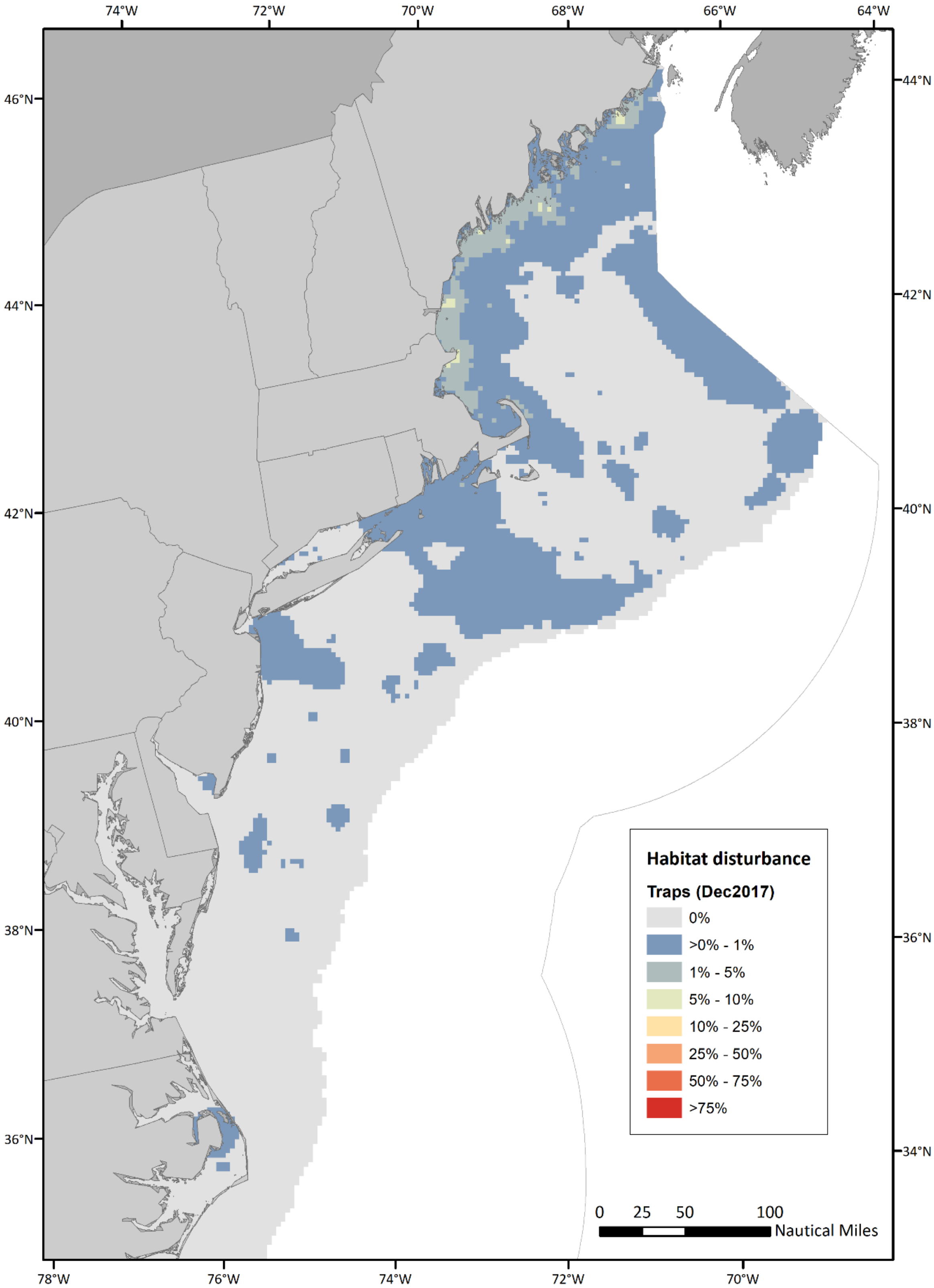
Map 11. Percent habitat disturbance, scallop dredge gear.



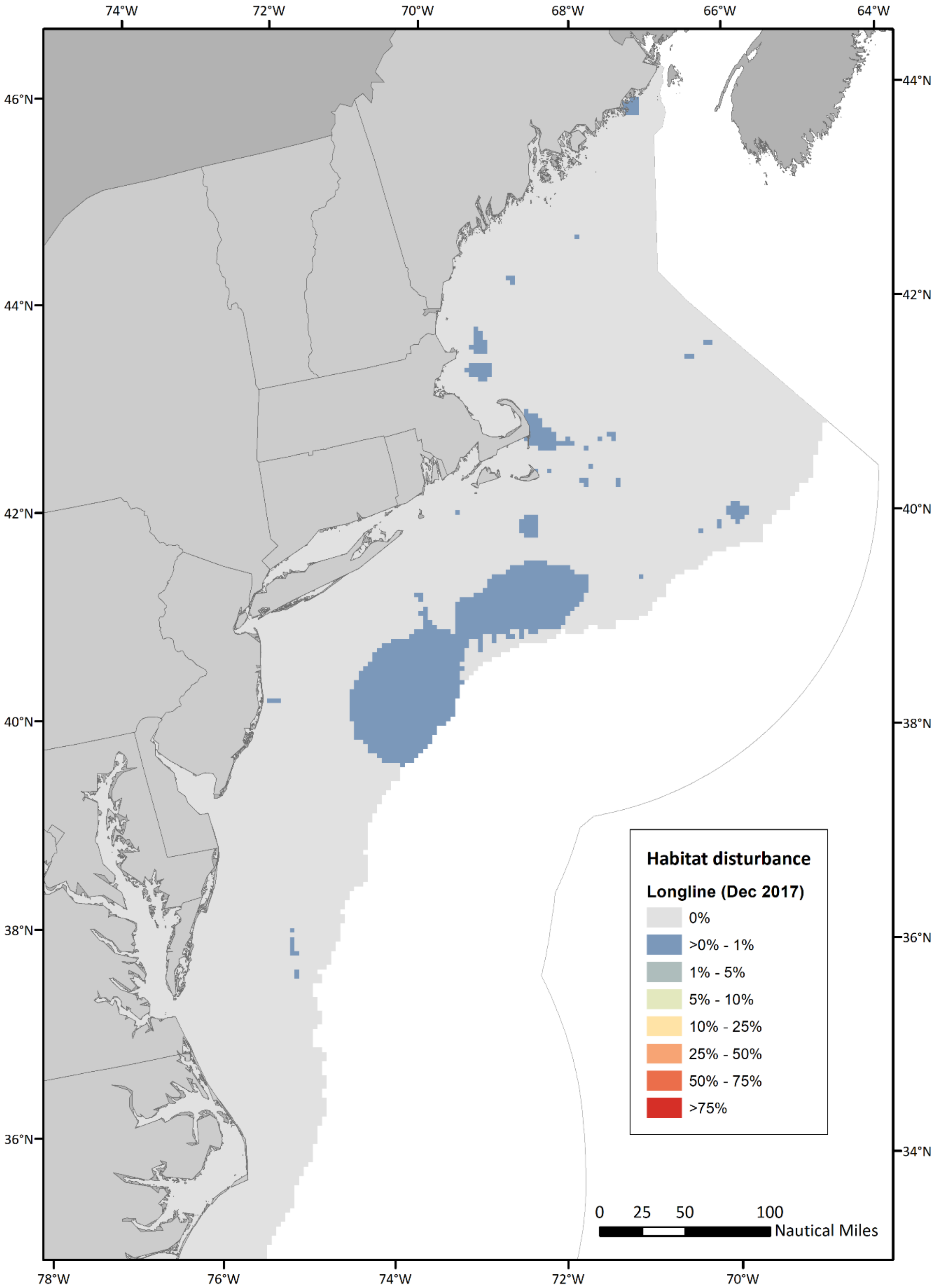
Map 12. Percent habitat disturbance, hydraulic dredge gear.



Map 13. Percent habitat disturbance, trap gear.



Map 14. Percent habitat disturbance, longline gear.



Map 15. Percent habitat disturbance, gillnet gear.

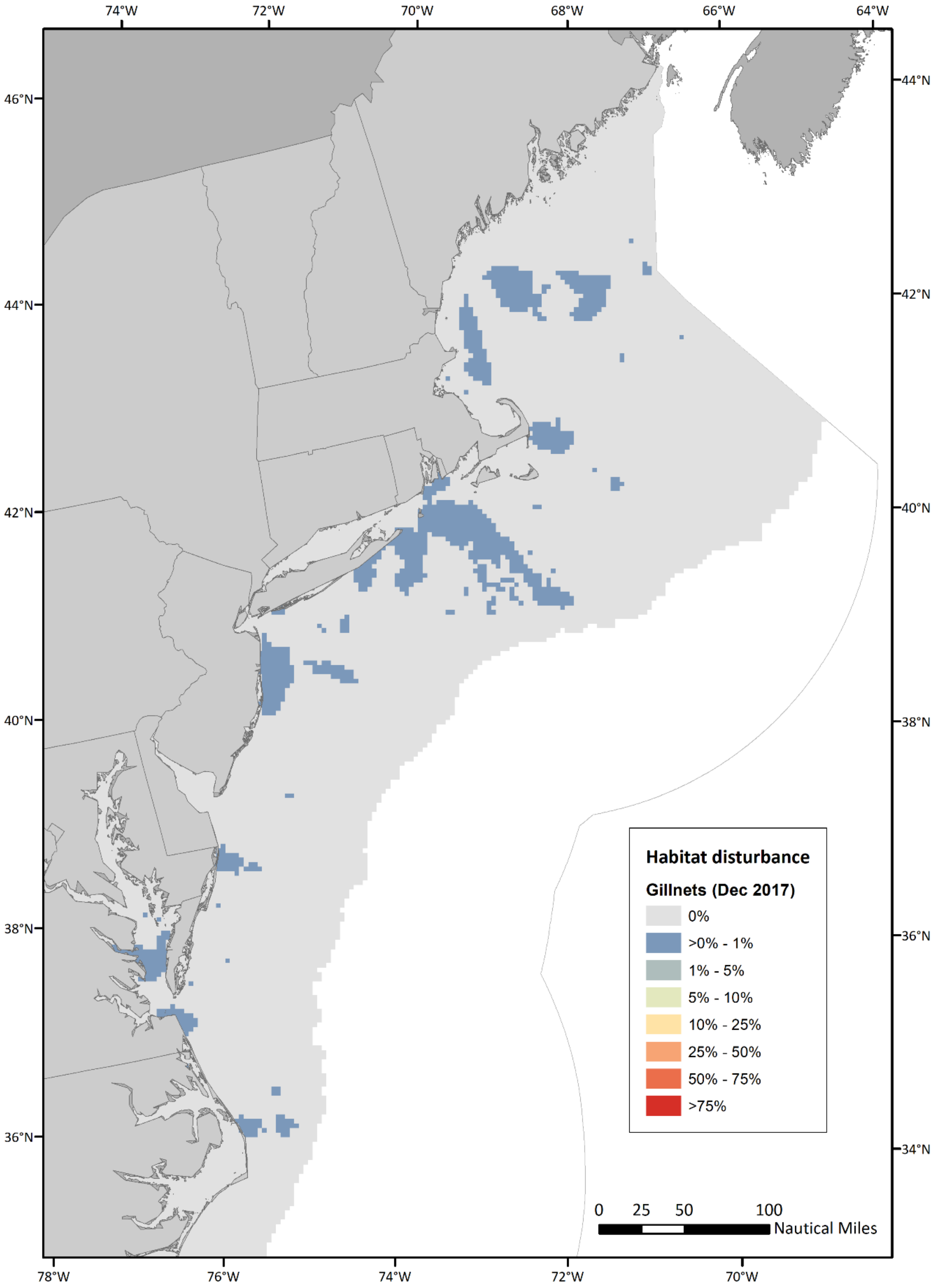
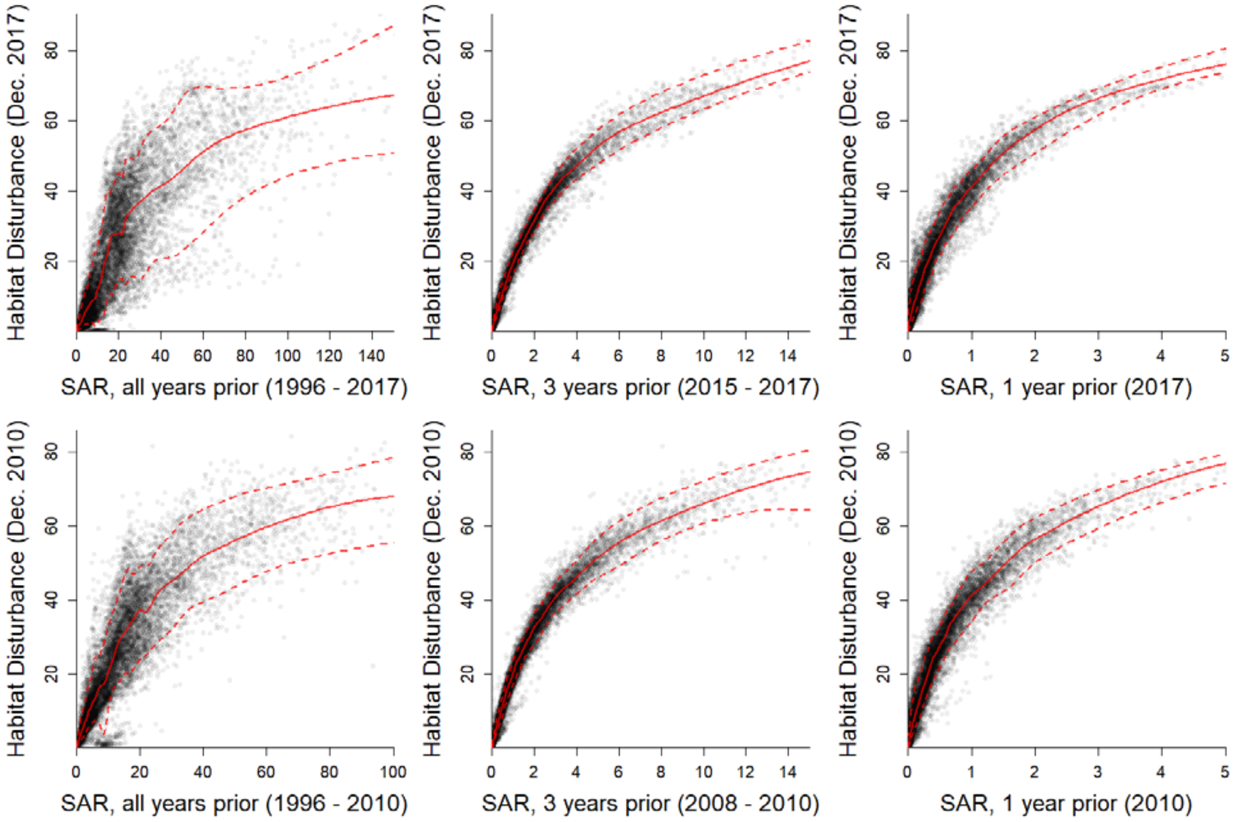


Figure 15. Swept area vs habitat disturbance. The top row shows habitat disturbance at December 2017; the bottom row shows habitat disturbance at December 2010. The left column compares habitat disturbance to the swept area ratio (SAR) of all gears combined for all years prior to the estimate of habitat disturbance; the middle columns shows the SAR from three years prior; and the right panel shows SAR from the prior year. The solid red lines show the rolling median; the dashed red lines show the rolling 95% quantile.



7.2 Sensitivity analysis

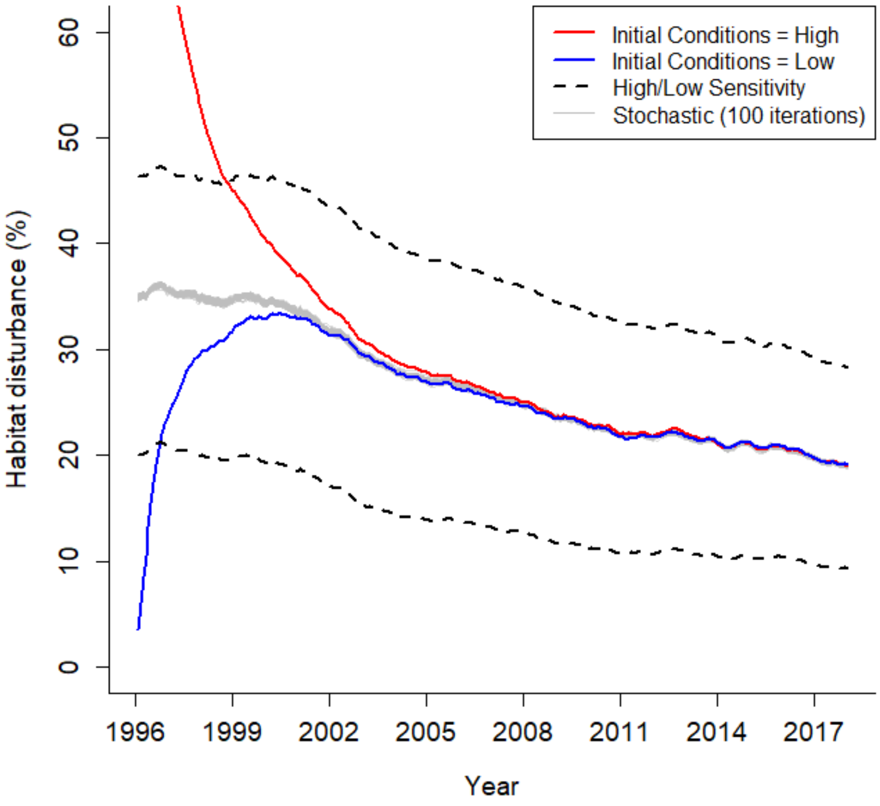
A sensitivity analysis was conducted to evaluate how uncertainties in recovery, susceptibility, and initial conditions affected model results. All recovery and susceptibility parameters were included as a range of values based on a score. When running the base model described above, recovery and susceptibility parameters were randomly selected from within these ranges, producing model outputs that may vary if the model was rerun. In the first set of sensitivity analyses, the model was rerun 100 iterations to evaluate how sensitive model outputs were to these stochastic processes. Results indicated that the random selection of recovery and susceptibility values added minimal uncertainty to domain-wide estimates of habitat disturbance. Overall variation among the 100 iterations was small, the mean difference high and low estimate for any given month was only 0.68 percentage points. For example, the December 2017 stochastic estimate ranged 18.8% – 19.3% disturbance.

A second suite of sensitivity analyses was conducted to construct upper and lower bounds of possible habitat disturbance. For these analyses, the model was run with the recovery and susceptibility values fixed at the maximum (highest susceptibility; slowest recovery) and minimum (lowest susceptibility; fastest recovery) limits of their respective range. Results from this analysis demonstrated that the upper bound estimate of habitat disturbance is about 42%

higher than the base model (results in Section 7.1) and the lower bound estimates were about 48% lower than the base model run. For example, by December 2017, the base model had estimated 19% habitat disturbance domain-wide, whereas the lower and upper estimates were 9.3% - 28%.

A final sensitivity analysis was conducted to evaluate the sensitivity of model results to the initial conditions (Figure 16). Two boundary condition scenarios were considered, one which began the model with 0% domain-wide habitat disturbance, and another with 100% domain-wide habitat disturbance. When initial conditions were 0% habitat disturbance, model estimates converged within the range from the stochastic simulations (Section 7.1) after 73 months (January 2002). When initial conditions were 100%, model estimates converged after 122 months (August 2007).

Figure 16. Sensitivity analysis results. The grey band is comprised of 100 individual lines of model runs using recovery and susceptibility values drawn randomly from within their ranges. The dashed lines show model run with recovery and susceptibility set at the maximum (highest susceptibility; slowest recovery) and minimum (lowest susceptibility; fastest recovery) limits of their respective range. The red line shows a model run with 100% disturbed initial conditions; the blue line shows a model run with 0% disturbed initial conditions.



7.3 Z_∞ analysis

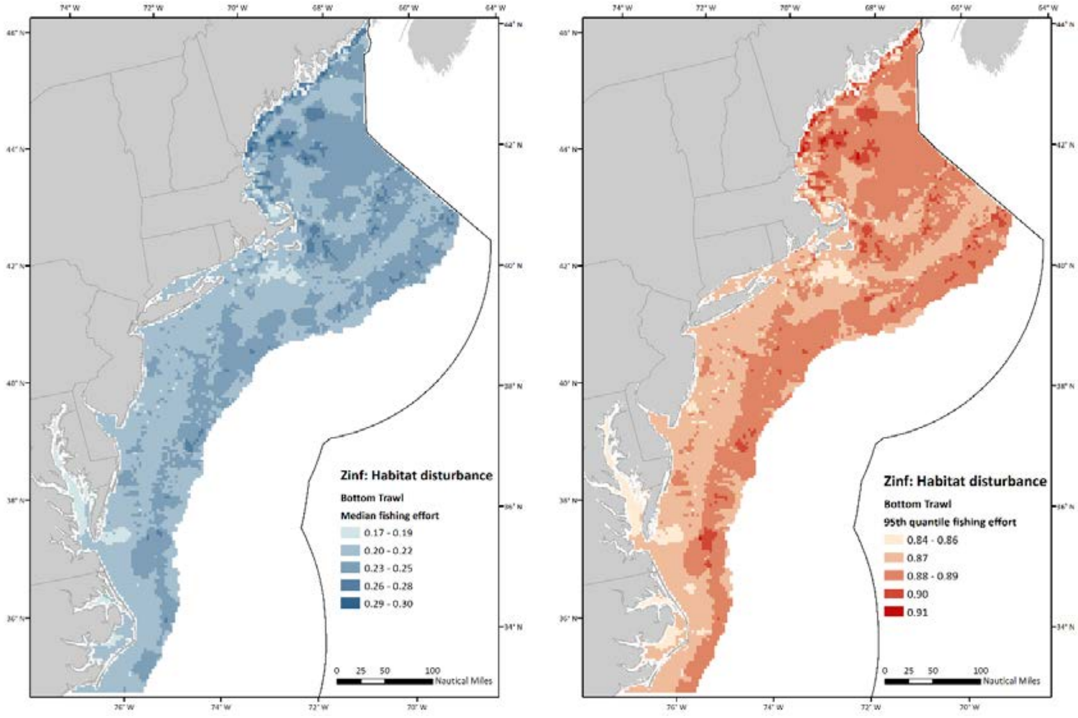
The Z_∞ analysis (named after a similar analysis with the original SASI model, where Z was used to represent the impact in each grid cell) consisted of applying a constant level of fishing effort across all grid and running the model until habitat disturbance reached equilibrium. This analysis demonstrates how differences in habitat may drive spatial patterns in habitat disturbance. Maps of Z_∞ habitat disturbance indicate regions that may be more vulnerable to fishing impacts.

Analyses were run for each gear individually, using the median and 95th quantile of yearly swept area ratio per grid cell as a constant level of fishing effort. The yearly values were divided by 12 to accommodate the monthly time step of the model. Fishing effort and summary statistics of domain-wide Z_∞ habitat disturbance values are given in Table 22. Maps of Z_∞ habitat disturbance values for each gear type are shown in Map 16-Map 21.

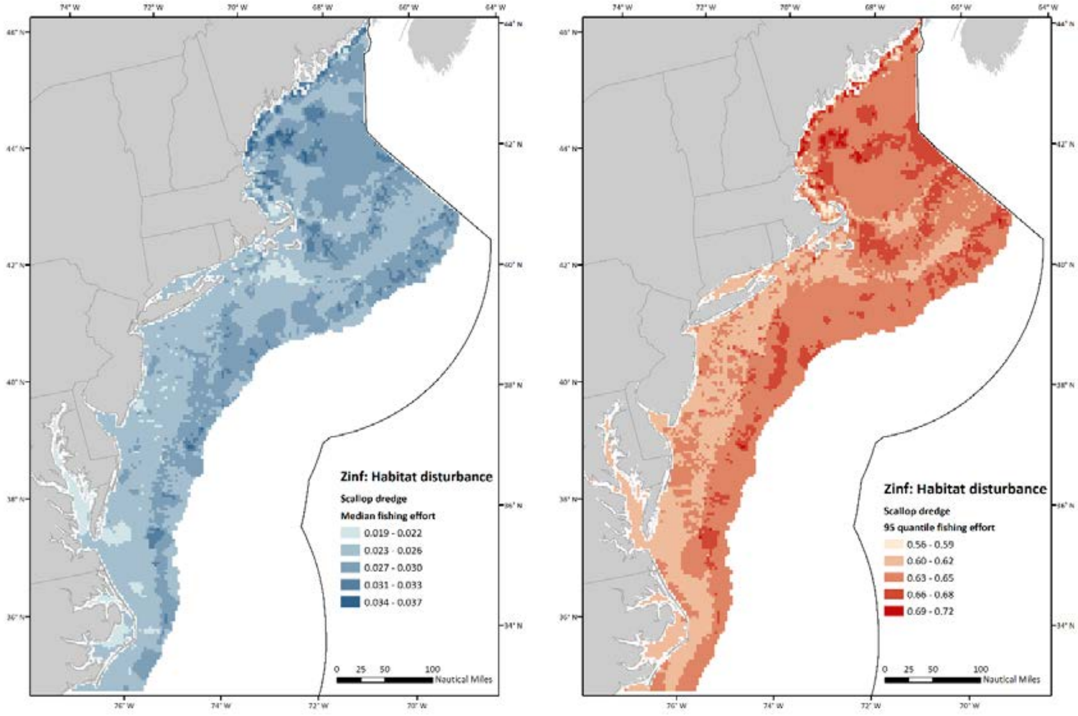
Table 22. Z_∞ analysis effort inputs and summary statistics

Gear type	Effort calculation	Swept Area Ratio ($year^{-1}$ $grid^{-1}$)	Mean habitat disturbance	Standard deviation habitat disturbance
Bottom Trawls	Median	0.17	26%	13%
	95% quantile	4.7	88%	2.4%
Scallop dredge	Median	0.015	4.5%	9.9%
	95% quantile	1.06	68%	7.6%
Hydraulic dredge	Median	0.0022	1.2%	6.1%
	95% quantile	0.090	18%	13%
Traps	Median	3.0e-4	0.2%	2.8%
	95% quantile	0.047	6.5%	11%
Longlines	Median	2.8e-4	0.2%	2.7%
	95% quantile	0.021	3.5%	8.9%
Gillnets	Median	7.7e-5	0.1%	2.8%
	95% quantile	0.0051	1.3%	6.4%

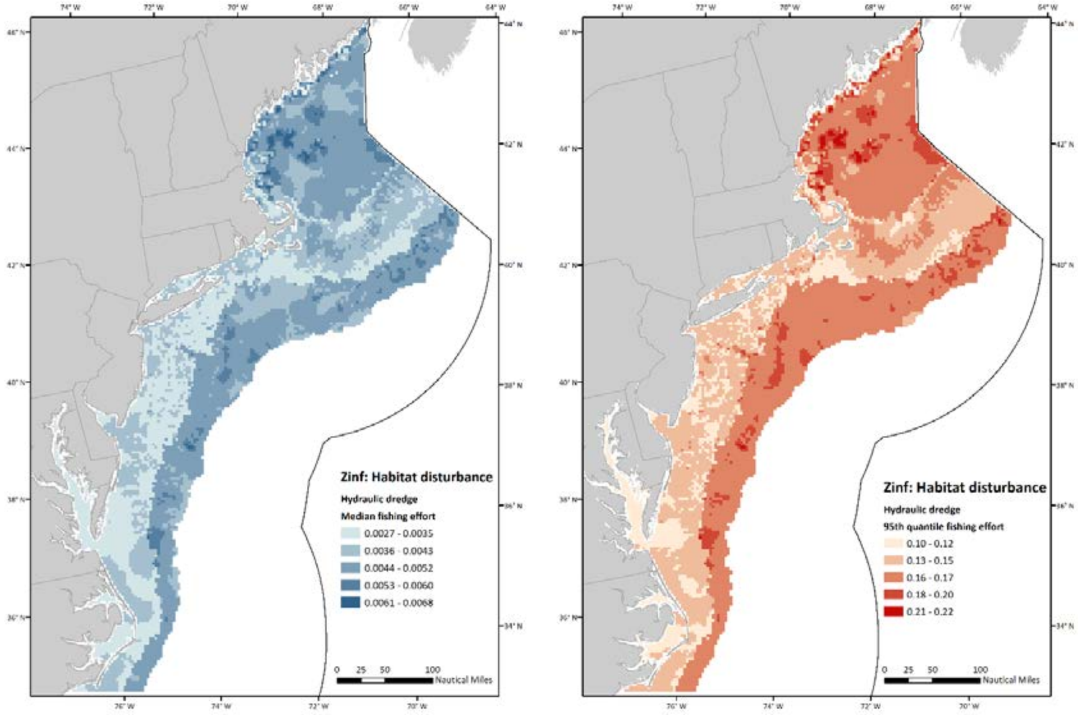
Map 16. Z_∞ habitat disturbance for bottom trawls.



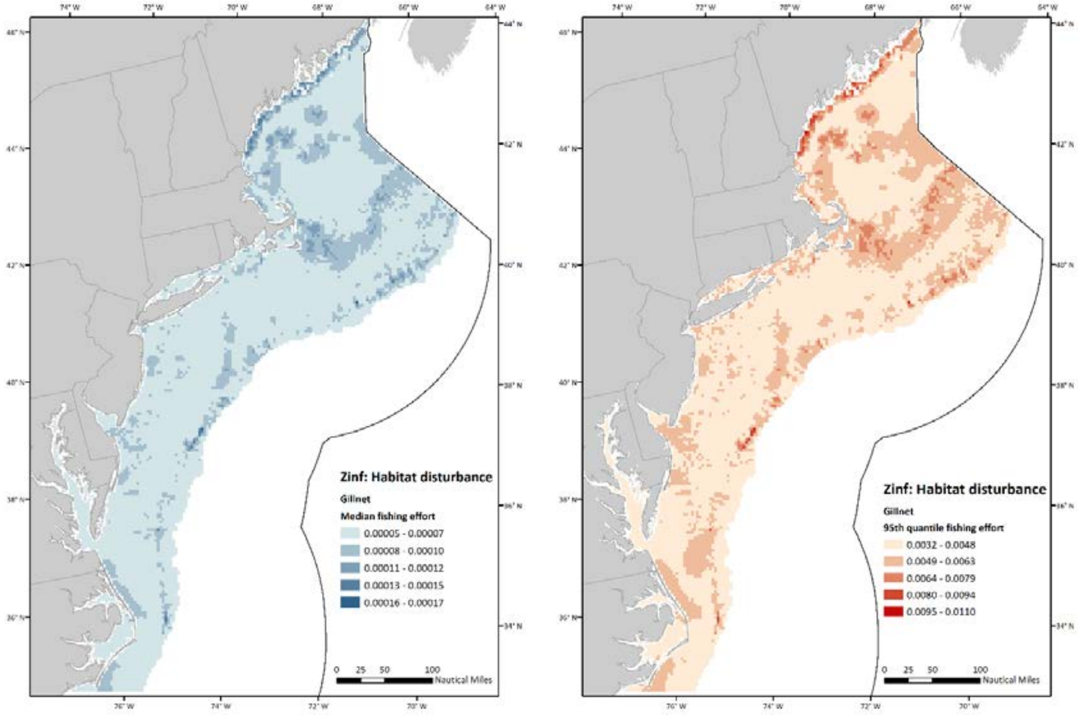
Map 17. Z_∞ habitat disturbance for Scallop dredges.



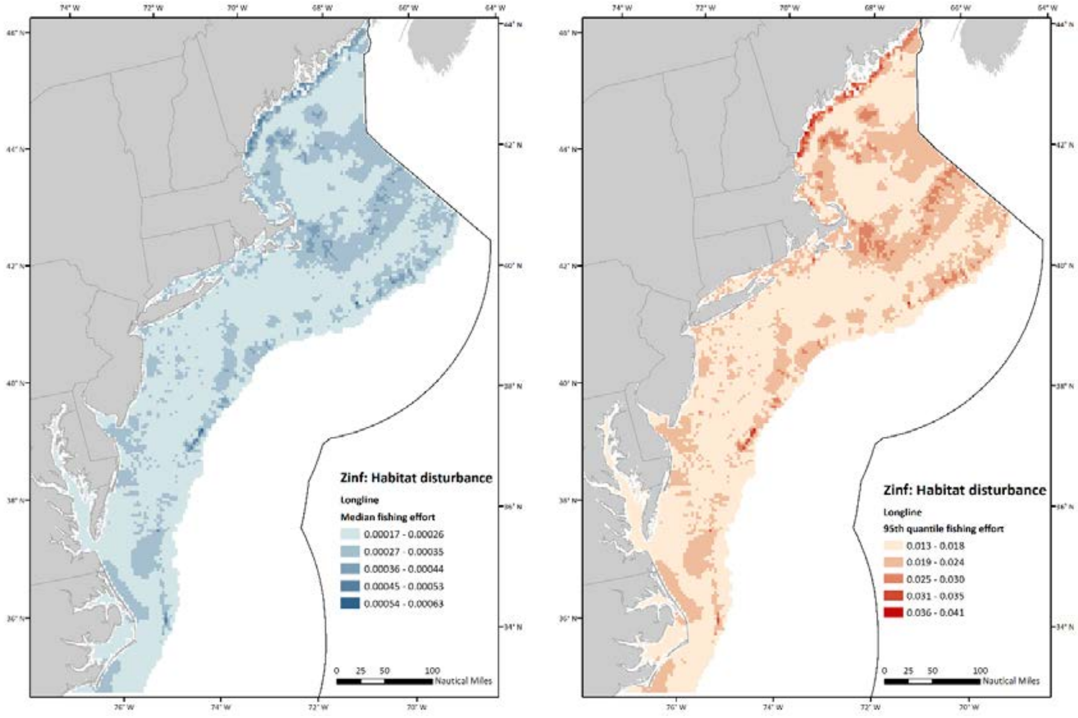
Map 18. Z_{∞} habitat disturbance for hydraulic dredges.



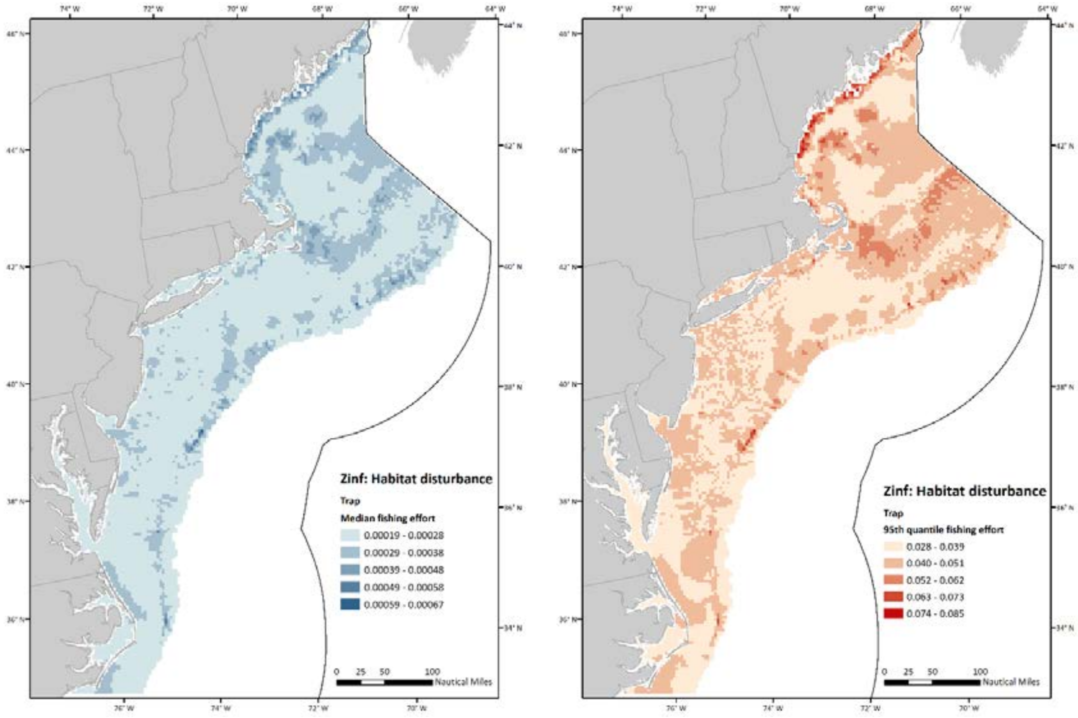
Map 19. Z_{∞} habitat disturbance for gillnets.



Map 20. Z_∞ habitat disturbance for longlines.



Map 21. Z_∞ habitat disturbance for traps.



8.0 Possible next steps

There are various ways that the model can continue to be modified or used in different management applications. Below is an initial list of ideas.

8.1 Ongoing model updates

The model should be updated with additional years of fishing effort data. This is anticipated as an annual task. Generally data for a given year are available midway through the following year. NEFMC would complete two steps, generating swept area tables by subtrip, and then joining those values to spatially explicit footprints to generate monthly raster data. APU would then grid these data and add them to the model, generating new output files and associated figures and maps. Alternatively, NEFMC could run the model in-house with support from APU.

The literature review and vulnerability assessment should be evaluated and updated as needed. This task would include examining new studies that would inform susceptibility and recovery scoring, adding those studies to the database and evaluating effects on S and R scores. This is anticipated as a task that would be completed every 2-3 years. NEFMC and APU would both participate in this task, sharing results across teams. APU could rerun the model with updated parameters if any scores change.

The sediment base maps should be evaluated and updated as needed. This task would include evaluating new datasets for inclusion (including recently collected data, and older data not previously incorporated) as well as gathering new data from existing datasets (e.g. from the SMAST drop camera survey). This task would involve collaboration with outside groups who own and collected the data, to obtain access and understand caveats that could affect model results. APU would update the basemaps and rerun the model with updated maps. This is anticipated as a task that is completed every 2-3 years.

8.2 Methodological changes and model sensitivity

Both NEFMC and APU are interested in testing how the model results are sensitive to different recovery trajectories. As fishing effort for a given grid cell and month is run through the model over time, it decays because the model is allowing recovery to occur. The rate of decay is based on the R scores for the features inferred to that grid cell, with R scores of 0-3 translating into ranges of years. SASI originally used a linear function for decay, with the same amount of impact being removed each timestep (year). Fishing effects uses an asymptotic decay function, with the same proportion of impact being removed in each timestep (month). This means that in the Fishing Effects model, impacts decline more rapidly at first, before approaching but never reaching zero.

Related to this issue, and because Fishing Effects uses a monthly time step, it would be possible to assume that recovery is occurring (or primarily occurring) during certain seasons. For example, biological features might show recovery only in certain months when these animals experience annual recruitment and growth.

8.3 Applications

The results of the model can be applied to analysis of routine fishery management actions taken by the Council, i.e. plan amendments and framework adjustments. This use would focus on the subset of model outputs most relevant to a particular FMP, i.e. gears used and the general locations where fishing occurs in that fishery. This work would be completed by NEFMC staff and PDT members. These analyses would look at recent trends in habitat impact and any changes over time, and relate them to patterns of effort in the fishery, using this information combined with the management alternatives in a given action to estimate the range of impacts that might be expected to result from the action. These analyses could involve more formal estimation of projected impacts using the model, if predicted fishing effort data were generated for each alternative scenario.

The results of the model could also be applied in the context of stock assessments, as is done in the North Pacific. For this use, the model outputs are subset spatially to look at trends in percent habitat impacted over the footprints within which essential fish habitat is designated for a particular species and lifestage. These results are then forwarded to assessment biologists to determine whether trends evident in the assessment seem to bear relation to patterns of habitat impacts.

Other efforts have included discussions about using the model results as a spatially/temporally specific index of impacts to inform broader ecosystem conditions. These include the Northeast Ocean Health Index, the ICES WGNARS Integrated Ecosystem Assessment, and the Northeast Regional Fish Habitat Assessment (a Council-led initiative). Council staff and the PDT would work with these outside teams to determine their needs and whether the model outputs would be suitable for use in these applications. Such collaborations would create incentives to keep the model up to date and may generate ideas for improvements to the work.

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Table 23. References from literature review by number.

#	Cite	#	Cite	#	Cite
11	Auster et al 1996	141	Hall et al 1993	292	Queiros et al 2006
17	Ball et al 2000	146	Hall-Spencer et al 2002	313	Rosenburg et al 2003
21	Bergman and VanSantbrink 2000	149	Hansson et al 2000	320	Sanchez et al 2000
24	Blanchard et al 2004	157	Henry et al 2006	325	Schwinghamer et al 1998
34	Brown et al 2005a	158	Hermsen et al 2003	330	Sheridan and Doerr 2005
35	Brown et al 2005b	164	Hixon and Tissot 2007	333	Simpson and Watling 2006
38	Burridge et al 2003	184	Kaiser et al 2000	334	Smith et al 1985
42	Caddy 1968	192	Kenchington et al 2001	335	Smith et al 2000
43	Caddy 1973	193	Kenchington et al 2005	336	Smith et al 2003
64	Clark and O'Driscoll 2003	194	Kenchington et al 2006	338	Sparks-McConkey and Watling 2001
69	Collie et al 1997	203	Knight 2005	352	Stokesbury and Harris 2006
70	Collie et al 2000	209	Koslow et al 2001	355	Stone et al 2005
71	Collie et al 2005	211	Koulouri et al 2005	359	Sullivan et al 2003
88	De Biasi 2004	214	Kutti et al 2005	360	Tanner 2003
89	de Juan et al 2007a	217	Langton and Robinson 1990	368	Tillin et al 2006
90	de Juan et al 2007b	225	Lindholm et al 2004	372	Tuck et al 1998
92	DeAlteris et al 1999	228	Link et al 2005	373	Tuck et al 2000
97	Drabsch et al 2001	232	MacKenzie 1982	382	Van Dolah et al 1987
101	Engel and Kvitek 1998	236	Mayer et al 1991	387	Wassenberg et all 2002
102	Eno et al 2001	238	McConnaughey et al 2000	391	Watling et al 2001
108	Fossa et al 2002	239	McConnaughey et al 2005	393	Wheeler et al 2005
110	Freese 2001	244	Medcof and Caddy 1971	404	Asch and Collie 2007
111	Freese et al 1999	245	Meyer et al 1981	406	Dellapenna et al 2006
113	Frid et al 1999	247	Morais et al 2007	407	Nilsson and Rosenberg 2003
119	Gibbs et al 1980	248	Moran and Stephenson 2000	408	Boat Mirarchi and CR Environmental 2003
120	Gilkinson et al 1998	249	Morello et al 2005	409	Boat Mirarchi and CR Environmental 2005
121	Gilkinson et al 2003	254	Mortensen et al 2005	414	Coggan et al 2001
122	Gilkinson et al 2005a	256	Murawski and Serchuk 1989	541	Probert et al 1997

#	***Cite***	**#**	***Cite***	**#**	***Cite***
123	Gilkinson et al 2005b	277	Palanques et al 2001	575	Lindegarth et al 2000
128	Gordon et al 2005	283	Pilskaln et al 1998	599	Simboura et al 1998
136	Grehan et al 2005	287	Pranovi and Giovanardi 1994	658	Hinz et al 2009
140	Hall et al 1990	291	Prena et al 1999	669	Thorarinsdottir et al 2008

10.0 Appendices

10.1 Appendix A

See attachment

10.2 Appendix B

See attachment

10.3 Appendix C: Fishing Effects model R code

```r
# Source code to run the Fishing Effects model
# Last edited on 04/09/2019
# Contains main function to run the model: FishingEffectsModel(),
# as well as supporting functions called within FishingEffectsModel().

# Required libraries
library(foreign)
library(reshape2)
library(rgdal)

library(maptools)

# FishingEffectsModel()
# This function runs the Fishing Effects model.  Output is a GIS Shapefile of habitat disturbance for all grid cell in the provded domain across all time steps.

# Function arguments:
# fullgrid: SpatialPolygonsDataFrame object that contains all grid cells attributed with a "GridID" and "Area" columns.  The "Area" must be in the same units as the fishing effort data.

# habitats: Dataframe object of habitat proportions in each grid cell.  Must contain a "GridID" column and a column for each of the habitat types   .

# f.effort : Dataframe object that represents the total area swept in each grid cell, monthly time step, and gear type.  Must include "GridID", "Gear", "t", "Sum" columns.  "GridID" is the unique identifier for each grid cell.  "Gear" is the type of gear.  "t" is the time step starting at t = 1.  "Sum" is the sum of swept area for that particular grid, time step, and gear type in the same units as "Area" in the fullgrid object.

# GearTable: Dataframe object with "Gear", "SuscTab", "ContactMin", "ContactMax" columns.  "Gear" is the gear type.  "SuscTab" is the name of the Suscepibility Table that corresponds to the SuscTables object.  "ContactMin" is the minimum contact adjustment for the gear.  "ContactMax" is the maximum contact adjustment for the gear.  Note that if contact adjustment is already incorporated into swept area in the f.effort object, set ContactMin and ContactMax to 1.
```

```r
# RecoveryTable: Dataframe object of recovery scores for each habitat feature
and habitat type.  Rows are each habitat feature.  Column are habitat types.
Habitat type names must match those in the habitats object.

# SuscTables: List object with two slots.  First slot holds a vector of Sucep
tibility Tables names that matches those in the "SuscTab" column of the f.eff
ort object. The second slot is another list holding a slot for a dataframe of
susceptibility tables.  The order of susceptibiltiy tables must match the ord
er of the vecotor in the first slot.  Each Susceptibility Table consists of r
ows for each habitat feature, and columns for each habitat type (like the Rec
overy Table).  The tables are populated with susceptibility scores for each f
eature/habitat combination.

# RecoveryCodes: Dataframe object with "Code", "Min", and "Max" columns.  The
"Code" column must contain all scores in the Recovery tables.  The "Min" and
"Max" columns represent the minimum and maximum recovery times that correspon
d to each score.  Recovery times must be in same time units as "t" in f.effor
t.

# SuscCodes Dataframe object with "Code", "Min", and "Max" columns.  The "Cod
e" column must contain all scores in the Susceptibility tables.  The "Min" an
d "Max" columns represent the minimum and maximum susceptibiltites that corre
spond to each score.

# InitCond: Dataframe object with "GridID" and "H" corresponding to intact ha
bitat (as a proportion) in each grid cell at start of the model run.

# max.time: Numeric object of number of time steps to run the model.  If NULL
(the default) the model will run through the maximum time step in the f.effor
t data, (i.e max(f.effort$t))

# outPath: Character string of output folder.

# outFile: Character string of output filename.  The output is a GIS Shapefil
e and should include a ".shp" extention.

FishingEffectsModel <- function(
        fullgrid,
        habitats,
        f.effort,
        GearTable,
        RecoveryTable,
        SuscTables,
        RecoveryCodes,
        SuscCodes,
        InitCond,
        max.time = NULL,
        outPath,
        outFile){
```

```
# Import data
if(is.null(max.time)) {
    t.tot = max(f.effort$t)
    }else {
    t.tot = max.time
    }

HabList = names(habitats)[-1]


# Merge fishing effort and gear table
fe = merge(f.effort, GearTable,
       by.x = "GearID", by.y = "GearID", all.x = T)
fe$SuscCat = factor(fe$SuscCat)

fe$adjArea = fe$nomArea * runif(nrow(fe), min = fe$caMin, max = fe$caMax) ##
Random uniform contact adj from min and max


# Aaggregate contact adj effort based on susceptibility group
fe.agg = aggregate(adjArea ~ GridID + t + SuscCat, data = fe, sum)

grid_order = fullgrid$GridID # establish consistent order of GridID


# Create habitat profile matrix for model.  Make sure grid order is same as I
_a
# and keep only grid cells with fishing effort
habProps = as.matrix(habitats[ match(grid_order, habitats$GridID),])



# Set parameters
nGrid = nrow(fullgrid)
SuscCat = levels(fe$SuscCat)
nSuscCat = length(SuscCat)
nHab = length(HabList)



eg = expand.grid(GridID=fullgrid$GridID, SuscCat = SuscCat) # create all comb
os of SuscCat and grid cells

m = merge(x = fe.agg, y = fullgrid[,c("GridID", "Area")], by = c("GridID"))

m$prop = m$adjArea/m$Area


# Populate Fishing effort array
F_a = array(NA, dim = c(t.tot, nGrid, nSuscCat)) #create empty array
```

```
for(i in 1:t.tot){
  mym = subset(m, t == i)

    mym = merge(x = eg, y = mym,
                by = c("GridID","SuscCat"),
                all.x=T)

    if(nrow(mym[is.na(mym$prop),]) >0 ) mym[is.na(mym$prop),]$prop = 0

    mym.x = dcast(GridID ~ SuscCat, data=mym, value.var = "prop", fun.aggrega
te = function(x) sum(x))

    mym.x = mym.x[order(mym.x$GridID),]
    mym.x = mym.x[,SuscCat]

    F_a[i, ,] = as.matrix(mym.x)


  }



#Fishing impacts (I')
I.prime_a = array(NA, dim = c(t.tot, nGrid, nHab))

for(t in 1:t.tot){
    q_m = suscept.f(SuscTables = SuscTables, SuscCat = SuscCat,
            HabList = HabList, SuscCodes = SuscCodes)
            # Get new susceptibility table for each month

    I_m = F_a[t,,] %*% q_m
    I.prime_a[t,,] = 1-exp(-I_m)
  }




# Recovery
rho.prime_a = array(NA, dim = c(t.tot, nGrid, nHab))


for(t in 1:t.tot){
    rho_v = recovery.f(RecoveryTable = RecoveryTable,
               HabList = HabList, RecoveryCodes = RecoveryCodes)
        # Get new recovery values for each month

    for(i in 1:nGrid){
        rho.prime_a[t,i,] = 1-exp(-rho_v)
```

```
    }
}

# Run model
H_prop_0 = as.matrix(InitCond[match(grid_order, InitCond$GridID), -1])
H_tot = model_runner(I.prime_a, rho.prime_a, H_prop_0 = H_prop_0)


undistProps = matrix(NA, ncol = t.tot, nrow = length(grid_order))

habitats_m = habitats[match(grid_order, habitats$GridID),-1]
for(t in 1:t.tot){
    undistProps[,t] = rowSums(H_tot[t,,]*habitats_m, na.rm = T)
  }

undistProps = data.frame(GridID = grid_order, undistProps)


disturbProps = data.frame(GridID = undistProps[,1],
                          apply(undistProps[,-1],2,
                                function(x) 1 - x))

all.grid = data.frame(GridID = fullgrid$GridID)
disturbProps = merge(x = all.grid, y = disturbProps, by = "GridID", all.x = T
)
disturbProps[is.na(disturbProps)] = 0
names(disturbProps)[-1] = paste("t", 1:(ncol(disturbProps)-1), sep = "")
return(disturbProps)

} #end function




# model_runner function
# Runs main impact/recovery dynamics
# Called from FishingEffectsModel()

model_runner = function(I.prime_a, rho.prime_a, H_prop_0){
  nTimeSteps = dim(I.prime_a)[1]
  nGrid = dim(I.prime_a)[2]
  nHab = dim(I.prime_a)[3]

  #Make array to hold H
  H_prop = array(dim = c(nTimeSteps, nGrid, nHab))

  for(t in 1:nTimeSteps){

      if(t == 1){      # First time step use H_prop_0 for t-1
        prior_state = H_prop_0
```

```
      } else{
        prior_state = H_prop[t-1,,]
      }

      H_from_H = (1-I.prime_a[t,,])*prior_state  # undisturbed remaining undi
sturbed
      H_from_h = (1-prior_state) * (rho.prime_a[t,,]) # disturbed recovered t
o undisturbed
      H_prop[t,,] = H_from_H + H_from_h  # Total proportion disturbed

    }

  return(H_prop)
}  # end function


# Suceptibility function
# Gets a random susceptibiltiy value for each month, grid cell, and gear type
# Called from FishingEffectsModel()

suscept.f = function(SuscTables, SuscCat, HabList, SuscCodes){
    gear.q = matrix(NA, nrow = length(SuscCat), ncol = length(HabList))
    i = 1
    for(gear in SuscCat){
      gear.m = as.matrix( SuscTables[[2]][which(SuscTables[[1]] == gear)][[1]
] )


      gear.m = gear.m[, HabList, drop = T]

      nSuscCodes = nrow(SuscCodes)


      for(column in 1:ncol(gear.m)){
         for(j in 1:nrow(SuscCodes)){
              gear.m[gear.m[,column] %in% SuscCodes[j,1], column] =
                 runif(sum(gear.m[,column] %in% SuscCodes[j,1]), min = SuscCo
des[j,2], max = SuscCodes[j,3])

         }
      }

      gear.q[i,] = colMeans(gear.m, na.rm=T)
      i = i+1

    }

    gear.q.df = data.frame(SuscCat = SuscCat, gear.q)
    names(gear.q.df)[-1] = HabList
```

```
    q_m = as.matrix(gear.q.df[,HabList])
    q_m[is.na(q_m)] = 0
    return(q_m)
} # end function



# Recovery function
# Gets random recovery values for each month and grid cell
# Called from FishingEffectsModel()

recovery.f = function(RecoveryTable, HabList, RecoveryCodes){
  RecoveryTable = RecoveryTable[,HabList]
  tau_m = RecoveryTable[,HabList] # Make sure sediments are in correct order

    for(column in 1:ncol(tau_m)){
      for(j in 1:nrow(RecoveryCodes)){
        tau_m[RecoveryTable[,column] %in% RecoveryCodes[j,1], column] =
          runif(sum(tau_m[,column] %in% RecoveryCodes[j,1]), min = RecoveryCo
des[j,2], max = RecoveryCodes[j,3])
      }
    }


    tau_v = colMeans(tau_m, na.rm=T) # Average recovery over all habitat feat
ures

    rho_v = 1 / tau_v

    return(rho_v)

} #end function
```