NOAA Technical Memorandum NMFS-NE-312

A decision support tool to assess risk of entanglement mortality to large whales from commercial fixed-gear fisheries in the Northwest Atlantic

US DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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Northeast Fisheries Science Center
Woods Hole, Massachusetts
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Editorial Notes

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GLOSSARY

Term	**Description**
Baseline	Sometimes referred to as “default”, reference term for fishery effort, gear configuration (and associated risk) prior to implementing management scenarios.
Cell	A 1 nm^2 grid unit in a high resolution run or 10 nm^2 grid unit in low resolution in which data is aggregated and assessed by the DST.
Endline	Vertical line attached to the end of a string to display a surface buoy.
Exempt	Existing areas exempted of management actions.
Gear Density	Total number of traps or nets deployed in a month per unit area.
Gear Fished	Number of traps or nets in the water.
Gear Height	Height of a gillnet. This with Gear Width used to describe the area of a water column occupied by a net that a whale may encounter.
Ground Gear	Gear other than endlines within the water column. While this can refer to groundlines in between trap/pots, only used here to describe gillnets.
High Resolution	Default, native resolution of the DST model and model inputs. High resolution runs aggregate gear density into 1 nm^2 cells.
Horizontal Line Strength	Used only for gillnet, the breaking strength in pounds of the head rope on a gillnet.
Lobster Management Area (LMA)	Seven areas established for lobster management.
Low Resolution	Option aggregated resolution in the DST model calculations and outputs. Low resolution runs aggregate gear density into 10 nm^2 cells.
MapRef	1 nm^2 grid describing the spatial domain of the DST.
Region	Descriptor for large area boundaries along the Atlantic coast used to divide risk and management into more discrete areas. Four options- Gulf of Maine / Georges Bank, Southern New England, Mid-Atlantic and Southeast.
Soak Time	The amount of time gear is deployed before retrieval. Applicable only for fisheries where gear is set, checked, and removed, rather than set, checked and reset. Also stated as Soak Duration.
Statistical Reporting Area (SRA)	Greater Atlantic Regional Statistical Reporting Areas used for commercial fisheries reporting.
String	A groundline attached to one or more traps or nets, usually associated with at least one endline used to display a surface buoy.
String Length	Number of traps or nets on a string.
Vertical Line Strength	Breaking strength, in pounds, of an endline.

ABSTRACT

This document describes the development of a Decision Support Tool (DST) from its inception as a request from the Atlantic Large Whale Take Reduction Team in 2018 through a second peer review in 2023 organized by the Atlantic Scientific Review Group. The DST was built to evaluate management options that reduce the risk of entanglement of large whales in commercial fixed-gear fisheries under the jurisdiction of the Atlantic Large Whale Take Reduction Plan by allowing stakeholders to compare candidate management actions to a baseline level of risk. Fishery input layers were developed for all fixed-gear fisheries on the United States East Coast, grouped by method type and target species. These layers quantify the amount of gear in the water, the duration of fishing, and the level of threat based on the gear configuration (i.e., rope diameter, net dimensions, and number of endlines) on a monthly basis. The DST overlays the fishery input layers onto estimated spatial distributions of whales to determine where and when whales are most likely to encounter fixed gear. The primary whale density models are derived from distance sampling methods and surface density models based on aerial- and vessel-based surveys. Relative risk units are then incorporated into the model taking into account the level of threat or lethality of various gear configurations and characteristics. Comparing proposed management scenarios to the baseline levels of risk can inform managers on the relative risk reduction benefits of a potential management action. This document provides details on the development of fishery input layers, the various fisheries management actions that can be evaluated with the DST and the workflow of actions within the DST model. It also provides insight into other potential uses of the DST, such as estimating relative risk attributable to individual fisheries, which may aid managers in decision making and inform assessments of commercial fishery-related mortality and serious injury.

1. BACKGROUND

The NOAA Fisheries large whale Decision Support Tool (DST) was built to assist fisheries conservation managers, other decision-makers, and stakeholders with visualizing and understanding spatiotemporal overlap between Category I and II fixed-gear commercial fisheries (e.g., trap/pot and gillnet fishing gear) under the jurisdiction of the Atlantic Large Whale Take Reduction Plan (the Plan) and whale distributions in waters off the east coast of the United States, with an emphasis on the North Atlantic right whale (*Eubalaena glacialis*; NARW). The DST was developed to model how risk of entanglement to right whales may change with shifts in the spatial distribution of whales or fishing effort and modifications to commercial fishing gear configurations.

Within the DST, the relative risk posed to right whales is calculated as the product of: (1) the density of vertical lines associated with fixed-gear fishing at a given location, (2) the threat vertical lines pose to right whales given the specific configuration of the gear relative to other gear configurations, and (3) the estimated density of right whales at the given location. The DST quantifies risk as the geographic overlap of vertical lines and whale density, with an added allowance for varying levels of threat associated with different gear configurations.

In October 2018, the Atlantic Large Whale Take Reduction Team (ALWTRT), a multi-party stakeholder negotiating group convened under the Marine Mammal Protection Act, met to discuss proposals to amend the Plan. The Plan was implemented in 1997 pursuant to Section 118 of the MMPA (16 U.S.C. 1387) to reduce mortality and serious injury of three stocks of large whales (fin, humpback, and North Atlantic right) incidental to certain Category I and II gillnet and trap/pot fisheries (fisheries designated with frequent and occasional deaths/serious injuries, respectively); these Category I and II fisheries are composed of U.S. state and federal fisheries described in Tables 2 and 3. At the conclusion of the meeting, the ALWTRT requested that National Marine Fisheries Service (NMFS) develop a more quantitative method to evaluate the level of entanglement mortality and serious injury risk reduction achieved by each of the proposed measures. The ALWTRT also requested that NMFS establish an entanglement mortality risk reduction target or goal to which the ALWTRT can build risk reduction proposals (NMFS 2018). The DST was first introduced to the ALWTRT at its next meeting in April 2019 and applied to the American lobster (*Homarus americanus*) and Jonah crab (*Cancer borealis*) trap/pot fisheries off the coast of the northeastern United States (NMFS 2019). This version of the DST underwent peer review coordinated by the Center for Independent Experts in November 2019 (NMFS 2020). Following the April 2019 ALWTRT meeting, the DST was used for subsequent work analyzing and implementing regulatory changes to the Plan in pursuit of 60% entanglement mortality risk reduction in commercial lobster and Jonah crab fisheries in the Northeast. These regulations were published in a final rule in the fall of 2021 (Federal Register 2021).

In preparations to guide ALWTRT recommendations toward additional entanglement mortality risk reduction goals, updates to the DST since 2019 have included an expansion of the model to all state and federal U.S. fixed-gear fisheries under the jurisdiction of the Plan (including other Category I and II trap/pot and gillnet fisheries), additional large whale species distributions (fin [*Balaenoptera physalus*] and humpback whales [*Megaptera novaeangliae*]), vertical distribution of NARW based on behavior (e.g., migrating, feeding), and new features to simulate a broader range of fishery management actions (e.g., line caps, soak limits). The DST was used to support the development of ALWTRT recommendations throughout 2021 and 2022, most recently at a meeting in December 2022 during which the ALWTRT made recommendations for new measures to reduce right whale entanglement mortality and serious injury in U.S. commercial fixed-gear fisheries regulated under the Plan (NMFS 2022). Given all the updates to the DST including new management actions, additional fishery inputs, and updated whale habitat layers, the DST underwent an additional peer review by the Atlantic Scientific Review Group in January 2023.

The DST does not attempt to incorporate more complex location- or situation-specific variables that may lead to severe entanglements, such as adjacent gear density or how environmental conditions affect the characteristics of vertical lines in the water. Empirical data for these variables are generally insufficient at this time. The DST provides the capacity for users to test different management scenarios and get feedback on how the results change the spatial distribution and gear configurations of the fishery and details about the relative risk reduction achieved by these measures. For comparison, the model output provides a baseline reflecting the current management measures and includes details on relative risk by month and the components that make up total risk, such as number of vertical lines, gear per string, vertical and horizontal line threat (including rope strength), and co-occurrence of whales with fishing gear. In addition to informing relative risk reductions under various management options, the DST can be used to inform the proportion of total risk posed by one or more fisheries. It can also inform the relative risk between gears (e.g. gillnets vs. trap/pots) and geographic areas (e.g. state vs. federal waters).

2. INPUTS

The modular design of the DST relies on inputs constructed outside of the DST function to generate estimates of baseline co-occurrence between whales and gear and the associated risk of the gear. Fishery inputs were developed for U.S. trap/pot and gillnet fisheries in state and federal waters from Maine to Florida using vessel trip reports (VTRs) supplemented with fishery-dependent data sources where available. Trap/pot fisheries are defined by a trap or pot placed on the sea bottom and attached to the surface via a vertical buoy line. More than 1 trap can be attached to a buoy line, referred to as a trawl or string, which can be fished with either 1 buoy line or 2 (1 at each end of the trawl). Gillnet fisheries use net panels either anchored to the ocean floor or drifting off the bottom. These panels are strung together with buoys holding the headrope

The primary fishery input to the DST is the gear map, a data layer with the density of fishing gear (represented by a gear fished metric) throughout the domain of the model. Gear map inputs were developed for various fishing fleets of gillnet and trap/pot fisheries, allowing for distinction between gear configurations across gear types, regions, seasons, and target species. Risk associated with traps, nets, and endlines from each fishery is estimated using a Gear Threat model, which accounts for rope strength as a variable that poses risk of entanglement if there is co-occurrence between gear and whales. A combined gear map layer is compiled from each of the individual fisheries, allowing the DST to estimate relative risk associated with fixed-gear fisheries coastwide, while management actions can be applied to individual fisheries and/or a defined subsets of fisheries.

The DST employs a whale habitat-based density model (Roberts et al. 2016 and subsequent updates; hereafter referred to as the Duke habitat model or whale habitat density layer) that estimates the spatiotemporal distribution and density of right whales throughout the DST domain. In short, the model uses whale sightings data from a variety of sources, matched with co-located oceanographic and habitat variables to predict whale density at any given location. Habitat models are available for NARWs, humpback whales, and fin whales. The default habitat model for NARW analyses was constructed from sightings over the last decade, from January 2010 through September 2020 (Version 12, released February 14, 2022).

2.1 Model Domain

A spatial grid at 1 nm^2 resolution, (adjusted to curvature of the earth), defines the spatial domain of the model. The domain was defined as all points on the U.S. East Coast that overlap the domain of the Duke habitat models. The domain was further constrained to depths between 0 and 2,000 meters (0 to 6,562 feet) in all regions except off Florida where depths were constrained to 700 meters (2,297 feet) to keep the model at an optimal size without losing space where whales and applicable gear occur. The model domain currently excludes most inshore marine/estuarine habitats (Chesapeake and Delaware Bay and Pamlico Sound), but does include Long Island Sound and many of the larger embayments in New England. At the north extent, the grid is further constrained to the U.S./Canada border and the Hague Line. Bathymetry in the grid was determined by overlay with the U.S. Coastal Relief Model as available in 2021 from the NOAA National Center for Environmental Information (NGDC 1999a, NGDC 1999b, NGDC 2001). The gridded model domain is described by a spatial object, MapRef, which is used as a spatial reference input to the DST. Each grid cell (hereafter “cell”) is assigned an index value and all cells are assigned a series of attributes that are described in Table 1. Within the DST, individual records representing fishing effort (e.g., trap abundance, trawl abundance, endline abundance) are attributed to a cell index that links to the cell indices in MapRef to apply spatial processes to or query spatial attributes from the fishing effort information.

2.2 Fishery Inputs

In order to quantify the relative risk and co-occurrence of the fixed-gear fisheries under the Plan and large whales, it is necessary to categorize the dynamics of commercial fishing fleets across state and federal waters along the U. S. Atlantic. Determining temporal and spatial patterns, catch composition, gear configurations, and fishing behaviors is an important first step in developing inputs for the DST model. Also important is understanding how spatial and temporal changes to a fishing fleet are reflected in the data when considering fishing regulations, spatial closures, species range shifts, fleet attrition, and depleted fisheries. A fishing fleet can be described as a group of fishers who are joined by common attributes, such as vessel type, fishing method, targeted species, and locality. This section describes the process of developing individual fishery inputs that would best categorize all of the Northwest Atlantic fixed-gear commercial fisheries.

2.2.1 General Data Needs

Data availability and quality to inform fishery inputs for the DST vary greatly across fisheries and spatial domains. We developed fishery inputs for each identified fishery (Tables 2 and 3) using varying combinations of state and federal VTRs, fisheries observer data, Vessel Monitoring Systems (VMS), and dealer and permit databases.

Inputs for all fisheries are built from available trip-level data collected by federal and state agencies. Minimum required fields for spatially allocating and characterizing fishing effort include: year, month, area, gear fished (number of traps or nets in the water), string length (number of traps/nets per trawl/string), and soak time. Additional fields are available for alternative methods of effort allocation and gear configuration, including: depth, latitude/longitude, and net panel height and length.

We collected VTRs from the Northeast Fisheries Science Center (NEFSC) and Southeast Fisheries Science Center (SEFSC) databases for federal trips and the Atlantic Coastal Cooperative Statistics Program (ACCSP) for state trips. These sources of catch and effort data come from fisher reports (logbooks) that provide information, such as gear type and fishing location, that summarizes the fishing effort for each trip made. This data may often be rather coarse in nature because vessels only report a region where fishing occurred. Alternatively, in the case where spatial coordinates are included with the report, only a single location is used to summarize the region over which the fishing effort took place. If a vessel changes gear or moves from one Statistical Reporting Area (SRA) to another, the trip report provides separate effort records.

From this data, we were specifically interested in where, when, and what type of fishing gear was used and which species were landed. If available, we compiled information on how much gear was used and how long it remained in the water (soak time). Data went through a QA/QC process which incorporated feedback from meetings with individual state managers as well as industry representatives.

Additional information from fishery observer data were obtained from the Northeast and Southeast Fisheries Observer Programs (NEFOP and SEFOP) and the At-Sea-Monitoring (ASM) Program, which were useful for determining gear configurations. VMS data, a collection of spatial positions at set time intervals obtained via satellite for vessel tracking, were incorporated where feasible to provide more precise fishing effort locations. Unfortunately, VMS data were only appropriate for a subset of the gillnet fisheries (e.g., VMS data was only suitable for use with the monkfish and skate gillnet fishery).

2.2.2 Gear Configuration

The gear configuration for each trip report is then summarized as 4 inputs: (1) gear (traps or nets) per string; (2) endlines per string; (3) total gear fished; and (4) rope strength. For gillnet fisheries, we also use net panel height and length to calculate the potential for a whale to encounter the fishing gear itself. These data effectively translate to the amount of fishing gear in the water and thus the amount of potential entanglement risk to whales. For example, gillnet fisheries with longer soak times, larger nets, and longer strings of gear would pose more risk than lesser versions of these configurations.

Trip reports do not typically specify the number of endlines (1 or 2) associated with a string or the strength of those endlines. Typical to all gillnet fishing, those fisheries assume 2 endlines. For trap/pot fisheries, the number of endlines was determined using regional regulations for number of traps per trawl and information from interviews conducted with state managers and stakeholders. For those trips where supplementary information was unavailable to determine the number of endlines on a trawl, we supplied inputs based on local or regional standards.

Gear configuration for federal gillnet fisheries relied primarily on observer data, as this is usually more detailed than what is available from VTRs. If observer coverage did not exist, the VTR was used as a secondary option. In rare cases where observer data and trip reports could not fill in missing data, gaps were filled using averages from adjacent SRAs or time periods. For each fleet and month, gear metrics—such as net dimensions, number of nets per string, number of strings per trip, tie down use (a fishing method that effectively lowers the net height), and soak durations—were used to describe gear configuration.

2.2.3 Effort Allocation Methods

Reporting requirements for describing trip location vary considerably across fisheries, gear type, and management boundaries. Four methods of distributing gear over space were constructed to account for this variability (Figure 3). Trip reports can describe the location of gear using SRA (or subarea), depth, and trip coordinates. Additionally, vessels in some fisheries are equipped with VMS, which allows for highly accurate distribution of fishing effort. As a general practice, the most spatially-explicit information provided by a trip report was used. Where VMS data are not available, coordinates offer the most precise localization of gear, though a single point may not adequately describe the distribution of effort in that trip. In many cases, however, coordinates were unavailable and gear was distributed according to the SRA or subarea reported. If depth was reported, SRA and depth would be used together to limit the available space within a SRA where the trip effort could have occurred. Due to these data availability nuances, effort allocation methods varied across fisheries and areas. This is discussed below for each of the fishery groupings.

Additionally, there are fisheries where not all active vessels are reporting effort. In these cases, it was necessary to estimate the effort from the non-reporting vessels and allocate this effort across the reporting vessels by applying a gear multiplier to individual trips. The sum of the product of the reported effort and gear multipliers equaled the total fishing effort of the fleet, both reported and unreported.

2.2.3.1 Adjustment of Fishing Effort by Soak Time

Because fishing effort is reported from individual trips but the DST runs in monthly time steps, it is necessary to use soak time to calculate the proportion of the month that gear from that trip is in the water and adjust fishing effort accordingly.

$$Soak\ Adjusted\ Fishing\ Effort\ = \frac{Unadjusted\ Effort\ \times\ Soak\ Time\ (days)}{Days\ Per\ Month}$$

For example, if a trip reports 10 traps fished for 12 hours in January, those traps are distributed evenly throughout the month of January based on the proportion of the month (0.5 days/31 days in January) that the traps are deployed. With this correction for soak time, these 10 traps, fished for 12 hours are the equivalent of fishing 0.16 traps continuously for the entire month of January and added to the fishery input layer accordingly. Fishing effort from all trips by a vessel are then summed within a month to get the total amount of gear effort by the vessel. The inputs are then mapped to the spatial domain of the DST model using one of the effort distribution methods.

2.2.3.2 Masking Closed Regions (Cell Status)

Closures and gear restrictions occur within the model domain throughout the year that need to be accounted for both within the DST model itself and when constructing fishery inputs. Particularly for trips that provide only SRA to describe the trip location, removing any portion of the SRA that is closed during that month is necessary to ensure that fishery inputs accurately describe where the trip occurred and prevent the DST from allocating fishing effort and ascribing risk to an area that is already closed. To do this, a Cell Status object is created for each gear type (e.g., trap/pot, anchored gillnet, sink gillnet) and fishery category (e.g., lobster/Jonah crab, whelk, monkfish) that stores information on the proportion of a month that is open to fishing for every cell in the DST domain (Figure 4). Cell Status objects are distinct to individual fisheries or gear because in some areas, a closure may only restrict a specific fishery. Based on current fishing closures for each month, each cell can be either closed (value = 0), and unavailable for gear allocation, open (value = 1), or partially open (value between 0 and 1) and available for gear allocation. These Cell Status objects are then passed to the functions that perform effort allocation (below) to ensure fishing effort is not placed in locations that are closed to that fishery.

2.2.3.3 Allocation by Geographic Area

Allocation by geographic area (GeoArea) is the simplest but least informative method for spatially allocating effort and is reserved for trips for which only some standardized regulatory or reporting area is recorded (e.g., SRAs, subareas). This is most common in small state fisheries where trip reporting requirements are less stringent. In this case, fishing effort is spread evenly across the area within the reported month (Figure 3) while accounting for any closures captured in the Cell Status object. In some cases, supplementary information on location of gear was available through stakeholder and state manager interviews that allowed trips to be further constrained (e.g., certain distances from shore, outside of certain depth ranges). For this method, the effort in a cell *c* in a month *m* for a given trip *t* is the product of the soak-adjusted fishing effort for the trip and the availability of the cell from the Cell Status object, divided by the sum of the availability of all cells (*n*) in the area.

$$Effort_{t,c,m}\ =\ Soak\ Adjusted\ Fishing\ Effort_{t,m}\ \times\ \frac{Availability_{c,m}}{\sum_{c=1}^{n}\ Availability_{c,m}}$$

2.2.3.4 Allocation by Area and Depth

A potential improvement on allocation by geographic areas is using both reported area and depth (Depth) to further constrain effort allocation. Depth may be a helpful metric in narrowing down the regions of a spatial area where a trip may have occurred (Figure 3), particularly in regions like the Gulf of Maine (GOM) which has significant depth gradients. Initially, the allocation of gear follows the same method as the allocation by spatial area. The trip is first constrained to available cells in the reported area. From there, the depth reported for a trip is converted to a depth interval based on a supplied range. For example, if a trip reports a depth of 35 m and a 10 m depth interval is specified as an input argument, the initial depth range is 35 +/- 5 m or 30-40 m. The algorithm then allocates the effort across the set of all cells within the reported area and depth range. If no cells within the reported area are within the reported depth range, the algorithm increases the depth range by the specified interval—in this case, 25-45m for the second iteration—and again searches for locations within the reported area that fall within the depth range. This continues until appropriate cells are identified or the maximum number of iterations are exceeded. In the former case, the fishing effort associated with a trip is evenly distributed across the cells identified according to the above equation but where the denominator is this constrained set of cells. In the latter case, trips that cannot be placed on the map based on the reported spatial area and depth are returned by the function for further examination. We note that the specification of the depth interval is subjective in most cases and uninformed by data. In these cases, the depth interval is set to a value that is appropriate for the area fished (i.e., smaller depth intervals in shallower habitats), and the inputs are often built multiple times with different depth interval inputs to understand the sensitivity of this input to the resulting products.

2.2.3.5 Allocation by Trip Coordinates

Input development methods by spatial coordinates (Coords) provide a high level of spatial detail for placing fishing effort (Figure 3). This method utilizes both depth and distance buffers around reported coordinates to allocate effort in a way that hopefully mimics fisher’s behavior. If coordinates are unavailable for a subset of reported trips, the effort from these trips are redistributed across the remaining trips within the reporting area and month.

The spatial buffering around reported coordinates is accomplished by specifying spatial and depth buffers, ranges over which fishing effort is allocated around the reported coordinates. For each trip with coordinates, the depth in the reported cell is extracted from the bathymetry layer in MapRef. Depth neighborhoods for each trip are then commonly calculated based on a proportion of this calculated depth. For example, a buffer of 10% around a trip reported in 200 m depth would have a depth buffer +/- 20 m while trips in shallower waters would have a proportionally narrower depth buffer. A default value can be supplied across all trips that do not have a specified value.

The spatial buffer (in nautical miles [nm]) is used to determine the distance from the reported coordinates that trip effort is spread across. Given the coordinates provided for a trip, the spatial buffer is used to find all cells that are within a given distance of the reported location as candidate cells to allocate trip effort. For example, if a spatial neighborhood of 5nm is specified, then all locations within a 5 nm radius of the supplied coordinates are included. Like the depth buffer, this is commonly calculated as a proportion of the distance from shore for each individual trip, presuming that trips farther from shore will tend to have gear more widely spread, but fixed values can also be supplied.

The final allocation of effort from a trip report is evenly spread across all cells that meet both the depth and spatial criteria according to the above equation but where the denominator is the set of cells within both the depth and distance buffers. If the specified depth and spatial buffers are too narrow, no neighboring cells may exist within the specified ranges, in which case the trip is returned by the function without allocating the associated effort. Both the depth and spatial buffers could be informed quantitatively, using fine scale data on the distribution of fishing effort within spatial areas, but this is lacking in most cases and thus has not been implemented in any fisheries yet. Rather, we test a reasonable range of these buffer values and examine the outputs for realism and performance. Also, similar to "allocation by area and depth" above, the spatial autocorrelation of whale distributions seems to make risk calculations robust to assumptions of these buffer sizes.

2.2.3.6 Allocation by Trip and VMS Coordinates

The use of VMS data for fishery input development in the DST was limited to the federal monkfish and skate gillnet fishery. VMS data is categorized by declaration codes that identify vessels by target species and fishing method. Because of mismatches between declaration codes and the fisheries as defined in the DST, we were only able to use the monkfish gillnet data to inform fishing effort allocation. We constrained VMS data from 86 vessels to the years represented by the VTR data (2017-2020) and utilized time and coordinate location data of successive pings to calculate vessel speeds. Similar to Palmer and Wigley (2009), the tri-modal nature of the calculated speeds distinguished fishing activity (setting and hauling nets) from transiting. We then normalized the total VMS effort (number of pings with fishing effort) within an SRA and month to sum to 1 to describe the relative spatial distribution of effort. This provided us with highly detailed maps of the relative distribution of fishing effort for the associated fishery.

Because not all vessels in these fisheries report VMS data, we compared the VMS effort maps with coordinates recorded in federal observer trips to determine if there were any significant areas where fishing effort was not captured in the VMS data set. Input from industry also allowed us to investigate combining skate trips with monkfish as these species are frequently caught together. As we determined that the VMS data did not represent any significant bias in the distribution of effort within SRAs, we then allocated the reported effort for each trip into each SRA according to the distribution of VMS effort where *n* denotes all cells in the area that have non-zero VMS effort.

$$Effort_{t,c,m} = Soak\ Adjusted\ Fishing\ Effort_{t,m} \times \frac{Availability_{c,m} \times EffortFromVMS_{c,m}}{\sum_{c=1}^{n} Effort\ From\ VMS_{c,m}}$$

Where VMS coverage was lacking in an area, we used the allocation by coordinates method to allocate remaining effort.

2.2.4 Effort Outputs for Economic Analysis and Confidentiality Compliance

All of the above allocation methods produce an effort output object that is intended for economic analysis and/or producing maps that are compliant with data confidentiality requirements. This object is essentially a disaggregated gear map that records the amount of effort allocated to each cell from each individual trip. This is a valuable product for economic analysis as it allows for querying and tracing effort in any set of cells in the model domain back to the trips that generated the effort and associated vessels. Thus, one can directly extract the number of vessels seasonally fishing a region, the proportion of their effort within that region, landings impacts, affected homeports, and so on. The unique set of vessels fishing a cell are also passed to the DST as an input to determine if there are sufficient vessels (3 vessels or more) to include data from a cell in maps that are going to be publicly shared.

2.2.5 Endline Strengths

The strength of endlines needed to haul fishing gear increases with increasing water depth and number of traps on a trawl (Willse et al. 2022). Knowlton et al. (2016) determined that ropes with a breaking strength of ≤ 1700 lbs. were ideal for many fishing operations while greatly reducing severe entanglements of large whales. This rope strength became the standard for weak rope measures within the DST. The intention being that methods to reduce the strength of vertical endlines to 1700 lbs will reduce the risk of entanglement and serious injury to whales. Strengths of lines associated with vertical (buoy) endlines and horizontal lines (groundlines between traps or gillnet headropes) are calculated and included with the inputs for each fishery. With the exception of a few fisheries where maximum endline strengths are mandated, endline strengths are estimated from line diameters and a statistical model that relates line diameter to breaking strength.

For gillnet fisheries, line diameters are calculated from available observer data, either from the fishery being characterized or from available data from a comparable fishery. Such observer data is much sparser for the lobster and other trap/pot fisheries, so line diameters are estimated from an observed relationship between trawl length and rope diameter.

2.2.5.1 Predicted Rope Diameter from Trawl Length for Trap/Pot Fisheries

Our primary data source on the relationship between trawl length and endline characteristics comes from the NEFOP which only recorded rope diameter. Thus, calculating the rope strength associated with trawl lengths requires first characterizing the distribution of rope diameters observed for a given trawl length and then deriving a relationship between rope diameter and rope strength.

For each observed trawl, NEFOP observers recorded the trawl length and endline diameter. To characterize the expected distribution of rope diameters for a given trawl length, we truncated the rope diameter data at 5/16 inch and 3/4 inch to remove a few outliers, rescaled the rope diameters to a range of 0-1, and fit the data to a logistic regression (Figure 5). We then extracted and discretized the predicted line diameter distributions from the logistic regression to get proportions of line diameters expected for different trawl lengths (Figure 6).

2.2.5.2 Predicting Rope Strength from Rope Diameter

Data on the breaking strength of ropes from the lobster fishery came from two sources. Knowlton et al. (2016) acquired samples of rope taken from whale entanglement events and tested their breaking strengths. Data from these ropes are further characterized by polymer and fiber type, the condition of the rope (5 levels: very good to very poor), if the rope was leaded, and the test type used to determine breaking strength (whole rope vs. individual fibers). The Maine Department of Marine Resources (DMR) provided an additional data set from a recent study where lobstermen voluntarily submitted samples of endline for testing. This data was further characterized by age (number of seasons fished), and a descriptor of the rope segment (clear line, joined by a splice, or joined by a knot). To maximize the size of the data set, we looked to match as many of the attributes between the two data sets as possible.

For the data from Knowlton et al. (2016), we noted from residual analysis that rope condition at 5 levels had a remarkably linear trend. Thus, we recorded this attribute with numeric values from 1-5 and treated this as a continuous variable comparable to age for the DMR data. Second, we quantified the storage effect as the number of years between collection and observation using January 1, 2015, resulting in a mean storage time of 12.2 years (range 4.6-20.1 years). Storage was not a large effect in the final model, so the date has minimal effect on outcomes. Finally, we coded all data from Knowlton et al. (2016) as “clear” rope samples. Unfortunately, rope material was not available for much of the DMR data, so material type was dropped from the Knowlton et al. (2016) data set. For the DMR data, we assumed the rope was not leaded and had a storage time of 1 year.

With the combined data set, the best linear model included (1) a rope diameter interaction with section type (clear, spliced, or knotted); (2) an interaction between rope age and source (DMR vs. Knowlton) to capture the different metrics of age between the data sources; (3) test type as a factor (whole rope or rope fiber); and (4) storage time as a continuous variable, with a log-normal error distribution. Final model r-square was 0.58 with 290 degrees of freedom. As expected, rope diameter was the strongest predictor of breaking strength, increasing in breaking strength by 32.6% per 1/16 inch (Figures 7 and 8). Splices and knots in ropes are predicted to decrease breaking strength by 22.5% and 39.3%, respectively, and rope is predicted to weaken at a rate of 4.4% annually when fished and 1.1% annually when stored, though this storage effect also accounts for changes in rope technology and tends to be an unstable parameter estimate.

Finally, to characterize the expected age distribution of ropes in use by the fishery, it was necessary to model the rate at which endlines are lost or replaced to get the proportion of rope at each age. As empirical data on this was not readily available, collaborators at DMR estimate that fishers have a 10% loss allowance for lobster traps that seem to be similar to the actual rate of gear loss and that, of the samples submitted for strength testing and slated for removal, most were between 3 and 6 years of age. Thus, we incorporated a 10% stochastic removal rate of endlines due to loss and the mean age of removal at 4.5 years with a standard deviation of 1. The product of these 2 curves (Figure 9) results in the distribution of rope ages one would expect to observe in the fishery and was used to predict rope strength.

2.2.5.3 Predicted Rope Strength from Trawl Length

To obtain distributions of rope strength given trawl length, we created 1,000 random draws from the predicted rope diameter distribution for each trawl length, matched each with an appropriate random draw from the age distribution. We used this to predict a mean rope breaking strength from the statistical line strength model and then added a random draw from the line strength model error distribution. We then binned the calculated rope strengths from each trawl length into 100-pound bins and calculated proportions represented by each bin. Resulting distributions are strongly right-skewed, particularly for short trawl lengths where both the rope diameters and rope strength distributions are right-skewed. Single-trap trawls, for example, have a median breaking strength of 2,000 lbs. but a range from <1,000 to >5,000 lbs., (Figure 10). As expected, longer trawls are predicted to have endlines that break at much higher loads with median breaking strength for a 50-trap trawl around 7,000 lbs. (Figure 11).

For horizontal line strengths, groundlines in the trap/pot fisheries are assumed to be the same as vertical line strengths. Headropes in the gillnet fishery are calculated from line diameters recorded in observer data similar to vertical lines. Where weak links are mandated in gillnet headropes, a buffer of 30 feet on either side of the weak link is modeled to be functionally weak, and the proportion of headrope represented by these sections is calculated and assigned to the mandated breaking strength.

2.2.6 Cumulative Effort Distributions

As part of the process of building model inputs for individual fisheries, a set of cumulative effort distributions are calculated for the amount of gear fished (traps or gillnet panels), endlines fished, and soak times for each fishery, area, and month (Figure 12). These curves are, in turn, used for estimating the actual amount of effort that would be reduced if individual vessels were limited in the total number of traps or lines they are allowed to fish (gear caps or line caps, respectively) or the duration their gear is allowed to soak before hauling (soak limits).

2.2.6.1 Gear Effort Distribution

Gear effort distributions are calculated by characterizing the total number of gear units fished by each active vessel after which effort from each vessel is compiled into a distribution that describes total fishing effort across the fishery for an area and month. For each reporting vessel v, we calculate the gear fished across trips t by month m in year y and area a,

$$Gear\ Fished_{(v,a,m,y)} = \sum_{t=1}^{n} Gear\ Fished_{t,v,a,m,y}$$

where *n* represents the number of trips taken by a vessel in a month and year. We also calculate the proportion of effort across fished areas if the vessel fishes multiple areas using a gear multiplier. First, we calculate a total gear fished across all areas.

$$Total\ Gear\ Fished_{(v,m,y)} = \sum_{a=1}^{n} Gear\ Fished_{(v,a,m,y)}$$

We then use the total gear fished to produce a frequency distribution where the weight for each vessel in a given area is the frequency of the respective total gear fished for each vessel in the distribution.

$$Gear\ Weight\ For\ Vessel_{(v,a,m,y)} = \frac{Gear\ Fished_{(v,a,m,y)}}{Total\ Gear\ Fished_{(v,m,y)}} \times Gear\ Multiplier_{(v,a,m,y)}$$

We then calculate the quantiles of the frequency distribution at 1% intervals to characterize the distribution of effort for vessels active in each area and month. Thus, the calculated effort for a given quantile represents the portion of vessels in that area fishing at that effort level or below, and the sum of the area below a curve represents the total effort in the fishery for that area and month (Figure 12-A).

2.2.6.2 Endline Effort Distribution

Distributions of endlines fished are calculated similarly to gear effort but based on endlines fished by individual vessels as calculated from gear fished, string length, and presence of endlines on one or both ends of the string. For each reporting vessel, we use the reported gear configurations associated with each trip report to convert the amount of gear fished into endlines. We then calculate the total endlines fished by month across *n* trips within an area,

$$Endlines\ Fished_{(v,a,m,y)} = \sum_{t=1}^{n} \frac{Gear\ Fished_{(t,v,a,m,y)}}{Gear\ Per\ String_{(v,a,m,y)} \times Endlines\ Per\ String_{(v,a,m,y)}}$$

followed by the total endlines fished across *n* areas,

$$Total\ Endlines\ Fished_{(v,m,y)} = \sum_{a=1}^{n} Endlines\ Fished_{(v,a,m,y)}$$

and get the weight associated with a vessel with the proportion of endlines fished within an area and the gear multiplier,

$$\begin{aligned}&\mathit{Endline\ Weight\ For\ Vessel}_{(v,a,m,y)}\\&\quad=\frac{\mathit{Endlines\ Fished}_{(v,a,m,y)}}{\mathit{Total\ Endlines\ Fished}_{(v,a,m,y)}}\times\ \mathit{Gear\ Multiplier}_{(v,a,m,y)}\end{aligned}$$

We use the total number of endlines fished for all vessels fishing an area and month to produce a frequency distribution similar to the method used for gear fished, where the weight for each vessel in a given area is the frequency of the respective total endlines for each vessel in the distribution and calculate quantiles accordingly. Thus, the calculated effort for a given quantile represents the portion of vessels in that area fishing at that number of endlines or below, and the sum of the area below a curve represents the total endlines fished in the fishery for that area and month (Figure 12-B).

2.2.6.3 Soak Time Distribution

Distributions of soak times are calculated similarly to gear effort but are based on reported soak durations and weighted based on gear fished and the gear multiplier.

$$\mathit{Soak\ Weight\ For\ Vessel}_{(v,a,m,y)}\ =\ \mathit{Gear\ Fished}_{(v,a,m,y)}\ \times\ \mathit{Gear\ Multiplier}_{(v,a,m,y)}$$

We use the reported soak times for all vessels fishing an area and month to produce a similar frequency distribution, where the weight for a vessel in a given area is the frequency of the respective soak duration for each reported trip in the distribution and calculate quantiles accordingly. Thus, the calculated effort for a given quantile represents the portion of gear in that area fishing at that soak duration or less, and the sum of the area below a curve represents the total fished effort in the fishery for that area and month (Figure 12-C).

2.3 Trap/Pot Fisheries

All trap/pot fisheries within the model domain were summarized into fishery inputs for the DST. Fisheries were divided into state and federal fisheries based on the vessel permit type rather than trip location within state or federal waters. This was to account for dual-permitted vessels that can fish in both state and federal waters. For state-only permitted vessels, a separate fishery input was constructed for each state both to allow characterization and quantification of each state's fisheries and to prevent displaced effort from moving to adjacent state and federal waters.

State and federal trap/pot fisheries were further divided into species subgroups—whelk, fish, crab, and lobster/Jonah crab—though not all species subgroups are fished in each of the coastwide regions. In part due to 2021 management actions targeting entanglement in lobster and Jonah crab fisheries of the Northeast (NE) Trap/Pot Management Area, a separate designation for "other trap/pot" (OTP) was used to describe the trap/pot fisheries distinct from NE lobster and Jonah crab fisheries.

Trap/pot fisheries were defined based on reported gear types (e.g. lobster pot, whelk pot) where appropriate. Where gear types were vague (e.g. pot), the assignment of trips to fisheries were based on catch composition. To prevent double-counting of trips that landed multiple species, the species representing the greatest portion of reported landings for that trip was assumed to be the target species and used for species subgroup allocation. However, while the dominant landed species may not have been the target species, the species subgroup does not alter the gear configuration or eventual risk associated with each trip, as these are informed by the trip data itself. In addition to trip reports, interviews were conducted with representatives from each state for which trap/pot fishery inputs were constructed for assessment by the DST. Where appropriate, material learned or made available during these interviews was used for building accurate fishery inputs. In total, fishery inputs were constructed for 48 trap/pot fisheries operating in waters of the DST domain (Table 2; Figure 13).

2.3.1 Northeast Lobster and Jonah Crab Fisheries

2.3.1.1 Maine Lobster Management Area (LMA) 1

Inputs for the Maine LMA 1 fishery were constructed from state and federal trip reports for 2015-2018. DMR compiled and provided the trip reports and were closely involved in the development of fishery inputs. The fishery is modeled as two fisheries: 1 for state-permitted vessels operating inside 3 miles and 1 for federally permitted vessels that fish state or federal waters. Trip reports include fields for lobster fishing zone (A-G) and distance bins from shore (less than 3 miles, 3-12 miles, and 12+ miles). Thus, the combination of zone and distance from shore define spatial areas for allocating effort. Fishers also report a representative depth for each trip which is used to further constrain the spatial allocation of effort.

Because DMR only receives trip reports from a 10% subset of fishers, it is necessary to calculate expansion factors (gear multipliers) to scale up reported effort to estimated total fleet effort. Due to fleet heterogeneity and to minimize the sampling effects, expansion factors are calculated separately for each license class type, month, and year. Permitting data is first linked to both dealer data and trip reporting data to match vessels to license classes. License classes are then condensed into 5 classes: Classes 1, 2, 3, Student Class, and “Other” Class. Currently, tribal licenses constitute a negligible portion of the effort and are excluded from modeling. The dealer data is used to define the number of active fishers by year, month, and license class. This number is then divided by the number of active fishers who are filing trip reports to calculate the expansion factor to be applied to each trip report (Figure 14).

Original fishery inputs developed for Maine were based on spatial allocation by reporting areas without further spatial resolution. For the updated inputs, we compared inputs built using either the geographic areas method or the geographic areas with depth method (Figures 15-16).

Including depth information in the spatial distribution process tends to cluster gear around bathymetric features and place gear nearer to shore in shallower waters than the method that does not use the depth information. However, it also produces some empty spaces with no fishing effort in depths that were never reported for a spatial area but where we expect some effort to occur. We concluded that including this depth information, though still not optimal, was an improvement over excluding this information and produced a more realistic depiction of the spatial distribution of fishing effort. For distributing effort, we opted to use 20 m depth intervals for the state fishery, the federal fishery inside of 3 miles, and the federal fishery in the 3-12 mile range but used 40 m depth intervals outside of 12 miles as these values seemed to give results that were a compromise between over- and under-aggregating effort. Outputs built with different depth intervals demonstrated similar spatial patterns in risk and total risk scores. Therefore, the outputs are fairly robust to the depth interval assumption, partially due to the spatially-autocorrelated nature of whale distributions estimated for this region.

2.3.1.2 New Hampshire

Inputs for New Hampshire include both a state and federal fishery. Trip reports from the state fishery for 2015-2018 were collected by the state and provided to us through ACCSP. We used effort distribution by geographic area as higher resolution data was not available. A portion of the state fishery occurs inside the mouth of the Piscataqua River, which is outside of the domain of the DST and was not included in the model.

We used trip reports, permit data, and dealer landing data from federal databases to estimate fishing effort for the New Hampshire federal fishery. Not all federal vessels are required to submit federal trip reports, but a large portion of the New Hampshire federal fleet do submit trip reports. These reports include coordinates allowing fishing effort to be placed more precisely. Thus, it was necessary to determine the proportion of vessels that were active but not reporting and use this to build an expansion factor (gear multiplier) for the active, reporting vessels. We identified New Hampshire vessels based on home ports recorded in the permit databases and, within that subset, identified active vessels using the dealer data. We then used the total number of active vessels and the number of reporting active vessels to calculate expansion factors that were applied to the reporting vessels to account for the non-reporting fishing effort. We then used distribution by trip coordinates to place fishing effort adjacent to New Hampshire (Figure 17).

2.3.1.3 Massachusetts State and Federal Lobster Fisheries; LMA 1, LMA 2, and Outer Cape Cod (OCC)

We built six lobster inputs for the lobster fisheries around Massachusetts: state and federal fisheries for LMA 1, LMA 2, and Outer Cape Cod. Trip reports for 2015-2019 were assembled, partially processed, and provided by Massachusetts Department of Marine Fisheries (DMF). Massachusetts requires full trip reporting for all state and federal vessels with trip location reported at the scale of state Statistical Reporting Areas (SRAs; Figure 18), so effort is allocated using the geographic area method with no additional spatial constraints from depth or coordinates. A small portion of the Massachusetts LMA 1 federal fleet reports trips in SRA 513, north of the Massachusetts border. To prevent this effort from being displaced unrealistically far to the north, these trips are subjectively constrained to the area of 513 south of 43.1°N. Federal vessels reporting fishing in the SRA that includes the LMA 2-3 overlap are evenly distributed among cells that include LMA 2 and the 2-3 overlap.

Notably, trawl lengths are not directly reported in trip reports. Rather, the total traps fished and total endlines fished are reported, and trawl length is estimated from these. The data does not differentiate trawl lengths for those fishing a mixture of one and two endlines. For example, it is not possible to distinguish between vessels fishing 3-trap trawls with single endline and 6-pot trawls with 2 endlines. Similarly, vessels fishing some mixture of singles and 5-trap trawls, for example, may report an intermediate value that is not representative of either actual gear configuration. Therefore, these trawl length calculations are performed by DMF staff who are familiar with the common gear configurations by area.

2.3.1.4 Rhode Island

For state waters adjacent to Rhode Island (RI), all active vessels report to the RI Department of Environmental Management, thus full reporting exists. Trip reports from the state fishery for 2015-2018 were collected by the state and provided to us through ACCSP. We used effort allocation by geographic area as higher resolution data were not available.

For federal waters inside LMA 2, we used federal dealer reports and permitting data to define all active vessels and federal trip reports to identify vessels providing trip reports. We then calculated gear multipliers for reporting vessels to account for the active, non-reporting vessels, similar to New Hampshire, and used allocation by spatial coordinates to spatially allocate effort.

2.3.1.5 LMA 3

The majority of federal lobster vessels fishing this management area file federal trip reports allowing for spatial allocation by coordinates. Trip reports were extracted from federal databases and constrained to vessels with LMA 3 permits and coordinates or SRAs within LMA 3. As above, dealer and permit data were used to detect active vessels that were not submitting trip reports, and offsets were applied through a gear multiplier to the trip reports on a monthly basis to active vessels to account for the missing effort. We use a spatial buffer of 10% of the distance from land and a depth buffer of 10% of depth at coordinates.

2.3.2 Other Trap/Pot - Federal

VTRs queried from 2010-2020 were used to construct federal OTP fishery inputs. Soak time, total traps fished, and traps per trawl were generally provided in trip reports, though interviews with state managers provided supplemental information where data was unavailable. While state and regional characteristics were maintained in the translation from trip reports to DST inputs (e.g., gear fished), most federal OTP inputs were aggregated coastwide. Four coastwide federal OTP inputs were generated for whelk, fish, blue crab (*Callinectes sapidus*), and deep sea red crab (*Chaceon quinquedens*), while Southeast (SE) fish pots and Mid-Atlantic lobster were subset regionally.

The Mid-Atlantic lobster fishery was made distinct from the remaining coast because NE lobster is described separately (Sections 2.3.1.1-2.3.1.5). This distinction is an artifact of the 2021 ALWTRP rule focusing on entanglement risk from NE lobster rather than a distinction in region-species grouping. Therefore, federal Mid-Atlantic lobster is included with the OTP fishery, describing lobster/Jonah crab trap/pots in federal waters outside of the Northeast Trap/Pot Management Area. Fish pots in the SE are a very small fishery represented only by black sea bass (*Centropristis striata*) from south of Cape Hatteras, NC, to Florida. The characteristics and management history of the SE fish pot fishery were independent enough from the remaining coastwide fish pot fishery to generate a separate input.

Spatial coordinates were available for most fisheries reporting in federal waters, allowing for effort allocation by coordinates. Details of the species aggregated into each fishery category can be found in Table 2, along with effort distribution methods used for each of the regions and fisheries represented within these inputs.

2.3.3 Other Trap/Pot - State

Unless otherwise noted, trip reports from 2012-2019 were queried from ACCSP to construct state OTP fishery inputs. Details such as included species and gear distribution method for each state can be found in Table 2. Descriptions of individual state OTP inputs will focus on those states where additional data was queried outside of ACCSP or supplemented by interviews.

2.3.3.1 Rhode Island

Nearly 40,000 trip reports from RI state-permitted vessels were queried from ACCSP. The reports did not distinguish trips that occurred within exempt waters of Narragansett Bay from those that took place in non-exempt, oceanside waters. Communication with state managers was used to exclude some species (e.g., green crab [*Carcinus maenas*], American eel [*Anguilla rostrata*]) from consideration that were unlikely to be targeted outside of the Bay, as well as to reduce the ~500 rock crab (*Cancer irroratus*) trips by 50% to account for the portion likely to have occurred oceanside. In addition, while the majority of RI lobster trips were accounted for in the NE lobster/Jonah crab inputs, about 800 trips were reported in SRA 539, west of the Northeast Region. Therefore, an additional RI lobster input was constructed under the OTP designation, though comparison of trip reports between NE lobster/Jonah crab and OTP sources confirmed that no trips were double-counted. Inputs for fish pot and whelk pot trip reports from RI state-permitted vessels were not adjusted from the ACCSP trip reports.

2.3.3.2 Maryland and Virginia

Trip reports were initially queried from ACCSP. However, discussions with state managers revealed the benefit of querying data directly from the states to capture the spatial distinction of trips that occurred in exempt waters (Chesapeake Bay) versus non-exempt waters. In Maryland, transitioning from ACCSP to Maryland trip reports excluded blue crab entirely from non-exempt waters, though the trip reports supported the construction of WhelkPot, FishPot and lobster OTP fishery inputs.

A similar pattern in blue crab was observed for Virginia on the southern bank of the Chesapeake Bay. During interviews with state managers from Virginia, they requested that the trip data be queried directly from their database, resulting in a reduction from 16,000 blue crab trips initially assigned to Virginia non-exempt waters to just under 200 from 2012-2019. Enough trips were available to construct a blue crab input from the Virginia trip reports, along with whelk, fish, and lobster OTP.

2.3.3.3 North Carolina

Only a whelk fishery was found for North Carolina through the ACCSP data query, though the trip reports did not include data on the number of traps fished, soak time, or any other data necessary to describe gear configuration in fishery inputs. Trip reports from 2012-2019 were queried directly from North Carolina, which in conjunction with the state interview provided the information necessary to construct a whelk input. All but one of the 167 trips occurred north of Cape Hatteras, consistent with SE trap/pot closures.

2.3.3.4 South Carolina and Georgia

Blue crab is the only state trap/pot fishery operating in South Carolina and Georgia. Trip reports queried from ACCSP for Georgia assigned all trips to inshore waters, though state managers acknowledged that trips occur oceanside during the winter. However, trip reports from Georgia were unable to substantiate this with any empirical data. There were many trip reports for South Carolina from ACCSP, although there was no designation between exempted waters of inland bays and oceanside non-exempted waters. The blue crab fishery is thought to be relatively similar between Georgia and South Carolina, so expertise from state managers was used to estimate the amount of gear and gear configuration for the blue crab fishery. Ultimately, estimates of how many vessels are fishing for blue crab in non-exempt waters during the winter, along with estimates of the gear configuration, were provided and used to construct fishery inputs.

2.3.3.5 Florida

As with South Carolina and Georgia, ACCSP trip reports did not distinguish between oceanside and inland blue crab effort, though trip reports were available from the state of Florida. These trip reports were queried and used to construct an input for Florida blue crab.

2.4 Gillnet Fisheries

Gillnet fishing methods vary greatly by region and target fishery. In order to best represent fishing practices coastwide, we made use of the data available to capture details that would best reflect the method of fishing. This required a balance of identifying representative fleets while recognizing it was unrealistic to have a large number of groups given the importance of including fishing methods (e.g., gillnet type, mesh size). In order to apply regulations such as spatial closures, fishery groups needed to be defined by gillnet type (e.g., anchored, drift) and mesh size since these details are part of management regulations.

2.4.1 Gillnet Fisheries - Federal

Federal VTRs are the primary data source for the federal gillnet fishery groups. We began by constraining our data to the DST domain and identifying the top species caught across trip reports and ordering them by the proportion of the total number of trips. From there, we looked at the list of species that made up 95% of the cumulative proportion to get a starting list of species, adding in lesser caught species that we knew were both commercially important and would likely be caught together. Species were combined into groups primarily based on target fisheries (e.g., monkfish and skate species), but additional information, such as life histories and species co-occurrence, were also considered. Industry members were also consulted in various regions to help inform methods for grouping species. For example, fishers in the northern region typically focused on target species, such as monkfish or groundfish, while further south, there was a greater focus on fishing methods, in particular mesh size.

This process resulted in 5 federal species groups: MonkfishSkate, NEGroundfish, Dogfish, SharkSpp, and InshoreSpp. Once these species groups were established, we focused on determining the gillnet type and mesh size from which we could subset each species group in order to apply appropriate closures and incorporate any regional differences in fishing method. We used the VTR reported gillnet type and mesh size to further classify the fishery groups, generating 3 mesh size categories based on the Bottlenose Dolphin Take Reduction Team ranges: Small (≤ 5 in.), Medium (5-7 in.), and Large (≥ 7 in.). Gillnet type was defined as either anchor (attached to the seafloor) or drift (no attachment). While these further divisions of fishery groups could have resulted in a total of 30 federal gillnet fishery groups (6 gear configuration groups per species group), not all configurations applied to each species group. Thus, the federal gillnet fishery was broken into 18 fishery groups (Table 3; Figure 19).

Although region was important for understanding fishing practices across the entire east coast, it was too difficult to set strict boundaries for fishery groups spatially. Instead, regional and state constraints to the fisheries can be defined within the DST model itself.

Data from 2010-2020 was initially considered for federal gillnet. In order to capture the most recent fishing trends and changes in fleet dynamics due to regulations and species declines, fleet attrition, or range shifts, the federal VTR data was truncated to 2017-2020. This also better matched the range of years available for state gillnet trip reports, making the gillnet input data more consistent.

Input development for federal gillnet fishery groups was highly dependent on the level of detail available within the data sources. Three methods were used for input development: VMS, Coords, and Depth. Working from the greatest spatial precision method to the least, inputs were developed for each of the 18 fishery groups defined above (Table 3). In some cases, we used two methods to preserve as much spatial precision as possible. For example, when developing the MonkfishSkateAnchorLarge fishery input, VMS input development methods were used in areas where VMS coverage existed, and then the remaining trip data was developed with the Coords method.

2.4.2 Gillnet Fisheries - State

Ten separate state gillnet inputs were constructed using VTRs from 2017-2019. In addition to state VTRs, observer data and raw trip reports from Maine and North Carolina were used to construct the state gillnet inputs. Observer data and stakeholder input helped to supplement VTR data, which sometimes lacked spatial resolution and information needed to describe gillnet gear configuration. The VTR data was grouped using the DST region designations, though note that all of North Carolina is included in the Mid-Atlantic gillnet fishery, and there is no state gillnet fishery in the Southeast region. The VTR data set was also constrained to only those species that accounted for the top 95% of the cumulative proportion.

We provided state representatives initial data summaries constructed from the VTR and observer data to receive feedback and insight as to how appropriately the fishery inputs were describing local fisheries. As a result of this feedback, VTRs were requested directly from Maine and North Carolina to supplement the ACCSP VTR records. These raw trip reports were merged with the remaining region-specific trip reports from which a state gillnet fishery input was constructed.

Final results produced 10 total fishery groups for state gillnet (Table 3; Figure 13). The main fishery groups matched those for federal gillnet: MonkfishSkate, NEGroundfish, Dogfish, SharkSpp, and InshoreSpp. Some of these fishery groups were further categorized by gillnet type and mesh size, similar to the federal gillnet methods. Regional differences were also taken into account where they differed from neighboring regions. After identifying the fishery groups, we developed inputs for each fishery group based on the available data. Inputs were built using Depth, Coords, or GeoArea (usually SRA) methods depending on what was available for each fishery.

2.5 Whale Spatial Distribution Inputs

The DST model requires an input for the spatial distribution of whales; we used the Duke habitat model, recast to the MapRef grid. This entails an estimate of the total number of whales present for each cell in the DST domain on a monthly basis. Thus, aggregating across space within a month provides an estimate of whales within a bounded area, and comparison among months can be used to examine seasonality of probable whale presence.

While models exist for other species of whales, the focus here will be on NARWs. The NARW habitat density layer has been updated several times since the inception of the DST with a number of improvements and ranges of years included in model estimates. Recognizing that whale distributions and seasonal migration patterns have changed over the past decades, the NARW habitat distribution model has multiple options for inputs ranging across various years. While previous versions and older ranges of years were useful for explorations of uncertainty in whale distributions and robustness of fishery management plans, we focus on the most recent Version, 12. Version 12 utilizes sightings data from January 2010 through September 2020, noting that survey data from the New England Aquarium does not extend beyond this terminal month and southeast data does not extend beyond the 2019/2020 calving season. The models are estimated at a 5 km resolution and were recast to the domain of the DST by overlaying the points within the DST domain on the whale habitat model raster and extracting the overlapping values (Figure 20). Thus, whale density values for individual cells in the DST will have the same value as some neighboring cells if they fell into the same spatial unit in the original whale model.

2.6 Whale Vertical Distribution Inputs

To account for the vertical distribution of whales in the water column, the DST incorporates an input that contains two objects. The first object is a set of calculated relative proportion profiles at depth, binned into 5 m depth increments that sum to 1 and are stored as quantiles with options for different whale behaviors. The second object is a list of which profiles apply for any given cell and month. Thus, for any given month and cell in the DST domain, one can query the relative presence of whales in any given depth range within the water column.

Currently, the only existing input for whale vertical distributions is based on the Continental Shelf Associates (CSA) Ocean Sciences report to the Bureau of Ocean Energy Management (Barkaszi et al. 2021). The input includes different estimates of the whale vertical distributions given its different activities, including foraging, migrating, or calf rearing (Table 4). While this is a regional and monthly product, the vertical distributions within a behavior do not change seasonally or spatially. However, an "ensemble" model is also included which changes the weighting of the 3 behaviors seasonally and spatially (e.g., foraging, migrating, calf rearing) and is currently used as the default for DST model runs.

As the application of this product was built for modeling vessel strike probability, vertical distributions are supplied for <10 m, 10-20 m, and 20+ m depth bins. Thus, for the DST, relative proportions below 20 m are distributed evenly through the remaining water column. At this time, the vertical distribution of a whale in the water column does not impact the likelihood that it encounters different portions of the vertical line. Rather, it is used to estimate the encounter rates for whales and ground gear relative to vertical lines. Ground gear is not accounted for in trap/pot fisheries, but gillnet fisheries do contribute ground gear risk, which would vary with the change in the vertical distribution of whales and dimensions of the net panels.

2.7 Whale Dimensions

For modeling the encounter probability of horizontal lines (net panels) relative to vertical lines, the DST model requires cross-sectional dimensions for a representative right whale. We used information and methodology described in Christiansen et al. (2020) as a guide to compute right whale dimensions for the DST model. Based on a digitized aerial photograph of a right whale from Christiansen et al. (2020), we extracted different relative morphometrics for right whales (i.e., fluke length, body width, and total body length) using the measure tool in Adobe Illustrator (v2.5.2.1; Figure 21). Based on the ratios of extracted measurements to the length of the individual whale in the image, we calculated scalar values for maximum body depth (sagittal plane) and width (transverse plane), including the fluke and flippers.

Since 1990, the average total body length of right whales has decreased (Christiansen et al. 2020). To reflect this change in the model, we set the total body length to 10 m, the estimated current length of right whales (Christiansen et al. 2020). We then used the proportions computed from the photogrammetry measurements to calculate the size of the remaining body segments (e.g., fluke length, body diameter). For these calculations, we incorporated a circular cross section for the body of a right whale and a 120° insertion angle of the flippers (Figure 22).

To calculate the total height of space occupied by a right whale (body and flippers), we used the side proportions of an isosceles triangle with the hypotenuse as the sum of the body radius (105 cm) and flipper length (120 cm). This resulted in a total height occupied by a right whale of 218 cm and width of 380 cm.

3. MODEL STRUCTURE AND FUNCTION

The DST quantifies risk as the geographic overlap of fixed gear from fisheries (primarily vertical lines for trap/pot but includes horizontal nets for gillnet) and whale density, with an added allowance for varying levels of threat associated with different gear configurations. The basis of the model is that

$$Risk_{c,m} = Whales_{c,m} \times Gear\ Density_{c,m} \times Gear\ Threat_{c,m}$$

where *c* and *m* denote a DST cell and month, respectively. Risk is calculated for each cell *c* and month *m* and summed across all months and cells. The DST was developed in the R language, written as a function that is called from a separate script file where the user is able to specify inputs and configurations for a model run. The DST has a modular design, consisting of various inputs including fishery effort and gear configurations, whale density, and whale vertical distribution, with a number of submodels that are used within a model run to perform necessary calculations and transformations. These inputs and submodels are built outside the DST function and can be readily substituted for alternative inputs and submodels at the time the model is run. The DST function operates as a deterministic series of calculations with all parameter estimation occurring outside the tool in submodels that have been previously constructed. Flow of information is one-way, as shown in Figure 23. Fishery inputs developed for gillnet and trap/pot fisheries in state and federal waters from Maine to Florida are used to define the initial density by location and month.

3.1 Model Inputs and Setup

Details of the structure and function of DST input files are described in Section 2, though a brief summary of each of those files is described here.

A. Fishery Layer – Fishery input file including the following data for all modeled fisheries:

   a. Gear Map – Amount of gear fished for each modeled fishery at each index location (cell) of the DST MapRef by month.
   b. Line Strength Model – Distribution of rope strengths estimated for each fishery vessel.
   c. Cumulative Effort Distribution – Distribution of total traps fished, total lines fished, and soak time fished for each fishery, month, and area.
   d. Gear Per String Model – Summary of gear configurations for each fishery, vessel, and month. Includes number of traps/nets per string, gear height, and gear length.
   e. Endlines Per String – Number of gear units that can be fished on a string with a single endline for each fishery and area.

B. Threat Model – Model describing mortality/serious injury threat to an entangled whale based on rope strength (currently exists for NARWs and humpback whales).
C. Whale Map – Whale spatial density model describing estimated density of whales in each cell of the DST by month.
D. Vertical Distribution – Model describing distribution of NARWs within the water column (currently exists only for NARWs).
E. Input Actions – List of inputs describing management actions to be applied to the fishery layer.

3.2 Running a Scenario

The DST imports and assesses the inputs described to generate initial characteristics of gear distribution and configuration, and then modifies those characteristics according to the specified scenario actions. The DST assesses and modifies gear in a stepwise fashion to account for all previous scenario actions as it generates the full landscape of risk associated with a scenario run. Where applicable, each of the following sections introduces how the inputs generated above are incorporated into the model followed by how those inputs can be modified in a scenario run.

Management actions are frequently intended for particular fisheries, areas, and months rather than for application throughout the entirety of the DST spatial domain and fisheries. For each management measure tested in a scenario, the users can supply any combination of the following constraints.

1. Spatial Constraints:

    1.1. Region
    1.2. State
    1.3. State or Federal Waters
    1.4. Statistical Reporting Area
    1.5. Lobster Management Area
    1.6. Shapefile
    1.7. Depth
    1.8. Distance from Shore

2. Time Constraints:

    2.1. Month

3. Fishery Constraints:

    3.1. State or Federal Waters
    3.2. Individual Fishery (e.g., Monkfish/Skate in New Jersey State Waters)
    3.3. Fishery and Gear Type (i.e., lobster, other trap/pot, gillnet)

3.2.1 Constraining the Model and Management Measures

Measures can be combined to construct more precise constraints on management actions. This can be especially useful for subsetting spatial areas. For example, combining distance from shore or depth gradients within a region, state, or management area can offer a more practical or precise application of a management measure. Measures can include constraints on the spatial extent and fisheries included in the model run or management measures to be assessed in the model run, each of which themselves can be constrained spatially or to specified fisheries. Spatial constraints on measures are applied to the MapRef object and thus can be specified by Region, State, LMA, SRA, distances from shore, depth ranges, or within the extent of a polygon shapefile. Similarly, specific constraints by fishery input group can also be applied. Multiple constraints can be applied to individual measures to accomplish the finest detail both spatially, temporally, and specific to gear type or fishery. Scenarios can also be analyzed on different spatial or fishery scales or to understand relative risk in a specific region or within a specific fishery.

Because these measures often interact, modifying the same fishing effort multiple times through a model run, the order that the measures are enacted matters. This order of implementing measures aligns with the model progression, first tracking gear units (traps or net panels) and strings of traps or panels, to quantifying endlines and gillnet headropes (to calculate co-occurrence), then applying strength of lines to determine gear threat and finally entanglement risk.

3.2.2 Gear Density and Distribution

Gear density is generated for each fishery, month, area, and vessel during input development. Once the domain of the model (i.e., the spatial extent and included fisheries) is set, the first set of actions in the DST involve modifying gear density according to the specified management actions. Gear density is affected by 4 optional management actions: gear reduction, gear caps, closures, and soak limits.

3.2.2.1 Gear Reductions

Gear reductions are a management measure where traps or net panels are simply removed from active fishing, either seasonally or year-round. This is most often used in association with a closure where the gear is expected to be removed from the water rather than redistributed into adjacent areas, but it is also applicable where fishing effort is being reduced through management action or other unspecified process. Spatial, temporal, and fishery criteria are used to identify the set of fishing gear affected by the measure, and the percentage specified for the measure is multiplied by the effort at each location to calculate the amount of effort removed from the model.

The following example demonstrates the functional difference between applying a gear reduction versus a closure. In Figure 24, two example scenarios are shown. The first demonstrates a 100% gear reduction imposed for the South Island Restricted Area (SIRA) year-round, meaning that all gear is removed rather than displaced. Removing gear from SIRA year-round results in a total of 1% reduction in gear relative to all fixed-gear coastwide, 4% reduction in co-occurrence, and 6% reduction in risk. In the second example scenario, instead of removing the gear, the SIRA closure is applied as a true closure where gear is redistributed to adjacent areas, the impact of the closure changes. In this example, 100% of the gear displaced by the year-long SIRA closure is relocated to neighboring cells, resulting in a 0% reduction in gear coastwide. The displacement of the gear from SIRA results in a 3% reduction in co-occurrence and a 3% reduction in risk. The higher percent reduction in co-occurrence and risk is achieved relative to the amount of gear removed or moved highlights the importance of removing or moving gear outside of this closure area, but greater risk reduction is generally achieved when gear is removed from a closure. When gear is moved, it is still likely to be in an area that can co-occur with whales, and therefore pose an entanglement risk, and additional care has to be taken to minimize movement of gear to areas with equal or greater risk than inside the desired closure. When translating management actions into DST scenarios, it is important to consider realized outcomes of an action based on anticipated fishery behaviors of either removing gear from the water or relocating gear outside of the closure areas. With additional data on the expected response to a closure, it is also possible to estimate risk reduction in a scenario where a mix of gear removal and relocation are expected.

3.2.2.2 Gear Caps

Gear caps operate by lowering the maximum number of traps or nets that individual fishers are allowed to fish. The submodel for gear caps is built from VTRs where fishers have reported the total amount of gear (traps or nets) being actively fished per license and month. Gear cap measures are assessed for each fishery, area (e.g., SRAs, LMAs), and month based on the cumulative quantile curve described in Section 2.2.6. To get the estimated reduction in gear density, we first take each cumulative curve and truncate all values above the gear cap measure to the specified new level (Figure 25). We then calculate the proportional reduction from a measure as the sum under this truncated cumulative curve, divided by the sum under the original, non-truncated curve, and multiplied by any percentage specified as part of the measure.

$$Updated\ Gear\ Fished_{(a,m,f)} = Gear\ Fished_{(a,m,f)} \times \left(\frac{Gear\ Cap\ Truncated_{(a,mf)}}{Gear\ Effort\ Original_{(a,mf)}}\right)$$

Depending on the distribution of vessels fishing above the gear cap, this measure may reduce fishing effort, with resulting decreases in co-occurrence and risk. The magnitude of co-occurrence and risk reduction will depend on the distribution of vessels fishing above the implemented gear cap and where and when that affected fishing effort occurs. To demonstrate this, 2 examples of gear caps are shown for a given fishery. In the first example, a gear cap of 200 traps is applied to the fishery, while in the second example, a gear cap of 50 traps is applied. The gear cap of 200 produces no co-occurrence and no risk reduction because the current amount of gear being fished is below this scenario gear cap (Table 5). Therefore, no vessels are fishing above 200 traps, and there is no reduction in gear, co-occurrence, or risk associated with this measure. However, when the gear is capped at 50 traps, the gear, co-occurrence, and risk decrease by approximately the same magnitude, 37%. Note, the fishery used in this example fishes single endlines attached to single traps, which is why all 3 of these variables decrease by approximately the same proportion. The magnitude of this reduction relates to what proportion of the fishery fishes more than 50 traps and how many more than 50 traps that subset of the fishery is fishing.

If a gear reduction measure is applied to a fishery, area, and location that is also affected by a gear cap measure, the gear reduction changes the underlying effort distribution and the gear cap measure would overestimate the associated effort reduction. To address this potential bias, the effort distributions are corrected in the model by the proportion of effort removed by the prior gear reduction measure(s) before any gear cap measure is applied.

3.2.2.3 Closures

Alternative to gear reductions, closures remove gear from an area but allow that gear to relocate to adjacent cells where that fishery is also operable. Closures can be specified using any of the spatial constraints available to DST actions, as well as applied to individual fisheries or months. Because the DST operates in monthly time blocks, if a closure is intended to apply for only a portion of a month, a percentage can be applied to the closure action.

Implementing closures happens in two steps within the DST. First, the spatial and fishery constraints for all measures in the model run are assessed to find the set of all fisheries and cells that are unaffected by closure measures. This is a necessary first step to prevent gear from one closure being redistributed into another area that will be closed by a subsequent measure. Second, each of the measures is individually implemented, and the affected gear is redistributed into adjacent areas when possible.

For an adjacent area to qualify as an option for relocation, the fishery from which the gear is being relocated must also be active and present in the adjacent area. In addition, the model receives an input that constrains the set of areas that gear can be moved to for a given source area. This allows some additional control of how redistribution occurs, allowing some tuning of which adjacent areas are available to gear redistribution to follow likely fishing behavior following a management action and to speed computing time. For example, state-fishery gear can be restricted to move within state waters, while federal-fishery gear can move to adjacent state or federal waters depending on the permitting. Similarly, gear in the Maine lobster fishery cannot move beyond the immediately adjacent lobster zones to reflect management rules on how much gear can be fished outside a fisher’s permitted zone. For lobster gear in offshore LMA 3, coastwide other trap/pot, and gillnet, each SRA has a pre-identified set of adjacent SRAs that were determined to be within a reasonable neighboring distance.

When multiple cells are available for the gear to relocate, as is typically the case, the DST performs a simple benefit-cost analysis where the benefit is the presumed catch rates associated with fishing at the new location and the cost is related to the distance gear has to be moved. Because the catch rates and other factors that make fishing more or less viable at another location are not easily derived, the DST uses the known distribution of fishing effort by the same fishery outside the closure as a proxy for the benefit of fishing that location. Thus, the benefit of moving gear to another location is directly proportional to the density of gear already at a location. At this time, the model does not place any limits on the amount of gear that can be fished in a cell, so crowding of gear is not accounted for in this calculation.

The cost of moving gear from a cell inside the closure *i* to any adjacent cell outside the closure *j* is calculated as a function of the distance between cells with a relocation cost exponent *RCE*.

$$Cost\ OfMovement_{(i,j)} = Distance_{(i,j)}^{RCE}$$

The exponent *RCE*, is a user-specified input that can be used to skew the cost values to affect the redistribution patterns. The *RCE* defaults to 1, which makes cost a linear function of distance; every mile that gear has to be moved costs the same as the previous mile or next mile (Figure 26). However, an *RCE* > 1 would make it disproportionately expensive to move gear longer distances, effectively causing relocated gear to further accumulate around the periphery of a closure (Figure 27). An *RCE* < 1 makes it marginally less expensive to move gear incrementally further such that an *RCE* = 0 would distribute displaced effort directly proportional to the distribution of all gear outside the closure independent of distance from the closure.

This benefit:cost ratio is then used as a proxy for the appropriateness of moving gear to a given location outside of the closure. The total amount of gear redistributed from cell *i* to a new cell *j* is then calculated as the amount of gear in cell *i* multiplied by the tradeoff for moving gear where *n* is the number of adjacent cells where gear may be moved.

$$Gear\ Redistributed_{(i,j)} = Gear\ Fished_{\ (i)} \times \frac{Benefit{:}\,Cost_{\ (i,j)}}{\sum_{j=1}^{n} Benefit{:}\,Cost_{\ (i,j)}}$$

If no adjacent cells are available for the gear to redistribute, the gear is removed from the model and recorded accordingly.

While this methodology attempts the redistribution of gear from a closure, the actual industry response is likely to be more complex and nuanced depending on type of fishery, permitting, duration of closure, and availability of alternatives. If a closure is identified as a potential management option, stakeholder input is necessary to validate or modify the DST estimation of gear relocation or removal.

3.2.2.4 Soak Limits

Effort reductions from soak limit measures are calculated in much the same way as gear caps by lowering the maximum soak duration for a specified fishery or area. Unlike other methods of gear removal, managing soak times may not be a realistic management strategy to generate risk reduction across all fisheries. Soak limits may be more applicable to fisheries where gear is deployed and removed at the end of a trip, rather than fisheries where gear is set, checked, and reset. Soak limits are applied using the soak time cumulative effort quantiles provided in the fishery input layer. An example of these for a trap/pot fishery in the Mid-Atlantic is provided in Figure 28. Spatial, temporal, and fishery criteria are used to identify the set of trips affected by the soak limit measure. If the measure is only supposed to impact a percentage of the fishery, this can be specified, otherwise the default assumption is that it is applied to 100% of the fishery. The percentage of the fishery specified for the measure is multiplied by the proportion of effort in each month with longer soak durations than the imposed measure. The change in soak duration is then used to recalculate the gear fished metric in each cell *c*, month m, and fishery f, multiplying it by the fraction of the truncated soak effort distribution to the original soak effort distribution.

$$Updated\ Gear\ Fished_{(c,a,m,f)} = Gear\ Fished_{(c,a,m,f)} \times \left(\frac{Soak\ Effort\ Truncated_{(a,m,f)}}{Soak\ Effort\ Original_{(a,m,f)}}\right)$$

Note the soak limit can only be used to decrease the soak duration, and applying a value greater than that described by any soak limit quantiles for a fishery and area will result in no change. Using Figure 28 as an example where a 24-hour soak limit was imposed, the proportion of trips that would be unaffected by implementing a 24-hour soak limit can be calculated as the area under the quantile curve below 4 divided by the total area under the quantile curve. This method assumes that all other trip attributes, including distribution of traps, remain constant, while only the duration of the trips—and thus the amount of time that gear is deployed in the water—is reduced.

Depending on the distribution of trips that extend beyond the soak limit, this measure offers a mechanism for co-occurrence and risk reduction as the gear fished metric is estimated for a fishery and area over the course of a given month. Table 6 shows an example of imposing a 24-hour soak limit resulting in a 20% reduction in gear, co-occurrence, and risk. Note, however, that reduction in gear, co-occurrence, and risk are not always proportional, as the reduction will depend on the overlap of gear affected by a soak limit measure with timing and distribution of whales.

Unlike gear caps measures, the impacts of soak limit measures are unaffected by effort reduction measures that are applied earlier in the DST model. As a result, bias-correction in soak limit distributions are not required when other measures produce effort reductions that are applied to the same fishery, area, and month.

3.2.3 Calculation of String Densities from Gear Densities and Gear Configurations

During input development, a gear per string metric (the number of traps or nets per string/trawl) is generated for each fishery *f*, vessel *v*, and month *m*. The amount of gear (traps or nets) within each cell *c* is translated into the number of strings using gear per string derived during input development.

$$Strings_{f,m,v,c} = \frac{Gear_{f,m,v,c}}{Gear\ Per\ String_{f,m,v}}$$

3.2.3.1 Modifying String Lengths

Strings can be modified by specifying the number of traps or nets that can be fished per trawl/string. The fishery input layer provides a gear per string metric (the number of traps or nets per trawl/string) for each fishery, vessel, and month. Once gear reductions, closures, gear caps, and soak limits have been imposed, the remaining strings (or trawls) can be modified according to a minimum, maximum, or exact number of gear units to be fished on each string. Additionally, it is possible to request that string length be increased or decreased by a proportion. Modifying string length can act as a peripheral method to limit the number of vertical endlines by assigning a minimum number of gear that must be fished per string. Assuming that a fishery has a limited number of traps or nets per permit and increasing string length does not stimulate activity for unfished gear by increasing the number of traps per string required by management, those traps will be divided up into larger strings. Larger strings with a limited number of total permitted gear begets fewer total strings and subsequently fewer total vertical endlines. Figure 29 shows the distribution of gear per string in a group of trap/pot fisheries in the mid- and South Atlantic.

Suppose that a scenario is run applying a minimum gear per string of 5 traps per trawl. All of the fishery, vessel, and month combinations with fewer than 5 traps per trawl will then be modified to accommodate this minimum. To illustrate this we consider applying this string length action to a trap/pot fishery fishing singles (1 endline attached to 1 trap) with a total of 20 pots. In the baseline fishery layer, this vessel would be associated with 20 pots and 20 endlines. During this scenario run, the trawls are modified from single-trap trawls to 5-trap trawls, meaning that instead of fishing 20 endlines, the vessel is now fishing 8 total endlines on 4 trawls with 5 traps and 2 endlines per trawl. When this gear per string modification is expanded to the fisheries represented in Figure 29, the number of vertical lines is reduced by 58%, resulting in a 43% reduction in co-occurrence and a 36% reduction in risk. Note that while the model demonstrates endline reduction with this trawl-up measure, understanding the region- and fishery-specific dimensions behind trawl length is important. Accounting for what is realistic in each fishery and area is important to properly applying management actions in the DST framework.

Additionally, increasing string length presumably increases the needed strength of endlines to haul the gear (Willse et al. 2022). Thus, “trawling-up” measures may result in a risk tradeoff with fishers using stronger endlines that are potentially more dangerous in entanglement situations. The model allows for tracking changes in endline strength of redistributed gear by including a user-specified option to either recalculate endline strengths in response to changing trawl lengths or model a scenario in which fishers continue using the same endline strength value before and after the evaluated management action

3.2.4 Calculation of Endline Densities from String Densities and Gear Configurations

During input development, an endlines per string metric (the maximum number of traps or nets that can be fished with a single endline) is generated for each fishery, vessel, and month. Using this, the amount of gear on each string can then be used to determine if individual strings are associated with 1 or 2 endlines based on the maximum number of gear per single endline determined for each fishery and vessel in the endlines per string input.

3.2.4.1 Modifying Endline per String

Once the gear per string is calculated and potentially modified by management measures, additional measures can be specified to affect the number of endlines associated with a string. As discussed above, the endlines per string fishery input specifies the baseline maximum number of gear associated with a single endline for each fishery and area. The DST allows a measure that specifies a new maximum number of gear fished on a string with only 1 endline, in which case the model identifies the strings that previously had 2 endlines but would now have only 1 endline and recalculates total endlines accordingly.

3.2.4.2 Line Caps

Line caps are modeled in much the same way as gear caps and soak limits, using the cumulative effort output in the fishery layer where the estimated reduction in line density is visualized by truncating all values above the line cap in the cumulative line effort curve (Figure 30). We then calculate the proportional reduction from a measure as the sum under this truncated cumulative curve, divided by the sum under the original, untruncated curve, and multiplied by any percentage specified as part of the measure.

$$Updated\ Lines\ Fished_{(a,m,f)} \ = \ Lines\ Fished_{(a,m,f)} \times (\frac{LineCapTr_{(a,mf)}}{LineEffortOrig_{(a,mf)}})$$

In our example fishery, only about 20% of the fishery fishes more than 80 lines in January, while from July through October—the peak season for the fishery—closer to 75% of the fishery is fishing more than 80 lines. This seasonal variability in the line effort translates into the line reduction estimated from imposing a line cap of 80 lines (Table 7). Imposing this line cap in January produces only a 10% line reduction, while in August, the line cap generates a 25% reduction. In total, this line cap generates a 21% reduction in co-occurrence and risk posed by this fishery subset year-round.

Like gear cap measures, line cap distributions need to be corrected if prior measures in the DST (gear reductions, gear caps, and trawl length measures) reduce effort in fisheries, areas, and months that overlap the line cap measure. Similarly, as the effort reduction in these prior measures are calculated, the associated percent effort reductions are applied to the line cap distributions as bias-corrections such that line cap measures are more likely to accurately depict the effort reduction associated with these measures.

3.2.4.3 Calculation of Ground Gear Encounter Rates and Endline Equivalents

Starting with DST v3.4.0, the model allows for assessment of risk of ground gear (net panels and trap groundlines), quantifying these areas of entanglement risk on a similar equivalent to that of vertical lines in the model (Figure 31). Because the DST calculates the relative risk associated with fishing gear, rather than actual encounter probability, we use the whale vertical distribution model, gear dimensions, and whale dimensions to calculate the probability that a whale will encounter the ground gear relative to the vertical line and use the ratio of the two to convert ground gear encounters into vertical line equivalents. To get this ratio, we calculate an encounter space around both the ground gear and vertical line.

To get the encounter space associated with the ground gear, we calculate vertical and horizontal exposure components separately. The vertical exposure of gear to the whale is calculated from the ground gear height and body depth of a representative whale. For trap/pot fisheries, we typically default to a gear height of 0 due to the mandate of sinking groundlines in US fisheries, essentially making the encounter space for trap/pot groundlines zero. However, a non-zero value could be included for trap/pot fishery inputs to assess the risk associated with groundlines between pots, in which case the following calculations similar to net panels would apply.

For anchored gill nets, the portion of the net that is greater than a whale height is considered completely exposed to a whale as all portions of a whale could encounter this portion of the gear. However, where portions of the gear are less than a whale height from the top or bottom of the water column, exposure decreases linearly until exposure reaches 0 at the ocean bottom (Figure

32) or surface. Thus, where net height is less than whale body depth, the vertical exposure is the product of the net height and half the ratio of net height to whale body depths.

$$Vertical\ Exposure_{(c,f,m)} = Net\ Height_{(c,f,m)} \times \frac{Net\ Height_{(c,f,m)}}{2\ \times\ Whale\ Height}$$

If gear height is equal to whale body depth, this simplifies to:

$$Vertical\ Exposure_{(c,f,m)}\ =\ \frac{1}{2} \times\ Whale\ Height$$

and where gear height is more than whale body depth:

$$Vertical\ Exposure_{(c,f,m)}\ =\ \frac{1}{2} \times\ Whale\ Height\ +\ (Net\ Height_{(c,f,m)}\ - Whale\ Height)$$

for cell c, fishery f and month m.

The horizontal exposure of the gear is based on the number of net panels in a string and the length of each net panel. An adjustment factor of 0.6 is applied as the mean value of the sine function over 0 to 90 degrees to incorporate whale encounters at a random angle in the horizontal plane. Thus,

$$\begin{aligned} &Horizontal\ Exposure_{(c,f,m)} \\ &\quad =\ 0.6\ \times\ Net\ Panel\ Length\ _{(c,f,m)} \times Number\ of\ Panels\ Per\ String_{(c,f,m)} \end{aligned}$$

and total exposure or the encounter space of the gillnet is calculated as:

$$\begin{aligned} &Gillnet\ Encounter\ Space \\ &\quad =\ Vertical\ Exposure_{(i,f,m)}\ \times Horizontal\ Exposure_{(c,f,m)} \\ &\quad \times Whale\ Presence_{(c,m,o,h)} \end{aligned}$$

where $Whale\ Presence_{(i,m,o,h)}$ is the summed proportion of whale presence in cell i for month m between the ocean bottom (o) and the top of the gillnet (h), as drawn from the whale vertical distribution input.

Endline encounter space is simply calculated as the product of the water depth and the width of a representative whale.

With these 2 encounter spaces, we can calculate the probability that a whale encounters the net panels relative to the probability that a whale encounters the endline, or an equivalency between net panels and endlines as:

$$EndlineEquivalents\ =\ \frac{GillnetEncounterSpace}{(2\ \times\ EndlineEncounterSpace)}$$

which assumes 2 endlines on each gillnet string. In this way, endline equivalents can be multiplied by the number of gillnet strings in a cell and added to the model as equivalent endlines but are recorded as horizontal gear with their associated breaking strengths.

Prior to calculating ground gear encounter rates, the model allows for implementation of net height management measures. This allows for the height of gillnets to be shortened, thus decreasing the vertical exposure of the gear to whales and, presumably, decreasing the encounter space. Because the portion of the net that is below whale body height is not treated as fully exposed to whales, these net height reductions will have a nonlinear relationship to vertical exposure and encounter space (i.e., decreasing net height by half will decrease encounter space by more than half because the most exposed portion of the net has been removed).

The calculations of co-occurrence and risk associated with ground gear can be turned off through a user-supplied switch to the model, allowing users to select if risk associated with ground gear should be assessed in the model run. If ground gear risk is assessed in the model run, an additional user-supplied switch, provides separate model outputs for vertical vs. horizontal lines for the remaining stages of the model including vertical line equivalents, line strengths, gear threats, co-occurrence, and risk so the relative contribution of the 2 gear components can be compared.

3.2.5 Apply Strengths to Vertical and Horizontal Lines

Once ground gear is accounted for and translated into vertical line equivalents, the number of vertical lines or line equivalents are merged with the distribution of line strengths (i.e., proportion of lines at individual rope strengths) associated with that fishery and gear type as provided in the fishery input. This produces the number of endlines at a given strength.

3.2.5.1 Modifying Line Strengths

Maximum vertical line strength or maximum horizontal line strength measures can be applied to simulate the implementation of weak rope measures in buoy lines and gillnet headrope lines, respectively. Because the model tracks distribution of rope strengths for each endline, implementing these measures acts to truncate rope strength distributions to the supplied maximum rope strength (Figure 33). Such weak rope measures can be applied to a percentage of lines if either a portion of a rope or 1 of 2 endlines would be weakened by the measure, in which case only the specified percentage of lines above the target strength are truncated to the target strength. Note that this necessarily assumes that lines weaker than the target are not inadvertently strengthened to the new target. This assumption is probably valid for cases where weak inserts are being added to existing lines but may be biased for cases where fishers are replacing aging lines with new “weak” ropes.

3.2.6 Calculating Threat

The empirical gear threat model in the DST evaluates the factors that contribute to complex outcomes for entanglement events. Many entanglements, including mortality or serious injury events, go unobserved, and the gear type, fishery, and/or country of origin for reported entanglement events are often not traceable (Henry et al. 2016, Henry et al. 2022).

There is limited data connecting gear characteristics and entanglement circumstances to probable entanglement outcomes. To date, the best gear threat models rely on rope strength of individual endlines. Gear with higher breaking strength is expected to be more risky to whales because it is harder to break and therefore more likely to result in mortality or serious injury. A gear threat model was built using empirical information on the strength of ropes involved in serious whale entanglements and how the strength of the ropes observed in entanglements compares to the strength of ropes that whales would be expected to encounter.

Data on the distribution of rope strength observed in entanglements comes from Knowlton et al. (2016), subset to entanglements judged to represent serious injury cases. To get the distribution of rope strengths we expected whales to encounter, we used model runs of the DST, for both right whales and humpbacks, and extracted the densities and strength of endlines with co-located densities of whales (Section 2.5). We then took the product of the numbers of ropes for each strength interval and whale density by location and summed across locations to get the relative proportion of each rope strength, by species, that whales would be expected to encounter (Figure 34). For both right and humpback whales, there is some evidence of heavier ropes being more common in entanglement events than expected from encounter rates (Figures 35 and 36). However, both sets of profiles also have higher than expected proportions of entanglements in the lightest ropes and lower than expected proportions in intermediate-weight ropes.

We use the ratio of the two sets of proportions (observed vs. encountered) as a proxy for the threat associated with ropes of a given strength. For example, if a rope of a given strength is observed in entanglements twice as often as would be expected, we interpret this as being twice as lethal as a rope that is observed in proportion to the expected encounter rate.

For model fitting, we aggregated rope strengths to 500 lb. intervals and truncated all data below 1,250 lb. and above 5,250 lb. strengths, with values outside these bounds added to the nearest bin to reduce the sensitivity of ratios to very low numbers in denominators. We then bootstrapped the observed rope strength distribution 100 times, calculated observed-to-expected ratios, and rescaled the data to have all ratios less than 1. We then combined the data sets and fit a binomial generalized linear model (GLM) with separate intercepts for the two species. The resulting GLM model was then back-transformed to the original scale of the data and plotted over the bootstrapped data sets (Figure 37). The trendlines for both species increase with rope strength, reiterating that threat increases with rope strength. Some lack-of-fit to the models with apparent threat being over-estimated at intermediate rope strengths and underestimated at higher rope strengths, indicates an artifact in the derived data sets or misspecification of the statistical model. Despite this, we judge this to be the best candidate method for deriving an empirical threat index based on rope strength, providing a threat score for any given rope strength.

Given the issues with lack of model fit, we used the above bootstrapping method to further develop estimates of uncertainty or instability of models around the relationship between observed and expected rope strength distributions. The goal of this approach is to define a reasonable upper and lower bound on how rope threat, calculated from the selectivity ratios, changes with rope strength.

Rather than using bootstrapping to define the range in selectivity ratios predicted for a given rope strength, it is more appropriate to quantify uncertainty from the range of models produced by the bootstrapping exercise (Figure 38). As expected, model parameters (intercept, slope, and species interaction) are highly correlated, particularly slope and intercept. A principal components analysis of the parameter estimates suggests that >90% of variability in parameters can be explained by the first principal component, which correlates strongly with slope parameters (Figure 39). Thus, we define median, lower, and upper bounds on the model estimates as the models from the 0.5, 0.025, and 0.975 quantiles of the first principal component (Figure 40). These upper and lower bounds correspond with expected limits on how steep the relationship is between rope strength and gear threat, which also provide limits on the relative benefits of decreasing entanglement risk by changing rope strength. While the curve representing the lower bound has higher threat scores than the other two curves for ropes less than ~6,000 lbs. breaking strength, it is important to recognize that the relative threat score between any two rope strengths defines actual entanglement threat, not absolute individual values. Thus, it is informative to plot the ratios of combinations of values for each curve to understand the inferred threat reductions (Figures 41-43). Similarly, it is useful to examine individual profiles for each threat curve at a given target rope-breaking strength, like 1,700 lb. (Figure 44). For example, changing from rope with 3,100 lb. breaking strength to 1,700 lb. breaking strength, results in a 50% reduction in risk predicted from the median model. The upper bound curve predicts a 50% reduction in risk switching from 2,600 lb. rope to 1,700 lb. and a 75% reduction switching from 3,400 lb. rope. Conversely, the lower bound curve predicts that 50% reduction does not occur within the domain of the model when changing from 10,000 lb. rope to 1,700 lb. rope, which results in only a 38% reduction in risk.

The three curves in Figure 44 were implemented as alternative threat models in the DST since version 2.1. Thus, the current model has the option to produce output results and risk scores for all three threat models as well as a co-occurrence model where all ropes have equal threat, providing a range of outcomes given the uncertainty in the threat model.

3.2.7 Calculating Co-Occurrence and Risk

Once the threat of each individual line is calculated for a fishery, location, and month, total lines and threat scores can be summed across all fisheries within a cell and month to get total threat and vertical line densities. These time/location-specific densities are then merged with estimated whale densities to get time/location-specific co-occurrence and risk scores, respectively.

3.2.8 Baseline Risk of East Coast Fishery Layers

Combining all of the individual fishery input layers into one that covers the U.S. East Coast provides a baseline map of the seasonal densities of all fixed-gear fishing. This baseline provides a starting point, identifying areas where co-occurrence of fishing gear and whales are high as well as where risk reduction might be critical for reducing whale entanglements. It also allows for a geographic and fishery specific evaluation of the relative entanglement risk posed to whales. Coastwide, the greatest amount of co-occurrence and risk remains in GOM and SNE (Figure 45 and Figure 46). While seasonal variability is visible, areas of high risk are generally consistent throughout the year in these regions. Areas in the SE where little or no risk appears present are largely due to management measures already in place protecting marine mammals from fishing gear and seasonal absence outside of winter and spring calving.

The federal lobster fishery in the Northeast Region makes up the vast majority of coastwide risk (Table 8), though the distinction between state and federal lobster fisheries is based on the permit type rather than if fishing occurs within state or federal waters. Any state and federal permitted vessels would be classified as part of the federal fishery when allocating gear to adjacent cells during scenario runs. The federal fishery fishes 40% fewer lines than the state fishery because of longer trawl requirements in federal waters. Despite fewer lines, the co-occurrence in the federal fishery is more than double the state fishery (Figure 46), and risk in the federal fishery is more than three times higher than the state fishery. Rope strength is a compounding factor in quantifying the risk of federal fisheries within the threat model and contributes increased risk disproportionate to the increase in co-occurrence. Meanwhile, the state lobster fishery utilizes more vertical lines than any other fishery combined. In reference to the Northeast lobster and Jonah crab fishery as a whole, other U.S. commercial trap/pot and gillnet fisheries under the Plan account for approximately 6% of the baseline coastwide risk, ~3.6% from gillnet and ~2.7% from other trap/pot.

3.2.9 Combining Measures

Each model stage from gear reductions through implementation of weak rope is consecutive, building on the previous action. As a result, the eventual change in co-occurrence and overall risk at the end of a scenario run represents the collective sum of those actions and is not necessarily an additive representation of the individual measures. As a simple example, suppose 100% of a trap/pot fishery fishes 5 traps per trawl and each trawl is fished with 2 endlines. Assuming whales are evenly distributed throughout the spatial extent of this example fishery, 50% co-occurrence and risk reduction could be achieved for this fishery using modifications to increase string length (traps per trawl) or reduce endlines. If string length is modified from 5 to 10, then a fisher fishing 20 traps would reduce the number of vertical lines fished from 8 to 4, a 50% reduction. Similarly, if instead of modifying the number of traps per trawl, the number of endlines per trawl are reduced from 2 endlines per trawl to 1 endline per trawl, a fisher fishing 20 traps would reduce the number of vertical lines fished from 8 to 4. A scenario including both actions (increasing traps per trawl and decreasing endlines per trawl) does not result in 100% reduction in risk or co-occurrence. If both measures were modeled in conjunction, a fisher fishing 20 traps at 10 traps per trawl and 1 endline per trawl would now fish with a total of 2 endlines rather than the original 8, resulting in a 75% reduction in risk. This example demonstrates the need to evaluate the contribution of individual measures as well as the interaction between measures as scenarios become more complex with each added action.

4. MODEL ILLUSTRATION & RESULTS

In September 2021, NMFS amended the Plan based on feedback from the ALWTRT to reduce entanglement risk for large whales, particularly right whales. The 2021 final rule (86 FR 51970, September 17, 2021) implemented a series of management measures in the Northeast Trap/Pot Management Area, including time/area closures, minimum trap per trawl requirements, use of weak endlines or inserts, and gear marking requirements. To illustrate how the DST functions, we will apply the 2021 final rule management actions (summarized in Table 9) to the baseline fishery layer (Table 8 and Figures 45-46) and discuss model outputs. Because of the wide range in fishing effort, right whale occurrence, and risk along the coast and between months, maps of model results (gear density, co-occurrence and risk) are shown in log-scale where appropriate. The 2021 final rule amendments only applied to the Northeast lobster and Jonah crab fisheries. Therefore, maps are subset to the GOM/Georges Bank and SNE regions where scenario actions occurred for increased visibility. However, because risk reduction remains a process along the entire east coast, model output tables reflect coastwide values. For visual references to the coastwide baseline gear density in the fishery layers, please refer to the maps in Figures 13 and 19. Results presented here are from a low-resolution model run conducted using v4.1.03 of the DST.

4.1 2021 Final Rule

The 2021 final rule included three closures. First, the 2021 final rule expanded the geographic extent of the existing Massachusetts Restricted Area (MRA) under the Plan to mirror the area included in the 2021 Massachusetts State Commercial Trap Gear Closure to Protect Right Whales (322 CMR 12.04(2)), extending restrictions north to the New Hampshire border (Figure 1). Expansion of the MRA into Massachusetts state waters is largely assumed to result in lines being removed from the water instead of relocated into federal waters because many state fishers do not have federal permits. The MRA is in place from February 1 through April 30, while the MA State Waters trap/pot closure implemented by Massachusetts Division of Marine Fisheries extends through May 15 with the option to open early on April 30 or extend to the end of May, depending on right whale sightings and copepod abundance. Therefore, the MRA gear reduction action in state waters is restricted in the scenario for the months of February through May, assuming no co-occurrence of whales and gear would occur during this month in this specific region due to state management measures. At the end of Stage 1 of the DST where closures are applied, annual coastwide gear density is reduced by 1.1%, with monthly coastwide gear reductions of 4.4% and 8.9% in April and May, respectively (Figure 47). It is important to note that these risk reduction estimates only represent the time and space added to the closure under the 2021 final rule and Massachusetts state regulations and does not include the value of the Massachusetts Restricted Area as it was implemented in 2015.

The remaining two closure actions are modeled as closures to evaluate risk outcomes from gear relocation (closure scenario) rather than gear removal from the water (gear reduction scenario). The LMA 1 Restricted Area is in place from October 1-January 31 (Figure 48). This action reallocates gear to surrounding cells. SIRA prohibits the use of buoy lines from February 1 - April 30 (Figure 49). SIRA spans federal waters of LMA 2, LMA 3 and the 2/3 overlap and a closure scenario similarly captures the probable federal fishery response to reallocate gear outside of the restricted area boundaries. A gear cap was also applied in Stage 1 to LMA 2 and the portion of LMA 3 within the Northeast Region to account for existing line reduction due to fishery management measures that took place during rulemaking.

The 2021 final rule also modified the minimum number of traps per trawl (i.e., trawl/string length) and number of traps per single endline based on distance from shore (Table 9). In some locations, different minimum trawl lengths were specified for trawls with one or two endlines, both of which would be expected to reach equivalent risk reduction; here those were analyzed as minimum trap per trawl requirements with two endlines unless otherwise specified (see 86 FR 51970 and NMFS 2021 for more details). The trawl-up measures ranged from a minimum of 2 traps per trawl in portions of Maine Zones C, D, and E to a minimum of 50 traps per trawl in the Georges Basin Restricted Area. Coastwide, the mean string length increased by 15% from 5.4 traps per trawl to 6.2 traps per trawl (Table 10 and Figure 50).

Gear reductions, closures, gear caps, and minimum traps per trawl measures are intended to translate into reductions in endlines. Gear reductions, closures, and gear caps account for only a 1.6% reduction in gear (traps); after accounting for string length measures, the total number of endlines is reduced by more than 10%. This reduction in endlines would suggest that if a permit holder is allotted a certain number of traps, by requiring those traps to be fished on longer trawls, there is an inherent reduction in the total number of trawls and endlines observed in the model results. One measure explicitly specified the use of a single endline with the new minimum trawl length in Maine Zone B from 3-6 miles (5 up from 3), requiring that lobster traps were to be fished with at least 5 traps per string, and the string must only have 1 endline. This was specified to avoid increasing the number of endlines on trawls from 1 to 2 according to previous restrictions on the maximum number of traps allowed to be fished with a single endline. A summary of these measures can be found in Figure 51.

Maximum rope strength measures were modeled during the scenario run. In total, the weak rope measures accounted for a mean coastwide reduction in line strength of 8% from 2,200 lbs. to 2,000 lbs. (Table 10 and Figure 52).

Reduction in co-occurrence is evident from February-April for SIRA, from October through January for the LMA 1 Restricted Area, and for various months throughout the year in Massachusetts state waters (Figure 53). The restricted area actions were the only measures not implemented year-round, making their boundaries visible in monthly mapping results.

Despite the reduction in co-occurrence from time/area closures, co-occurrence remains relatively high in adjacent areas as where fishing effort was reallocated (Figure 54). Co-occurrence is highest in locations where both whales are frequently present (SNE), and where gear density is high. Inshore waters of the GOM represent the latter where co-occurrence is high year-round due to high densities of lobster gear, particularly in the northeast areas of down east Maine.

Change in risk (Figure 55) due to the 2021 final rule measures and areas of remaining risk (Figure 56) show similar trends as remaining co-occurrence. Note that the reduction in risk is moderately higher than the reduction in co-occurrence from the 2021 final rule actions (Table 10). This demonstrates the implementation of weak rope measures where a rope has been weakened but continues to exist in the water column. Therefore, though risk is reduced because the rope is weaker and should pose less of a threat of serious injury or mortality to a whale if it becomes entangled, this measure does not reduce the co-occurrence or incidence of entanglements.

5. DISCUSSION

The DST has become a useful tool for managers and stakeholders as they work toward a goal of reducing entanglement threats to protected species like the NARW. The DST has grown in many ways since its original development and peer review, expanding spatially along the entire East Coast of the U.S., broadening its scope to include more fixed-gear fisheries under the Plan beyond NE lobster and Jonah crab, improving analytical methods to include more management measures, and incorporating state and stakeholder input throughout development to more accurately model the fisheries and possible fishery response behavior to management action.

One of the biggest improvements to the model is the addition of gillnet and other trap/pot fisheries, making the model the most comprehensive tool for quantifying relative large whale entanglement risk of fixed-gear fisheries along the U.S. East Coast and comparing estimates of the risk reduction achieved from different fishery management scenarios. In addition, the expansion of the DST to include individual fishery input layers can inform estimates for relative entanglement risk attributable to individual state and federal fisheries managed under the Plan, and thus, assessments of mortality and serious injury from these commercial fisheries. Developing multiple methods for gear distribution within our fishery inputs allows us to address the differences in trip report data without compromising precision where data collection is rich. Incorporating supplementary data from observers, as well as spending considerable time working with industry members and managers, helped improve the quality of the trip report data and produce more accurate fishery inputs.

While we have developed methods for modeling fishing effort through our fishery inputs, newer versions will become necessary over time as fisheries change and ocean use evolves with the development of offshore wind energy and aquaculture. Changes in species distributions and abundances, fleet dynamics, and economic factors will require regular updates to our fishery inputs as data becomes available. As data collection improves, including the implementation of advanced technology for vessel reporting and monitoring, we will be able to increase our spatial and temporal characterization of fishing effort within our fisheries inputs.

The addition of fixed-gear (i.e., gillnet and other trap/pot) fisheries beyond NE lobster and Jonah crab required modeling new areas of fixed-gear fishery risk and gear configurations. Gillnets pose an additional entanglement risk beyond that posed by vertical lines alone, including fishing nets and head rope that extend off the seafloor, so the DST was modified to account for this new source of risk. Net dimensions, mesh sizes, use of tie downs, and soak durations were key additions that differ by region and target fishery. Incorporating these details into the model inputs also increased the portfolio of management actions available to reduce risk, allowing users to put limits on gear heights and apply soak limits.

Our efforts to account for whale dimensions and their vertical distribution within the water column are a step toward improving how we model whale interactions with different types of fishing gear. Additional information on whale behavior and habitat use could inform how we model co-occurrence and improve the gear threat model. Similarly, our understanding of how various gillnet fisheries use the water column and different types of drift and surface gear will be important for considering different encounter risk among different gillnet fisheries. We continue to explore alternative, more refined vertical distribution modeling efforts that are currently being developed for future versions of the DST.

Modeling gear threat continues to be a high priority but also an area where we are most data limited. This is largely due to our inability to actively observe whales as they encounter fishing gear and become entangled. Given the reliance of the gear threat model on rope strength, obtaining more details from fishers about their gear configuration may be an initial step toward improving the data going into the gear threat model. Entanglement specialists may also provide relevant details on the gear recovered from entangled whales and from their observations in the field.

As the model is updated in the future, it is our goal to document these updates in as transparent a manner as possible. From an open data science perspective, we developed the DST to be a tool for the benefit of all stakeholders while recognizing that the data within its products presents data-privacy challenges that limit sharing some types of fishery information. Data confidentiality limits our ability to share the full product publicly without restriction, particularly when it could disclose confidential information as prohibited under Magnuson-Stevens Act. As we shift from model development to model maintenance, we plan to work toward having the model in a format that allows broader use while maintaining the integrity of fisheries data.

Results provided by the tool help inform the management process, but are not intended to be the sole basis of management decisions. They provide a semi-quantitative reference among other sources of information that can be used to evaluate different management measures and relative risk posed by different fisheries. The DST performs best with the help of human-informed inputs and stakeholder engagement throughout the process is essential for refining fishery inputs and accurately modeling fisher behavior in response to different management scenarios. The DST has been continuously refined since 2019 while working closely with members of the ALWTRT to explore management scenarios, which has provided important opportunities to test the model, investigate results that might seem unusual, and work together to determine ways of improving the model and its use.

Results of the 2023 peer review of the DST commended the new updates to the model while providing some useful guidance for future improvement. Quantifying and evaluating uncertainty was a main focus across all inputs to the model. Understanding how different spatiotemporal scales of both the fishery and whale input layers affect model performance will enrich the DST results and their interpretation by managers. Many of these concerns from the peer review have already been addressed and future iterations of the model will include them more formally.

Extensive testing of different management measures provides important insight into the sources of entanglement risk to consider when implementing management measures, including that entanglement risk appears to depend equally on presence of whales and density of gear. Areas with extended whale presence in large abundances can have comparative risk to areas where fewer whales are present but where there are extremely large amounts of gear. In SNE, a region where right whales are frequently present while feeding, socializing, or migrating, whales are present nearly every month of the year (Quintana-Rizzo et al. 2021, O'Brien et al. 2022). This region is also a complex fishing ground and targeted by many different types of fisheries. These dynamics may require a multi-faceted risk reduction approach that is tailored to each region based on the nature of the risk.

Reviewing the results of various management measures also identifies areas for future work. One way in which the model might be improved is with its handling of gear allocation and distribution. For example, while we know gear movement around closures occurs, some cases where the model estimates gear movement may need to be further evaluated. Gear density around closures is also not currently limited, and determining practical amounts of gear that can be placed in a model cell is something that may need further consideration to align with actual fishing conditions.

The dynamic nature of human behavior, fisheries, and whale distributions must be considered when utilizing DST results for real-world applications. Because it uses a fixed set of data and is limited in its ability to account for real-world challenges, a human element is important when considering how its results might be affected by anomalous events, unanticipated responses to management measures, or implementation and enforcement logistics. The DST remains an important tool for comparing the relative risk reduction of various management actions on a spatial and temporal scale and provides a valuable means for users to evaluate these actions. In addition, running the DST under baseline conditions allows for a quantification of the relative risk among individual fisheries, gear types (e.g., gillnets vs. trap/pots), or geographic areas (e.g., state vs. federal waters) under current conditions, and thus, may help inform assessments of commercial fishery-related mortality and serious injury.

TABLES AND FIGURES

Table 1. A spatial grid defining the domain of the Decision Support Tool model (MapRef) is made up of various regional and fisheries management-specific attributes that help categorize management actions and provides a spatial reference for all model inputs.

MapRef Attribute	**Description**	**Reference Figure**
Region	Gulf of Maine/Georges Bank Southern New England Mid Atlantic Southeast	1
Statistical Reporting Area	Greater Atlantic Regional Statistical Reporting Areas used for commercial fisheries reporting	1
State Association	Includes state waters and adjacent federal waters, usually extending out to the boundary of the model domain. Cells in New England outside the coastal Lobster Management Areas are not associated with any state. These designations are not intended to be used as management boundaries but are convenient for constraining model actions to a subset of the model domain.	2 (A)
Lobster Management Area	Seven areas established for lobster management	2 (B)
StateFed	State or federal jurisdictions	
Exempt	Existing areas exempted of management actions	
Distance from shore	Calculated distances from the coastline excluding most small islands	
Depth	Depth (m) from Coastal Relief Map	

Table 2. Federal and state trap/pot fisheries are grouped into categories with details on what species are included and the input development method (Section 2.2.3) used to generate the fishery input.

State/ Federal	**Input Name**	**Species Included**	**Input Development Method**
Federal	Crab	deep sea red crab (*Chaceon quinquidens*), blue crab (*Calinectes sapidus*)	Coords
	Fish	black sea bass (*Centropristis striata*), scup (*Stenotomus chrysops*), tautog (*Tautoga onitis*), triggerfishes (*Balistidae*), cunner (*Tautogolabrus adspersus*), bluefish (*Pomatomus saltatrix*)	Coords, Depth, GeoAreas
	Lobster	American lobster (*Homarus americanus*), Jonah crab (*Cancer borealis*)	Coords, Depth, GeoAreas

State/ Federal	**Input Name**	**Species Included**	**Input Development Method**
	Whelk	channeled whelk (*Busycotypus canaliculatus*), knobbed whelk (*Busycon carica*), lightning whelk (*Sinistrofulgur sinistrum*), conchs	Coords
State	Crab	rock crab (*Cancer irroratus*), green crab (*Carcinus maenas*), blue crab, stone crab	GeoAreas
	Fish	bluefish, tautog, cunner, triggerfishes, black sea bass, scup	GeoAreas
	Lobster	American lobster, Jonah crab	Depth, GeoAreas
	Whelk	channeled whelk, knobbed whelk, conchs	GeoAreas

Table 3. Federal and state gillnet fisheries are grouped into categories with details on what species are included, gillnet type, mesh size category, and the input development method (Section 2.2.3) used to generate the fishery input.

State/Federal	**Input Name**	**Species Included**	**Net Type**	**Mesh Size Category**	**Input Development Method**
Federal	Dogfish	spiny dogfish (*Squalus acanthias*), smooth dogfish (*Mustelus canis*)	Anchor	Large	Coords
			Anchor	Medium	Coords
			Anchor	Small	Coords
			Drift	Medium	Coords, Depth
			Drift	Small	Coords, Depth
	InshoreSpp	Atlantic croaker (*Micropogonias undulatus*), bluefish (*Pomatomus saltatrix*), menhaden (*Brevoortia tyrannus*), striped bass (*Morone saxatilis*), summer flounder (*Paralichthys dentaus*), black sea bass (*Centropristis striata*), scup (*Stenotomus chrysops*), cutlassfish (*Trichiurus lepturus*), spotted sea trout (*Cynoscion nebulosus*), spot (*Leiostomus xanthurus*), spanish mackerel (*Scomberomorus maculatus*), king mackerel (*Scomberomorus cavalla*), king whiting (*Menticirrhus americanus*), harvestfish (*Peprilus paru*), weakfish (*Cynoscion regalis*), cero (*Scomberomorus regalis*), little tunny (*Euthynnus alletteratus*), dealfish (*Trachipterus arcticus*), cobia (*Rachycentron canadum*), blue runner (*Caranx crysos*)	Anchor	Large	Coords
			Anchor	Medium	Coords
			Anchor	Small	Coords
			Drift	Medium	Coords, Depth
			Drift	Small	Coords, Depth
	MonkfishSkate	monkfish (*Lophius piscatorius*), little skate (*Leucoraja erinacea*), barndoor skate (*Dipturus laevis*), smooth skate (*Malacoraja senta*), thorny skate (*Amblyraja radiata*), winter skate (*Leucoraja ocellata*)	Anchor	Large	VMS, Coords
			Anchor	Medium	VMS
	NEGroundfish	Atlantic cod (*Gadus morhua*), pollock (*Pollachius virens*), haddock (*Melanogrammus aeglefinus*), white hake (*Urophycis tenuis*),	Anchor	Large	Coords

State/Federal	**Input Name**	**Species Included**	**Net Type**	**Mesh Size Category**	**Input Development Method**
		yellowtail flounder (*Limanda ferruginea*), silver hake (*Merluccius bilinearis*), winter flounder (*Pseudopleuronectes americanus*), American plaice (*Hippoglossoides platessoides*), witch flounder (*Glyptocephalus cyanoglossus*), windowpane flounder (*Scophthalmus aquosus*)	Anchor	Medium	Coords
	SharkSpp	common thresher (*Alopias vulpinus*), Atlantic sharpnose (*Rhizoprionodon terraenovae*), blacktip (*Carcharhinus limbatus*), spinner (*Carcharhinus brevipinna*), hammerhead (*Sphyrna mokarran*), finetooth (*Carcharhinus isodon*), porbeagle (*Lamna nasus*), mako (*Isusrus sp.*), sandbar (*Carcharhinus plumbeus*), blue (*Prionace glauca*), dusky (*Carcharhinus obscurus*), tiger (*Galeocerdo cuvier*), bonnethead (*Sphyrna tiburo*), blacknose (*Carcharhinus acronotus*), bull (*Carcharhinus leucas*), lemon (*Negaprion brevirostris*)	Anchor	Medium	Coords
			Anchor	Small	Coords, Depth
			Drift	Medium	Coords, Depth
			Drift	Small	Coords, Depth
State	Dogfish	spiny dogfish, smooth dogfish	Anchor	Medium	GeoAreas
	InshoreSpp	Spanish mackerel, weakfish, spot, tuna (*Thunnus sp.*), butterfish (*Peprilus triacanthus*), harvestfish, king mackerel, Florida pompano (*Trachinotus carolinus*), cutlassfish, needlefish (*Strongylura marina*), bluefish, Atlantic croaker, menhaden, sea trout, sheepshead (*Archosargus probatocephalus*), pigfish (*Orthopristis chrysoptera*), striped mullet (*Mugil cephalus*), crevalle jack (*Caranx hippos*), black drum (*Pogonias cromis*), winter flounder, summer flounder, scup, black sea bass, tautog, white perch, striped bass	Anchor	Large	Depth
			Anchor	Medium	Depth, GeoAreas
			Anchor	Small	GeoAreas
			Drift	Small	Coords, Depth, GeoAreas
	MonkfishSkate	monkfish, little skate, barndoor skate, smooth skate, thorny skate, winter skate	Anchor	Large	Coords, Depth
	NEGroundfish	winter flounder, Atlantic cod, yellowtail flounder, silver hake	Anchor	Medium	Coords, Depth
	SharkSpp	common thresher, Atlantic sharpnose, blacktip, spinner, hammerhead	Drift	Small	GeoAreas

Table 4. The whale vertical distribution model from Barkaszi et al. 2021 Appendix 1 is used to determine whale behaviors by month and region, their position in the water column a necessary part of modeling interactions with gillnets.

Region	Month	Travel Speed (m/s)	Length (m)	Beam (m)	% Density Foraging	% Density Migrating	% Population Calf-rearing	% Time Foraging 0-10m	% Time Foraging 11-20m	% Time Foraging >20m	% Time Migrating 0-10m	% Time Migrating 11-20m	% Time Migrating >20m	% Time Calf-rearing 0-10m	% Time Calf-rearing 11-20m	% Time Calf-rearing >20m
Northeast	Jan	0.258	15	3	80	17	3	84	10	6	71	29	0	85	15	0
	Feb	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	Mar	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	Apr	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	May	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	Jun	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	Jul	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	Aug	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	Sep	0.258	15	3	48	49	3	84	10	6	71	29	0	85	15	0
	Oct	0.258	15	3	48	49	3	84	10	6	71	29	0	85	15	0
	Nov	0.258	15	3	48	49	3	84	10	6	71	29	0	85	15	0
	Dec	0.258	15	3	48	49	3	84	10	6	71	29	0	85	15	0
Mid-Atlantic	Jan	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
	Feb	0.82	15	3	5	80	15	84	10	6	71	29	0	85	15	0
	Mar	0.82	15	3	15	70	15	84	10	6	71	29	0	85	15	0
	Apr	0.82	15	3	15	70	15	84	10	6	71	29	0	85	15	0
	May	0.82	15	3	15	70	15	84	10	6	71	29	0	85	15	0
	Jun	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
	Jul	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
	Aug	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
	Sep	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0

Region	Month	Travel Speed (m/s)	Length (m)	Beam (m)	% Density Foraging	% Density Migrating	% Population Calf-rearing	% Time Foraging 0-10m	% Time Foraging 11-20m	% Time Foraging >20m	% Time Migrating 0-10m	% Time Migrating 11-20m	% Time Migrating >20m	% Time Calf-rearing 0-10m	% Time Calf-rearing 11-20m	% Time Calf-rearing >20m
	Oct	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
	Nov	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
	Dec	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
Southeast	All	0.4	15	3	0	5	95	84	10	6	71	29	0	85	15	0

Table 5. Baseline estimates of gear, co-occurrence, and risk associated with an example fishery are used to demonstrate the effects of implementing two scenario gear cap management actions (200 and 50).

Variable	Baseline	Scenario (200 Gear Cap)	Scenario (50 Gear Cap)
Gear Numbers	4481	4481	2832
Co-Occurrence	3913	3913	2459
Risk	291	291	183

Table 6. Baseline estimates of gear, co-occurrence, and risk associated with an example fishery are used to demonstrate the effects of implementing a 24 hour soak limit scenario.

Variable	Baseline	Scenario (24-Hour Soak Limit)	% Reduction
Gear Numbers	4327	3485	20%
Co-Occurrence	4697	3765	20%
Risk	401	322	20%

Table 7. Baseline estimates of number of endlines fished in an example fishery are used to demonstrate the effects of implementing a line cap scenario of 80 endlines.

Variable	Baseline	Scenario (Line Cap of 80 lines)	% Reduction
January	75	68	10%
February	90	80	11%
March	118	105	11%
April	114	101	12%
May	130	110	15%
June	212	167	22%
July	343	260	24%
August	365	275	25%
September	349	263	25%
October	283	210	26%
November	113	89	21%
December	104	85	18%
Total	2297	1813	21%

Table 8. Baseline estimates (rounded to the nearest hundred) grouped by the three primary fishery inputs of the amount of gear fished, number of vertical lines, co-occurrence with North Atlantic right whales are produced through a high-resolution baseline model run of the Decision Support Tool (V4.1). Note that the fishery inputs can be broken down further to inform relative risk of individual fisheries (e.g., those managed under a specific Fisheries Management Plan or Marine Mammal Protection Act List of Fisheries).

Fishery	Permitting	Gear Fished (traps, panels)	Number of Vertical Lines	Co-Occurrence	Risk
Lobster	Federal	6,706,800	1,584,000	483,400	71,300
	State	6,931,400	2,499,100	218,000	22,800
Other Trap/Pot	Federal	166,700	13,700	6,500	1,200
	State	63,900	16,600	15,200	1,500
Gillnet	Federal	54,900	8,300	16,300	2,800
	State	1,400	1,200	5,700	800
	Total	13,925,100	4,122,900	745,100	100,100

Table 9. The 2021 final rule measures implemented by the 2021 Atlantic Large Whale Take Reduction Plan were modeled in the Decision Support Tool to provide a real world example of a scenario containing multiple management actions. Actions are grouped by measure type with spatial area, month(s), and detailed specifications.

Measure Type	Area	Month	Action
Line/Gear Reduction	Maine Zones A, B, F & G from Exemption Line to 3 mi	Year-Round	Minimum of 3 Traps / Trawl (1 buoy line)
	Maine Zones C, D & E from Exemption Line to 3 mi	Year-Round	Minimum of 2 Traps / Trawl (1 buoy line) or 4 Traps / Trawl (2 buoy lines)
	Maine Zone A East from 3 to 12 mi	Year-Round	Minimum of 10 Traps / Trawl (1 buoy line) or Minimum of 20 Traps / Trawl (2 buoy lines)
	Maine Zone A West from 3 to 6 mi	Year-Round	Minimum of 4 Traps / Trawl (1 buoy line) or Minimum of 8 Traps / Trawl (2 buoy lines)
	Maine Zone B from 3 to 6 mi	Year-Round	5 Traps / Trawl (1 buoy line)
	Maine Zones C, D, E, F & G from 3 to 6 mi	Year-Round	Minimum of 5 Traps / Trawl (1 buoy line) or Minimum of 10 Traps / Trawl (2 buoy lines)
	Maine Zone A West from 6 to 12 mi	Year-Round	Minimum of 8 Traps / Trawl (1 buoy line) or Minimum of 15 Traps / Trawl (2 buoy lines)
	Maine Zone B from 6 to 12 mi	Year-Round	Minimum of 5 Traps / Trawl (1 buoy line) or Minimum of 10 Traps / Trawl (2 buoy lines)
	Maine Zone C & G from 6 to 12 mi	Year-Round	Minimum of 10 Traps / Trawl (1 buoy line) or Minimum of 20 Traps / Trawl (2 buoy lines)
	Maine Zones D, E & F from 6 to 12 mi	Year-Round	Minimum of 5 Traps / Trawl (1 buoy line) or Minimum of 10 Traps / Trawl (2 buoy lines)
	Massachusetts Lobster Management Area 1 from 6 to 12 mi	Year-Round	Minimum of 15 Traps / Trawl
	Outer Cape Cod from 3 to 12 mi	Year-Round	Minimum of 15 Traps / Trawl
	Lobster Management Area 1 over 12 nm	Year-Round	Minimum of 25 Traps / Trawl

Measure Type	Area	Month	Action
	Lobster Management Area 3, South of the 50 fathom line on the south end of Georges Bank	Year-Round	Minimum of 35 Traps / Trawl
	Lobster Management Area 3, North of the 50 fathom line, including LMA3-only vessels fishing in LMA 2/3 overlap	Year-Round	Minimum of 45 Traps / Trawl
	Georges Basin Restricted Area	Year-Round	Minimum of 50 Traps / Trawl
	Lobster Management Area 2*	Year-Round	15% gear reduction
	Lobster Management Area 3, Northeast	Year-Round	Gear Cap 1548
Closure	Lobster Management Area 1 Restricted Area	Oct. 1 – Jan. 31	Closure
	South Island Restricted Area	Feb. 1 – Apr. 30	Closure
	State Waters of Massachusetts Lobster Management Area 1 and Outer Cape Cod	Feb. 1 – May 31	Closure (Gear Reduction)
Weak Rope	Throughout Gulf of Maine & Southern New England	Year-Round	Misc. Max Rope or Insert Strength of 1700 lbs.

* These actions were included to reflect the interim final rule (88FR 67667, October 2, 2023) published by National Marine Fisheries Service based on the Atlantic States Marine Fisheries Commission's recommendations for aggregate ownership caps in Lobster Management Areas 2 and 3 and a maximum trap cap reduction in LMA 3.

** This action was appended to mirror the area included in the 2021 Massachusetts State Commercial Trap Gear Closure to Protect Right Whales (322 CMR 12.04(2)). For more information and a complete list of the 2021 final rule management actions refer to NMFS (2021).

Table 10. Results of the implementation of the 2021 final rule management actions is categorized by reduction in gear, vertical endlines, rope strength, overall co-occurrence, and overall risk and varies by month.

Month	Gear Reduction Post Closure & Gear Cap	Mean String Length Reduction Post Trawl-Up Measures	Vertical Line Reduction Post Endline Actions	Reduction in Mean Rope Strength	Reduction in Co-Occurrence After All Actions	Reduction in Risk After All Actions
Jan	1.4%	-24.1%	15.8%	7.5%	42.2%	44.5%
Feb	4.7%	-25%	19.7%	7%	25%	33.8%
Mar	4.2%	-32.4%	22.4%	6.6%	40.1%	46.7%
Apr	5.2%	-21.1%	18.8%	7.1%	59.6%	59.2%
May	9.4%	-11.5%	18.2%	7.6%	69.5%	67.1%
Jun	0.9%	-9.6%	8.3%	8.2%	23.5%	32.9%
Jul	0.7%	-7.3%	6.3%	8.2%	27%	33.9%
Aug	0.6%	-7.7%	6.3%	8.2%	32.6%	34.9%
Sep	0.6%	-8.9%	7.2%	8.1%	29.1%	35%
Oct	0.5%	-9.1%	7.4%	8%	47.3%	46%
Nov	0.6%	-10%	8.1%	8%	44.4%	45.2%
Dec	1.0%	-14.9%	10.9%	8.1%	25.7%	34.7%
Total	1.6%	-15.1%	9.1%	8.1%	43.7%	46.5%

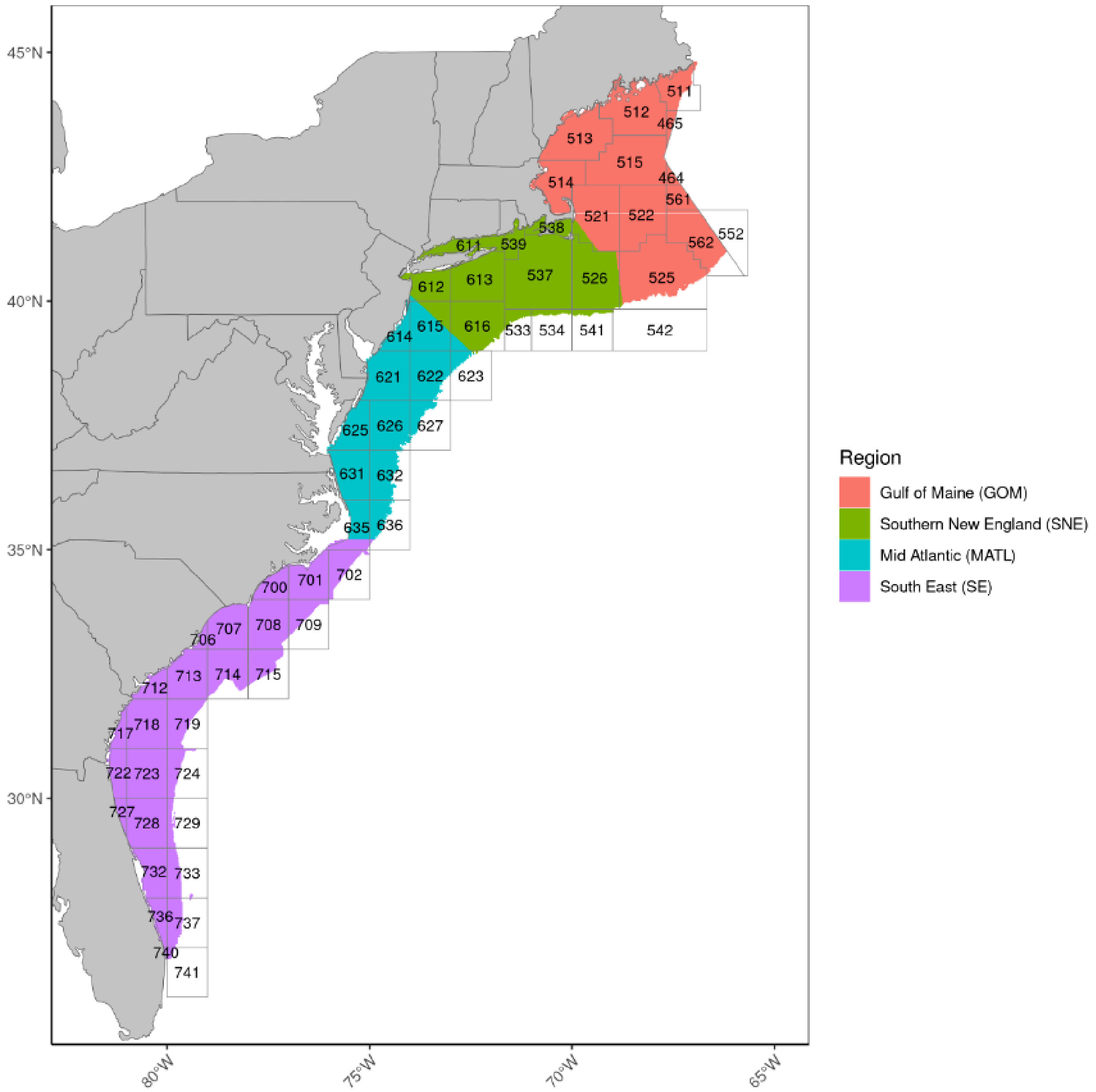

Figure 1. The Decision Support Tool works within a gridded spatial domain (MapRef) defined with regional constraints and Statistical Reporting Areas (SRAs).

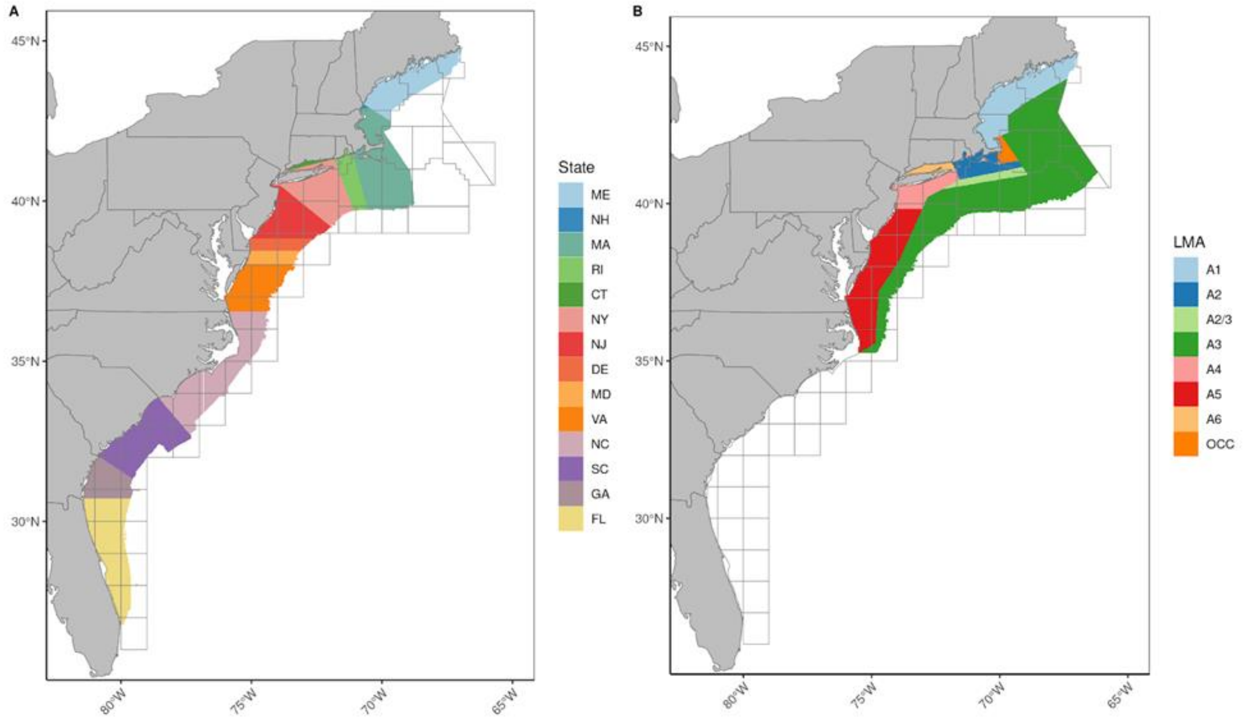

Figure 2. (A) State boundaries were drawn and (B) Lobster Management Areas (LMAs) were incorporated in addition to Statistical Reporting Areas (grey lines) in order to spatially constrain model runs of the Decision Support Tool.

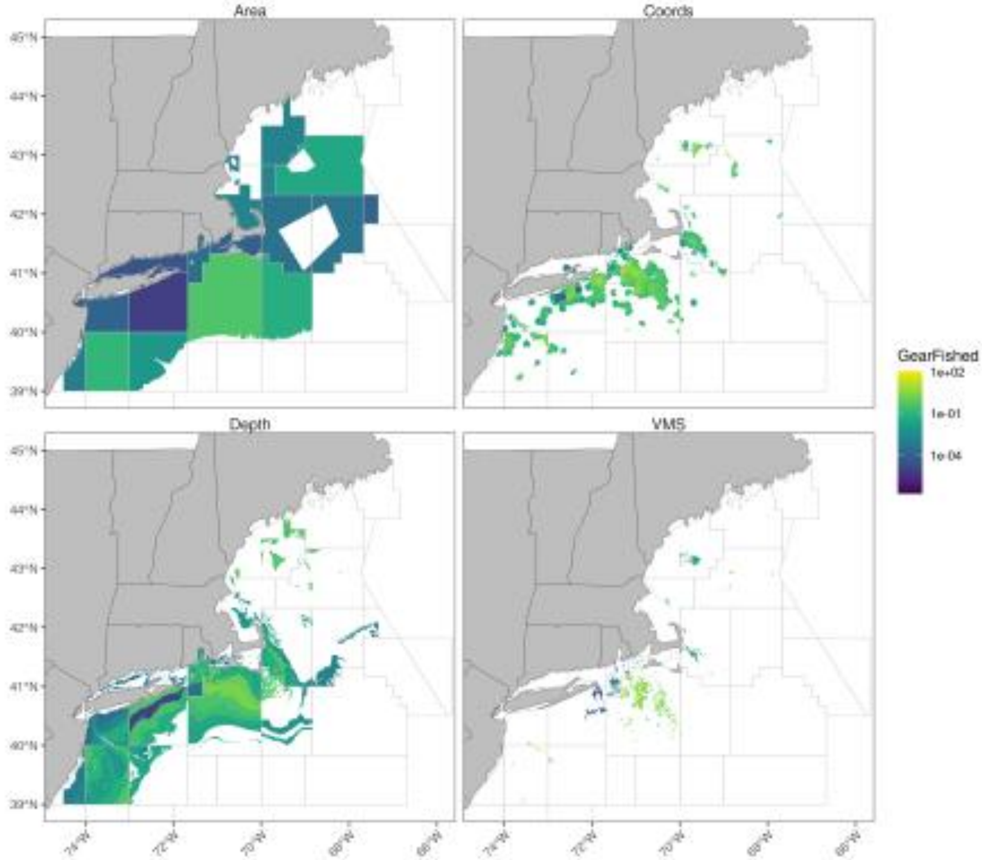

Figure 3. The development of the fishery inputs uses four main allocation methods (Area, Coords, Depth, and VMS [Vessel Monitoring Systems]), each with varying levels of spatial precision obtained from the amount of detail available in trip reporting.

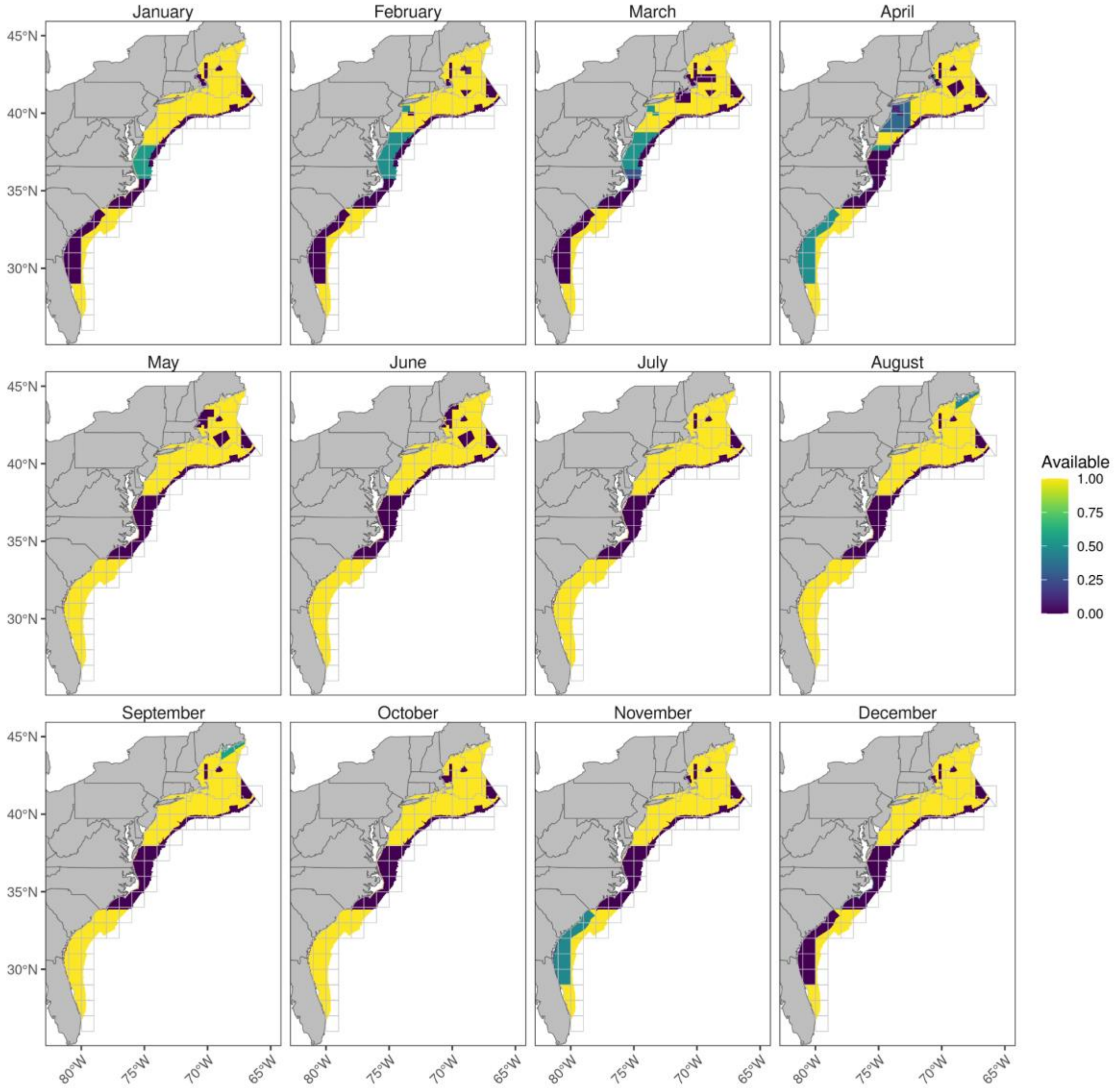

Figure 4. An example map of a Cell Status object for anchored large mesh gillnet fisheries with monthly accounting of time and area closures shows how cells are either available or unavailable for gear placement within the Decision Support Tool MapRef grid. The color gradient shows the proportion of the month that an area is open in order to consider closures that do not extend for an entire month. Yellow indicates areas that are open the entire month for gear placement, dark purple indicates areas that are closed the entire month, and colors in between match the proportion of the month that an area is open.

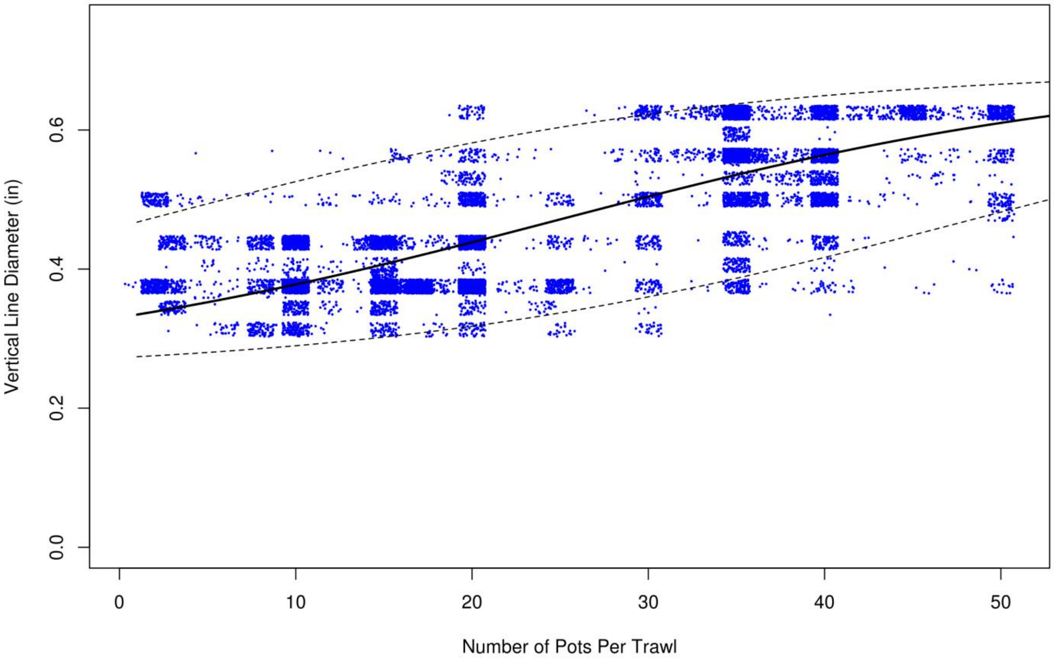

Figure 5. Trawl length is used to predict rope diameter as a first step in determining rope strength. Data points are jittered to show density of data for discrete data intervals. Overlay trend lines are the results of a logistic regression fitted to the data with confidence intervals of + / - 2 standard deviations shown as a dashed line.

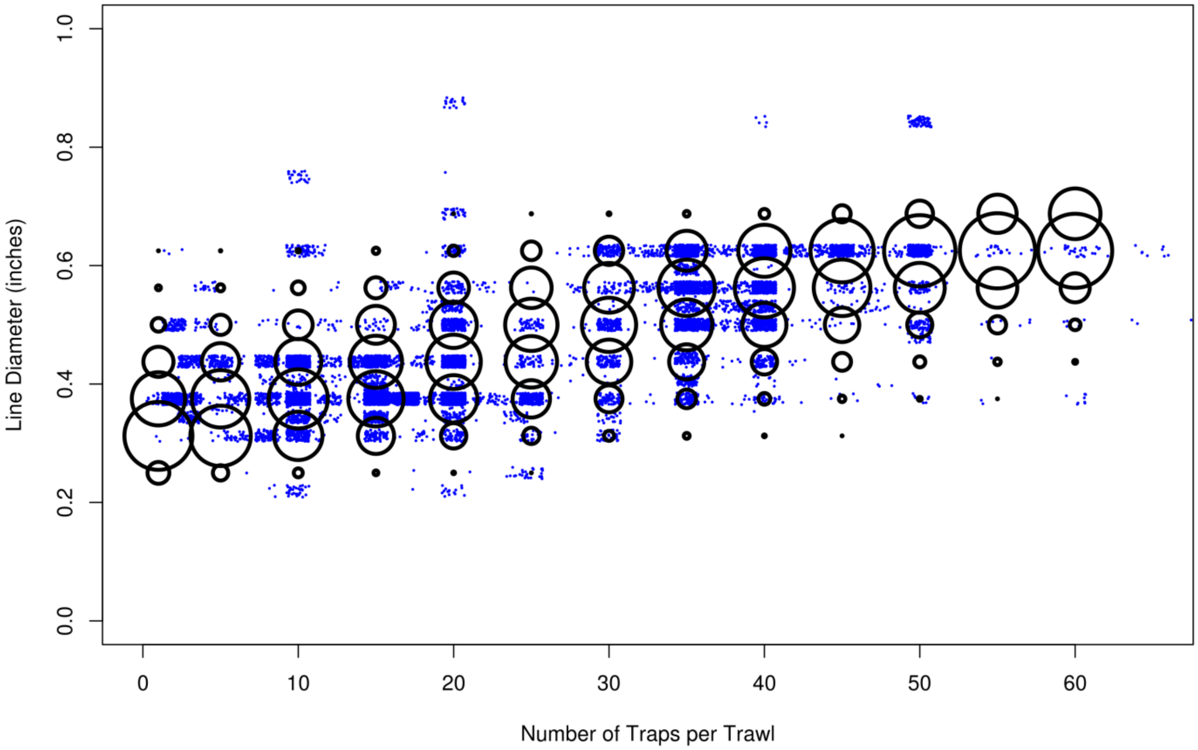

Figure 6. Predicted line diameter distributions estimated from the logistic regression (Figure 5) are used to determine proportions (represented by the size of the bubble) of line diameters expected at a given trawl length. Jittered points (in blue) represent the raw data describing the relationship between line diameter and the number of traps per trawl.

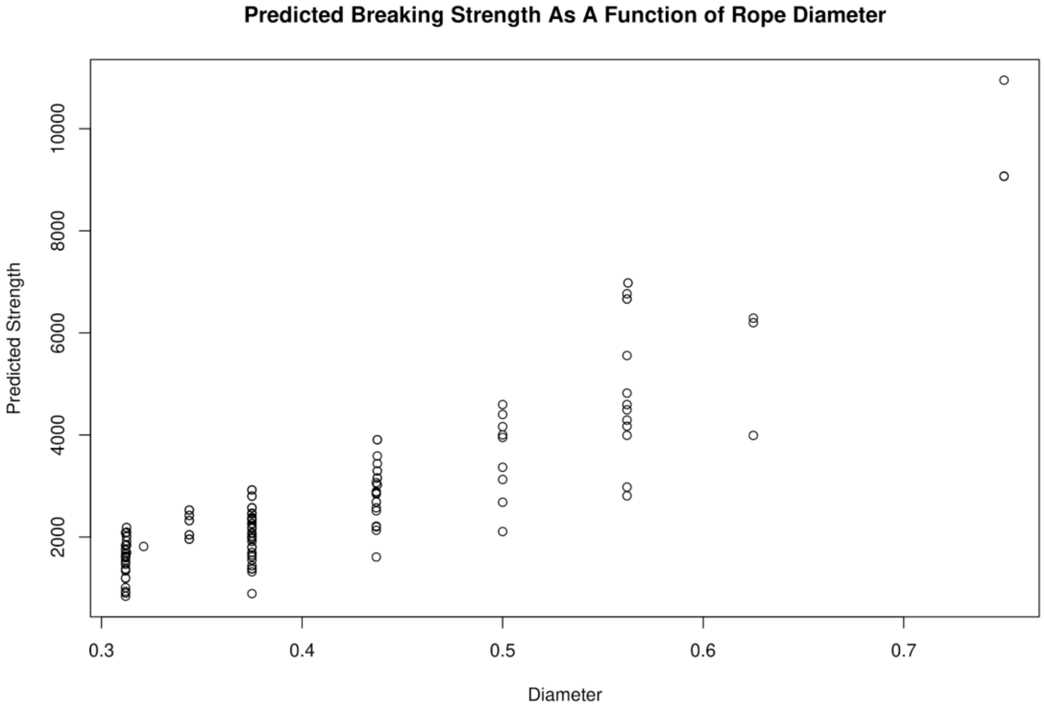

Figure 7. A relationship between rope diameter (inches) and observed breaking strength (lbs.) was determined from rope samples collected from entangled whales (Knowlton et al. 2016) and samples of vertical endlines submitted by Maine lobstermen. These data include rope sections with splices and knots.

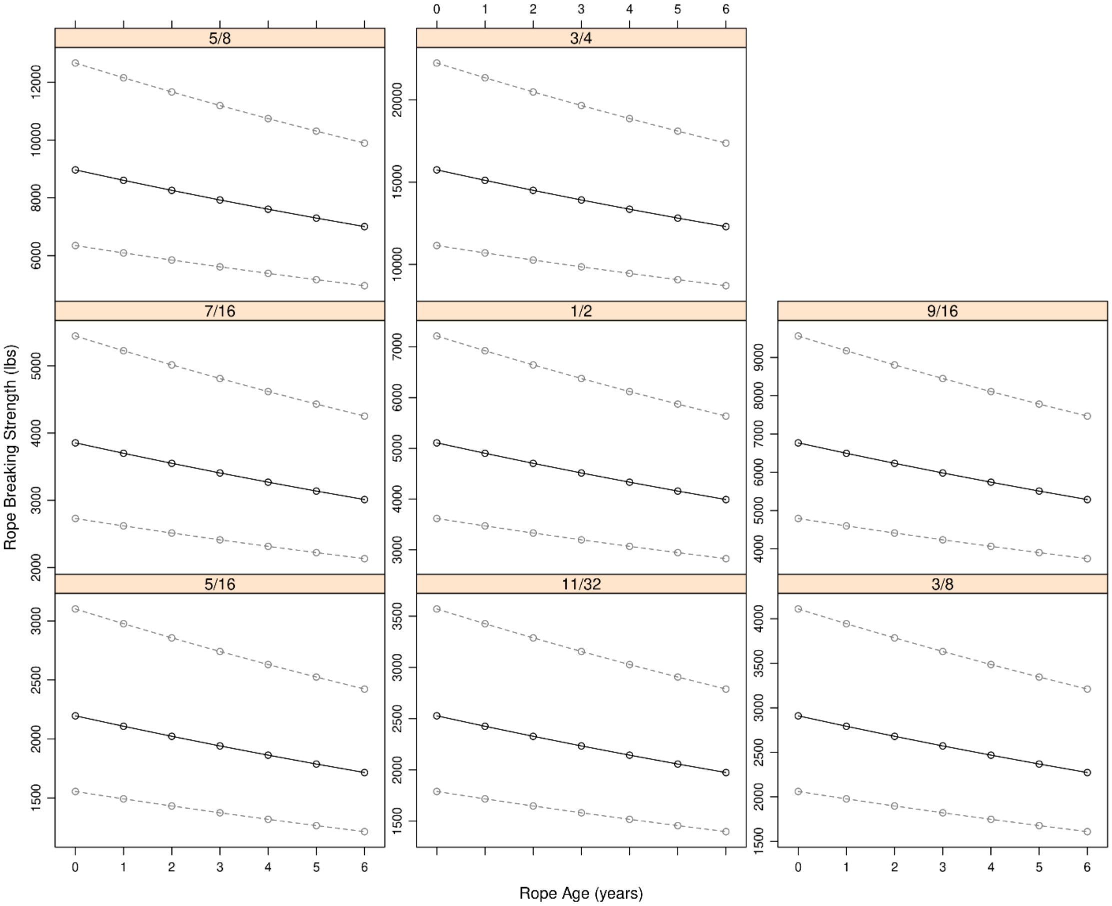

Figure 8. Predicted rope breaking strength at different diameters (including confidence intervals of + / - 2 standard deviations) decreases with age from the combined rope strength data set.

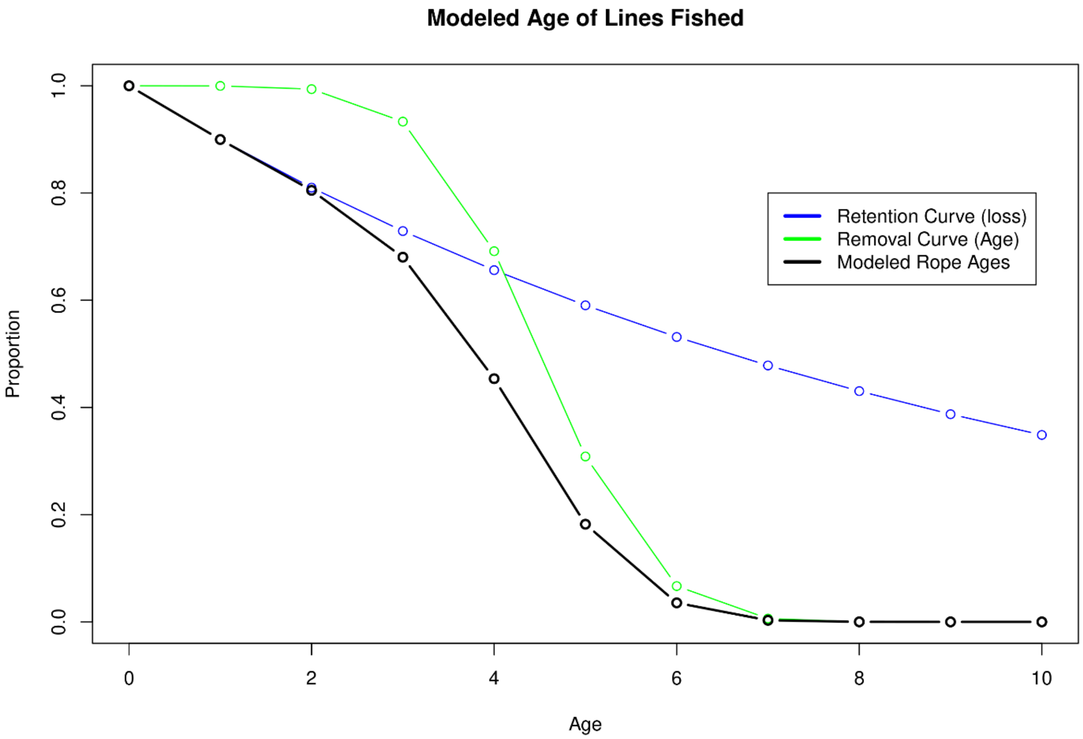

Figure 9. Distribution of modeled rope age (black) is the product of a 10% annual loss of lobster gear observed from Maine fishers (random loss rates; blue) and the range of rope ages submitted for line strength testing (active removal rates due to wear; green) where most were between 3 and 6 years of age (4.5 years on average).

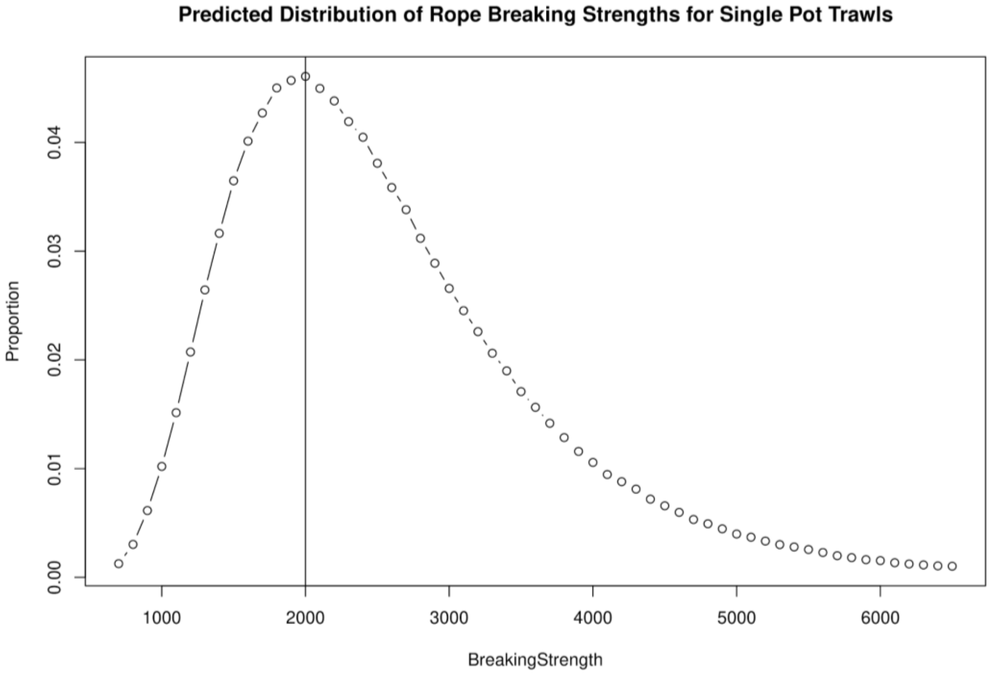

Figure 10. Rope breaking strength (lbs.) proportions for given trawl lengths were generated from the predicted rope diameter distributions (Figure 6). This example shows the predicted distribution of breaking strength for endlines on single pot trawls with a median breaking strength of 2,000 lbs.

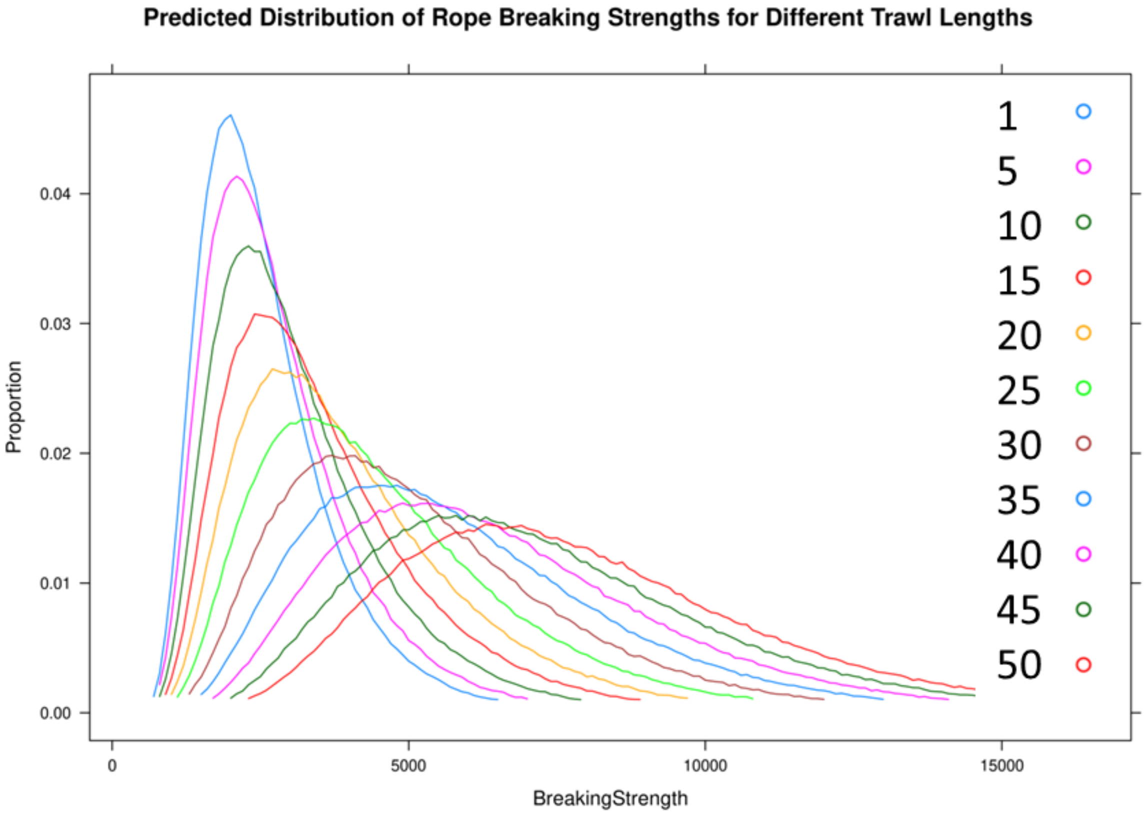

Figure 11. Distributions of rope breaking strength proportions are generated for trawl lengths up to 50 pot trawls.

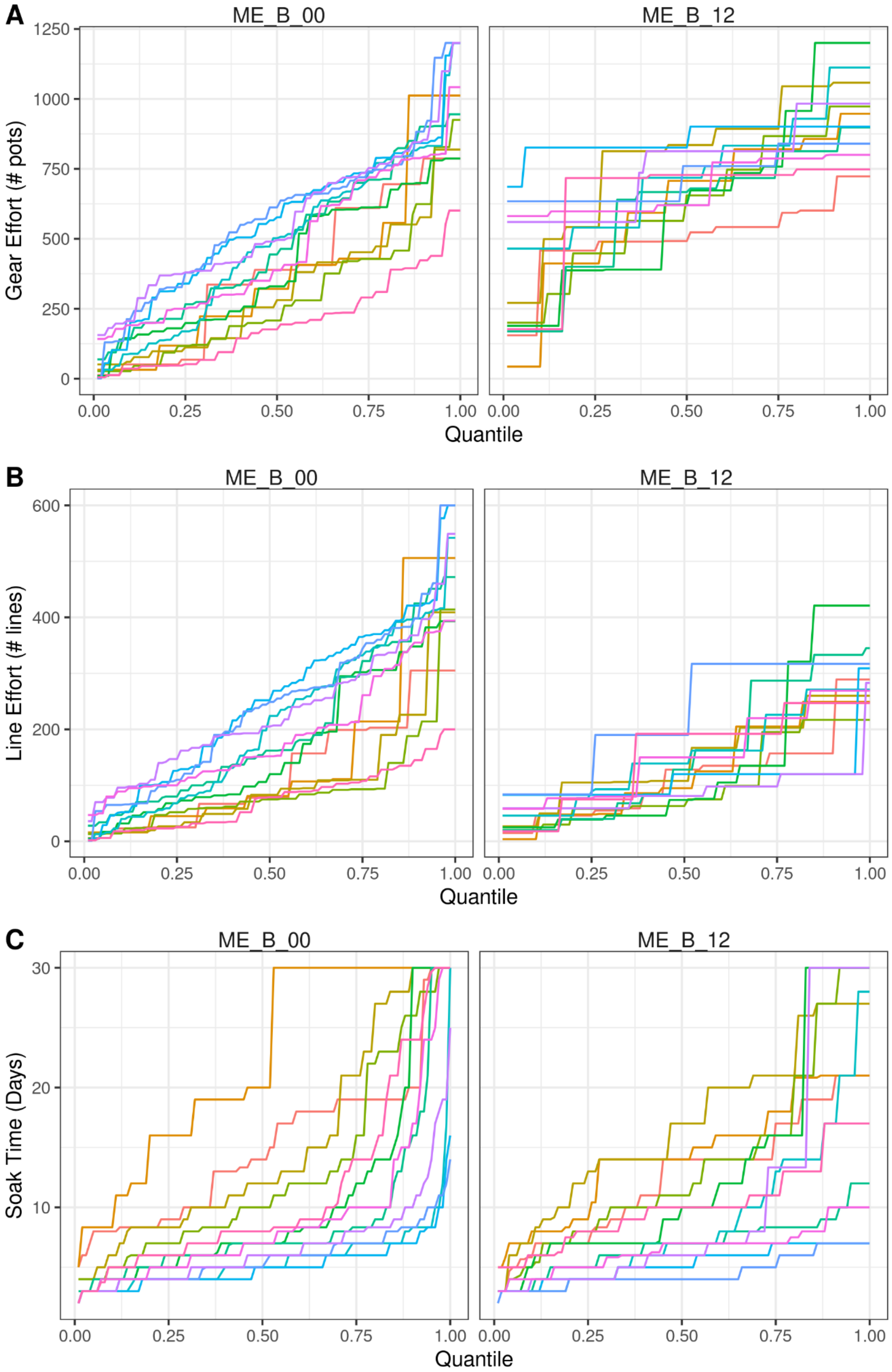

Figure 12. (A) Gear, (B) endline, and (C) soak time cumulative effort distributions for Maine Zone B federal lobster fleet fishing inside state waters (ME_B_00) and 12+ miles offshore (ME_B_12). Effort values for a given quantile represent the proportion of active vessels for an area that are fishing at or below that level. Gear effort may exceed total gear allowances at the high end of the distribution as an artifact of trips overlapping months, introducing a bias in gear reduction measures for some values.

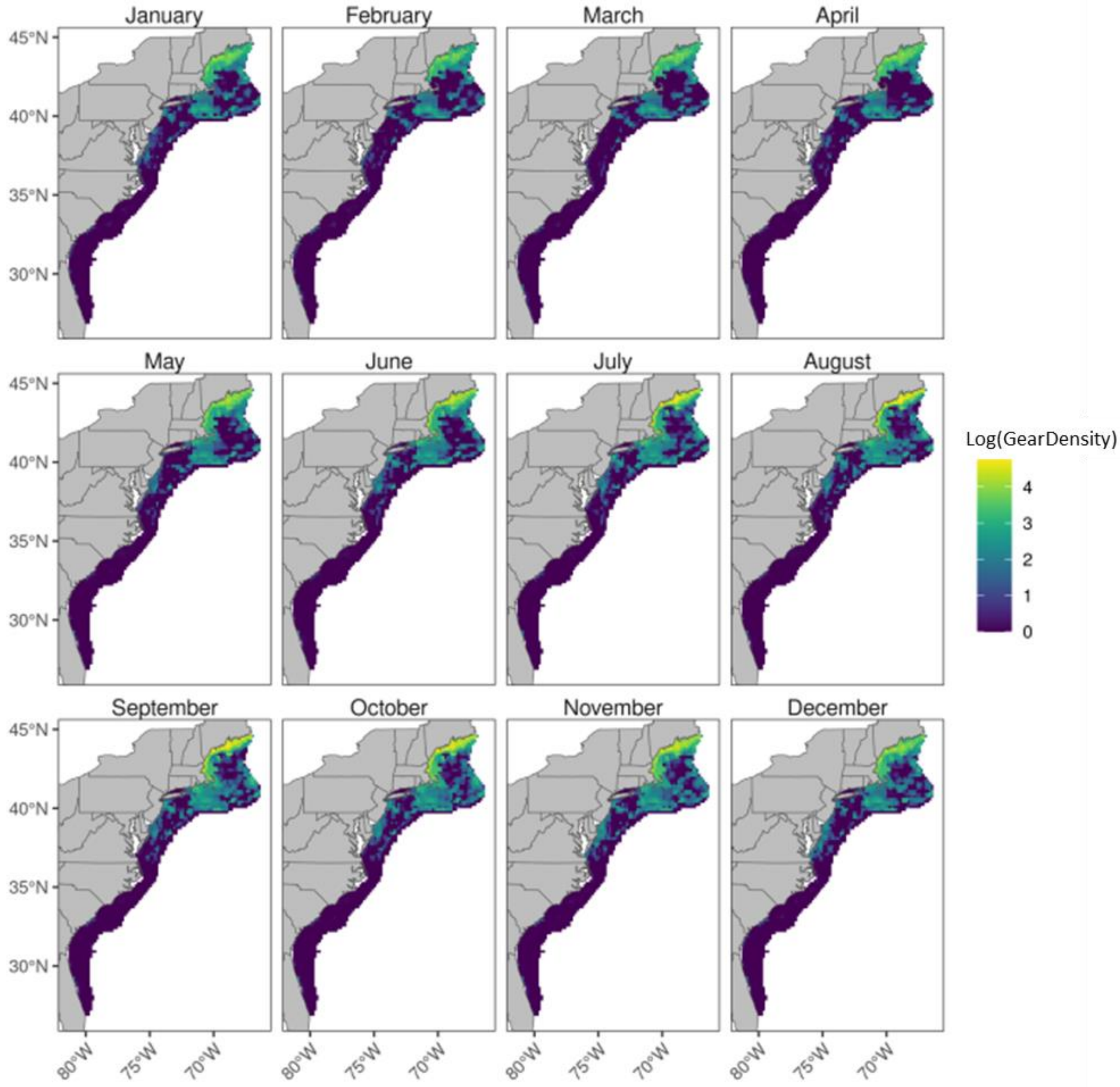

Figure 13. Baseline gear density (log-scaled) quantify the amount of fixed gear for East Coast trap/pot fishery inputs from state and federal fisheries including lobster, whelk, fish, and crab pots.

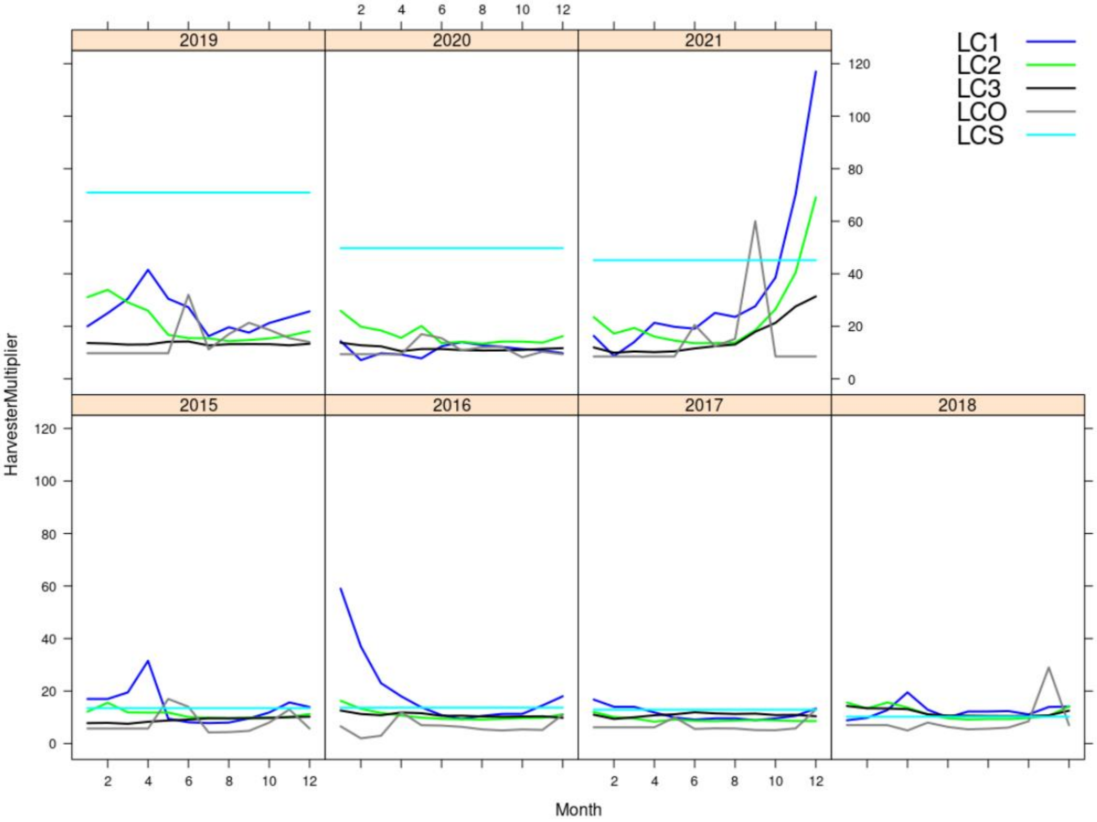

Figure 14. Because the Maine lobster fishery has a 10% reporting rate, harvester multipliers are calculated for expanding trip effort by year, month, and license class (LC).

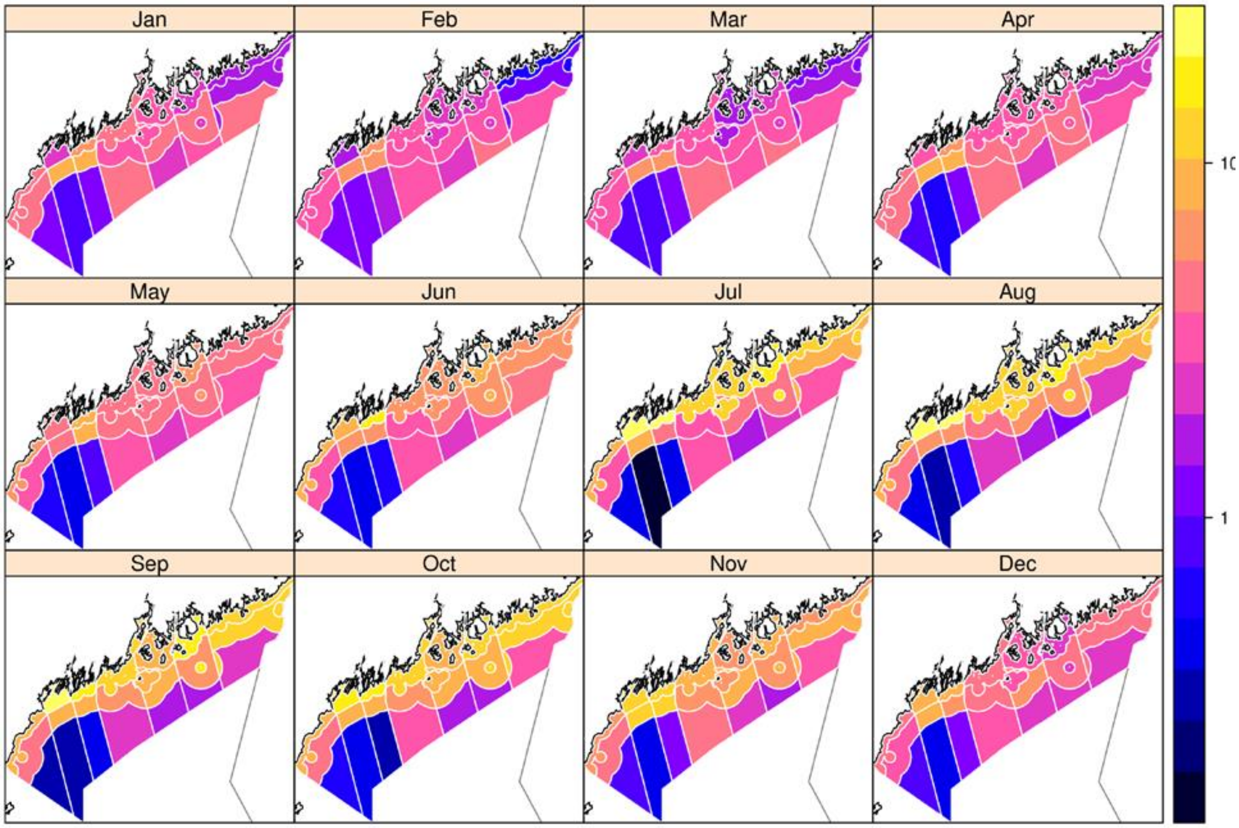

Figure 15. Distribution of fishing effort (log-scaled) for Maine LMA 1 lobster fishery using the GeoAreas (geographic areas) allocation method.

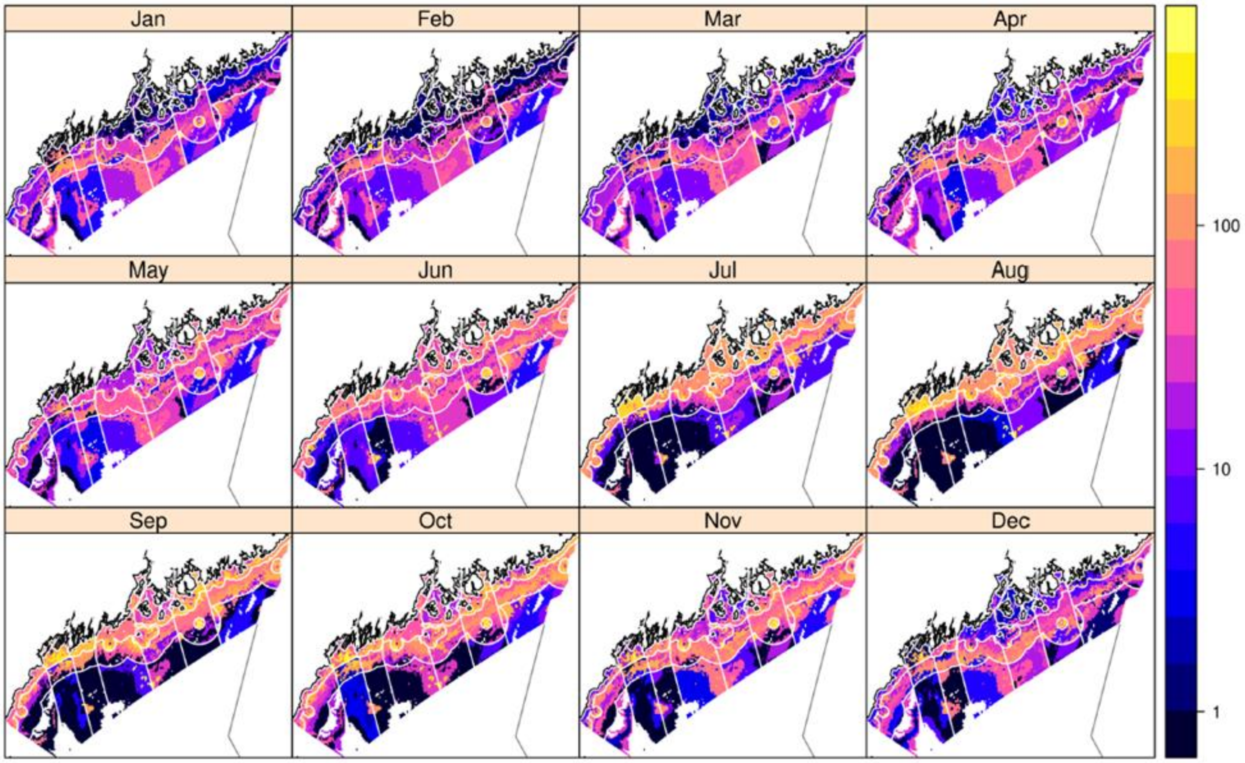

Figure 16. Distribution of fishing effort (log-scaled) for Maine LMA 1 lobster fishery using the Depth (geographic areas and depth) allocation method.

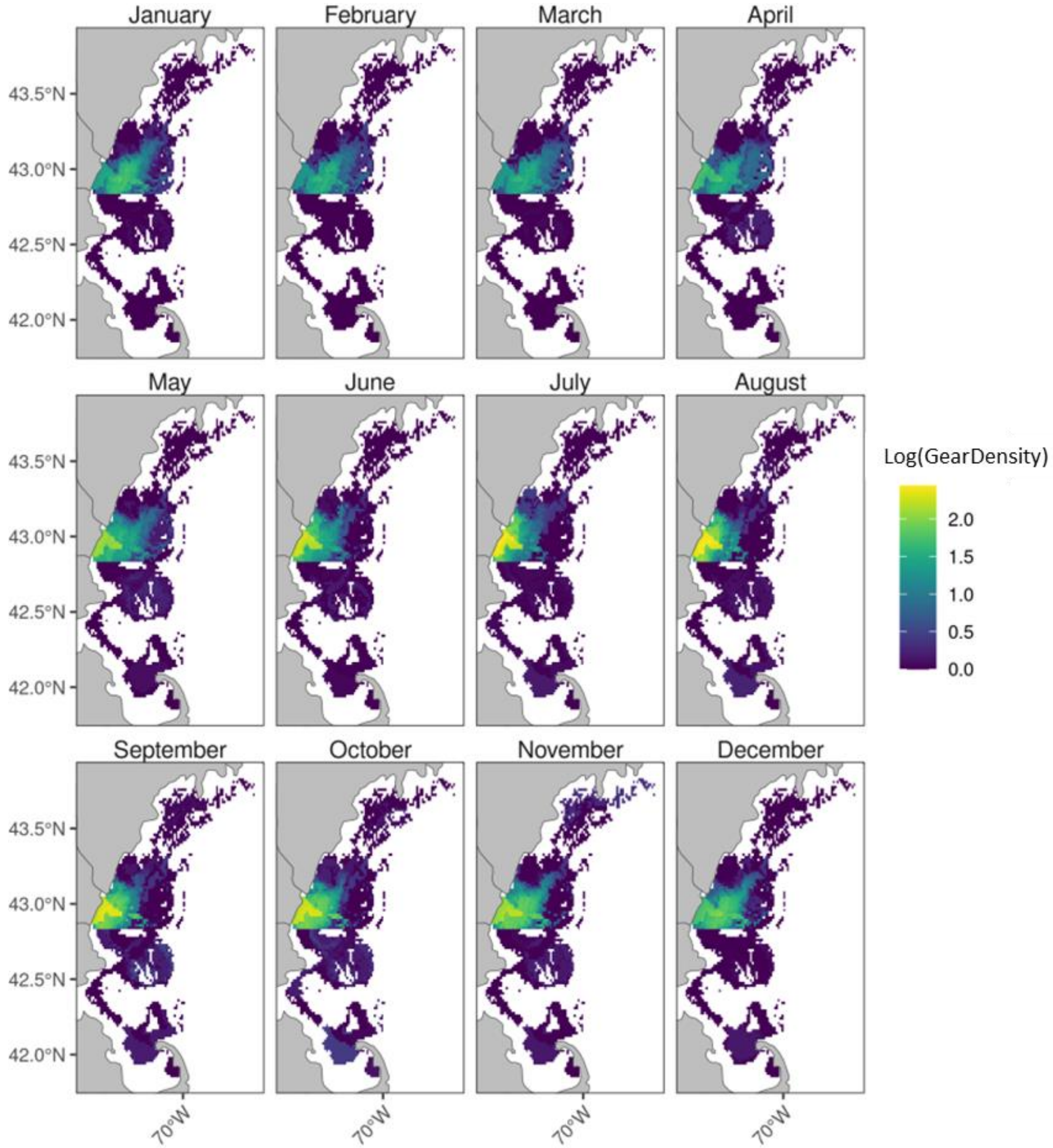

Figure 17. Distribution of fishing effort (log-scaled) for the New Hampshire state and federal lobster fisheries.

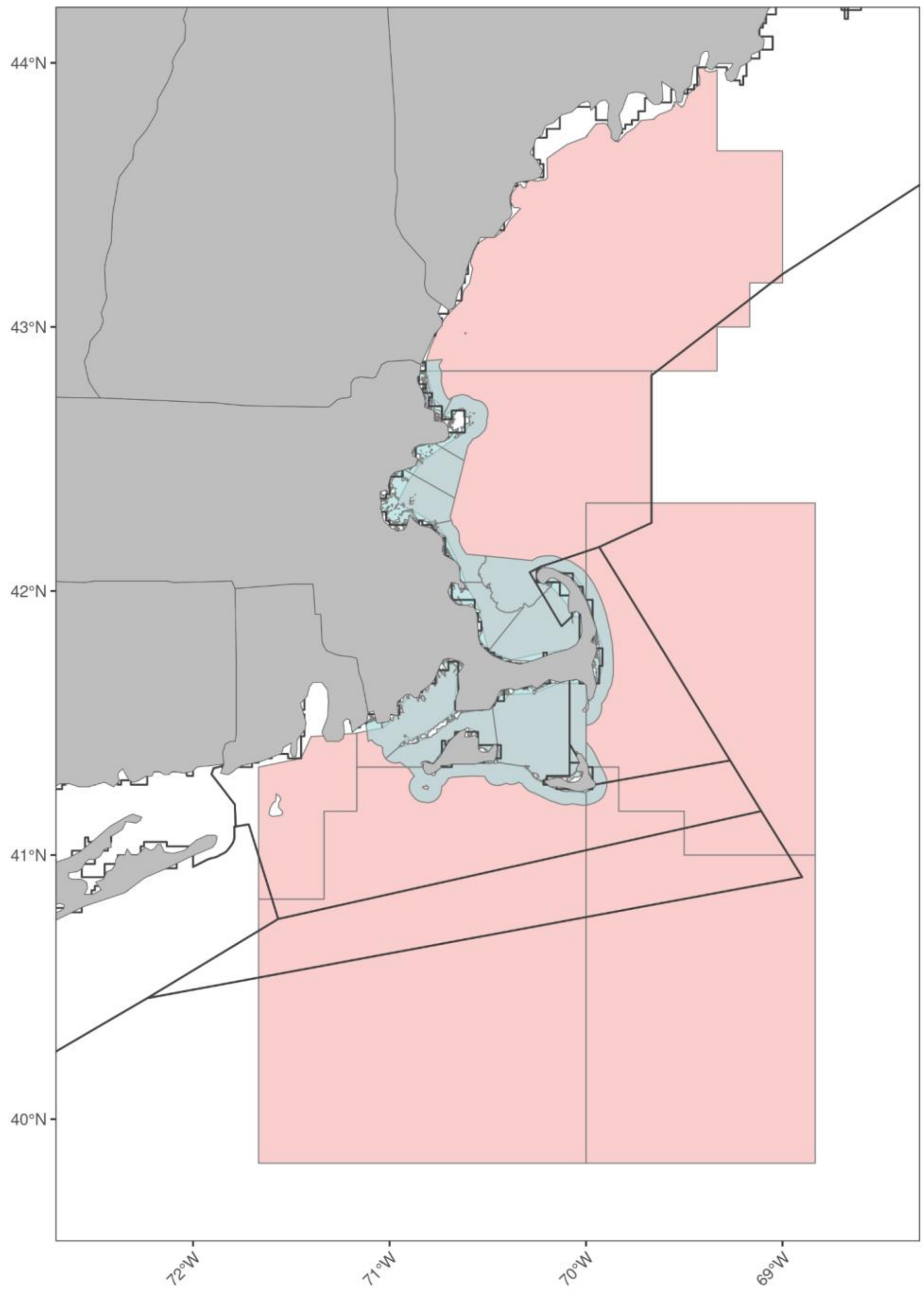

Figure 18. Massachusetts Statistical Reporting Areas (blue) with federal Statistical Reporting Areas (red) and Lobster Management Areas (black lines) overlaid.

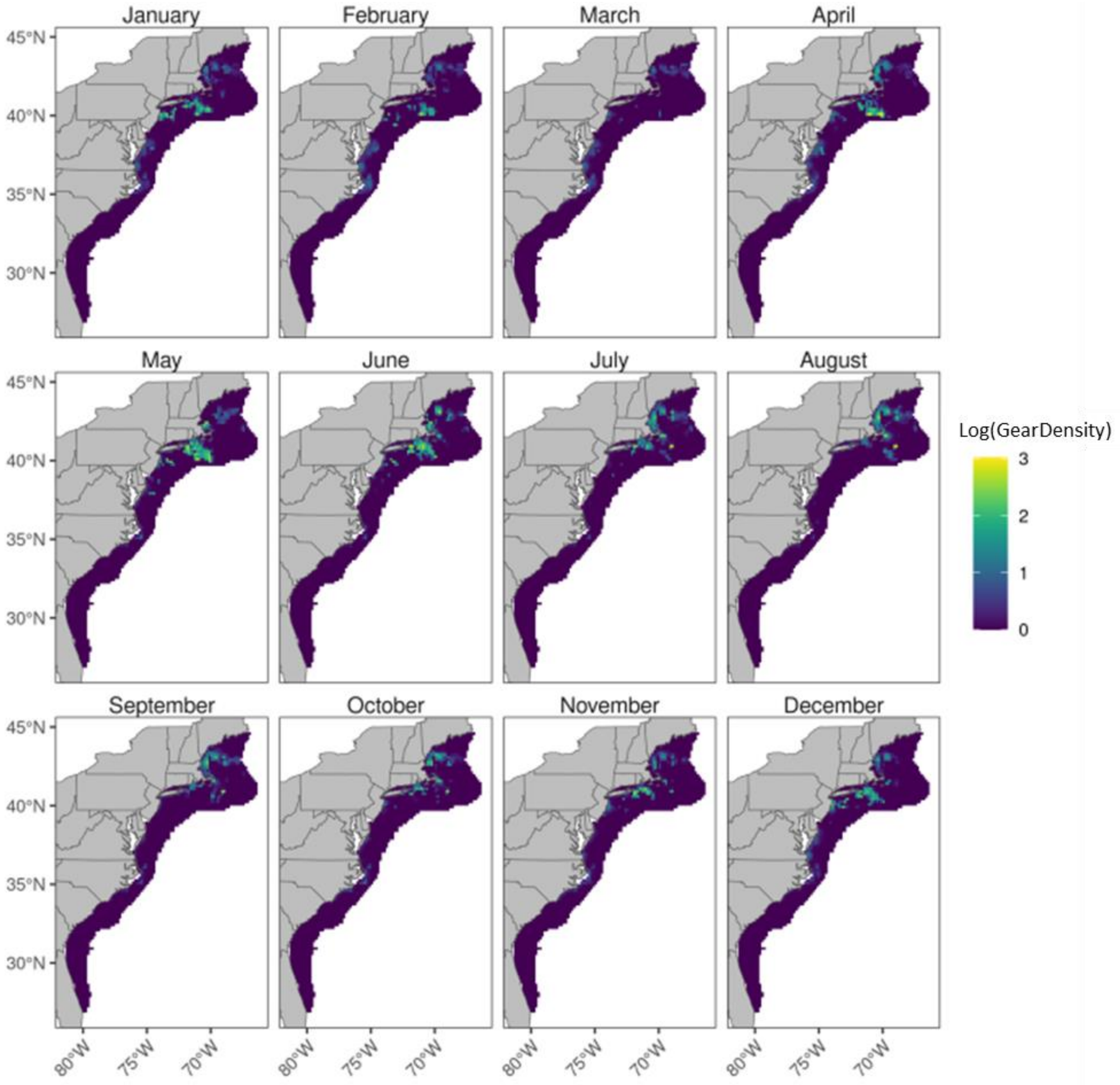

Figure 19. Baseline gear density (log-scaled) for East Coast gillnet fishery inputs from state and federal fisheries.

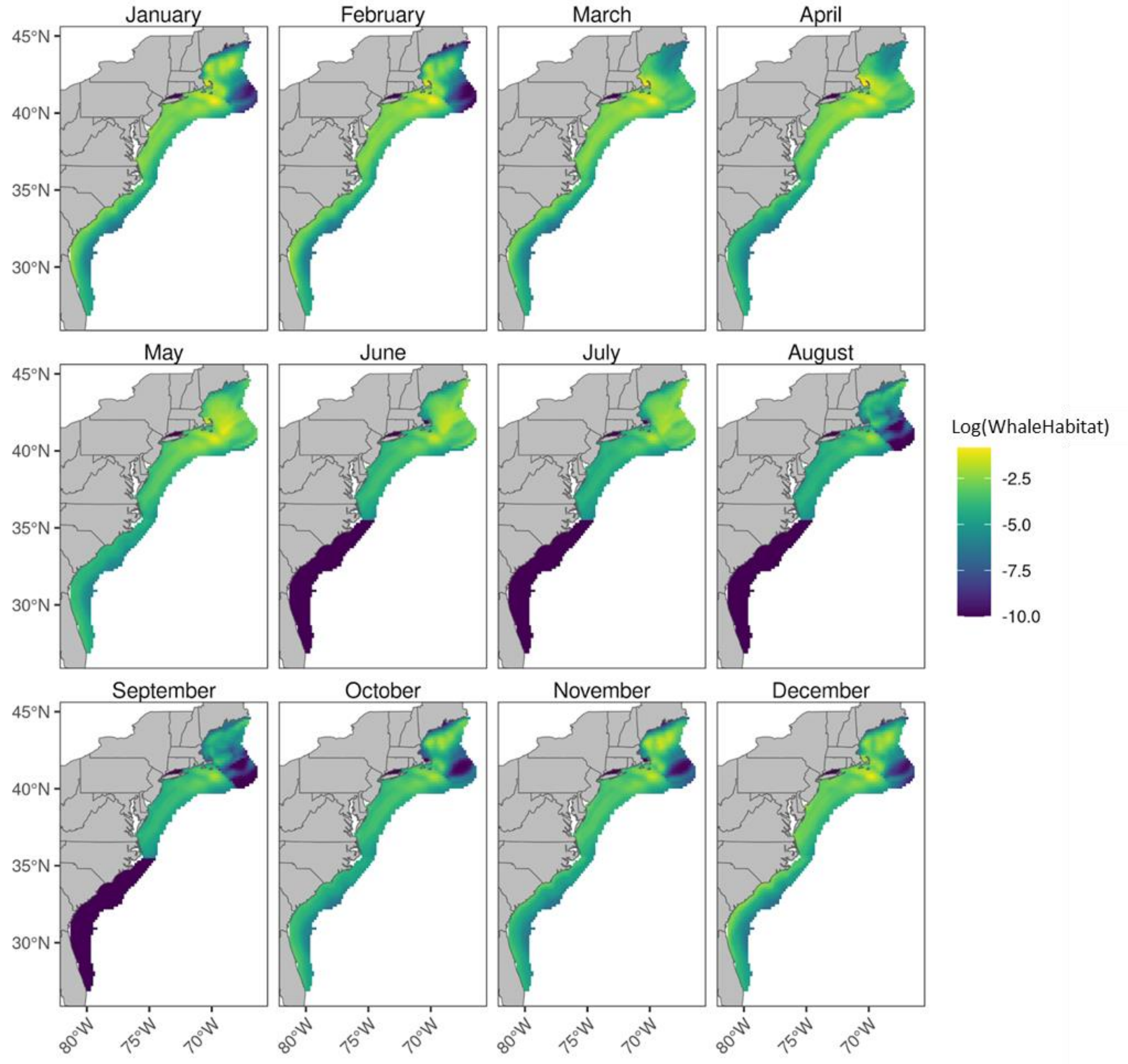

Figure 20. Monthly North Atlantic right whale (*Eubalaena glacialis*) density (Roberts et al. 2016; v12) is recast to the MapRef gridded domain of the Decision Support Tool.

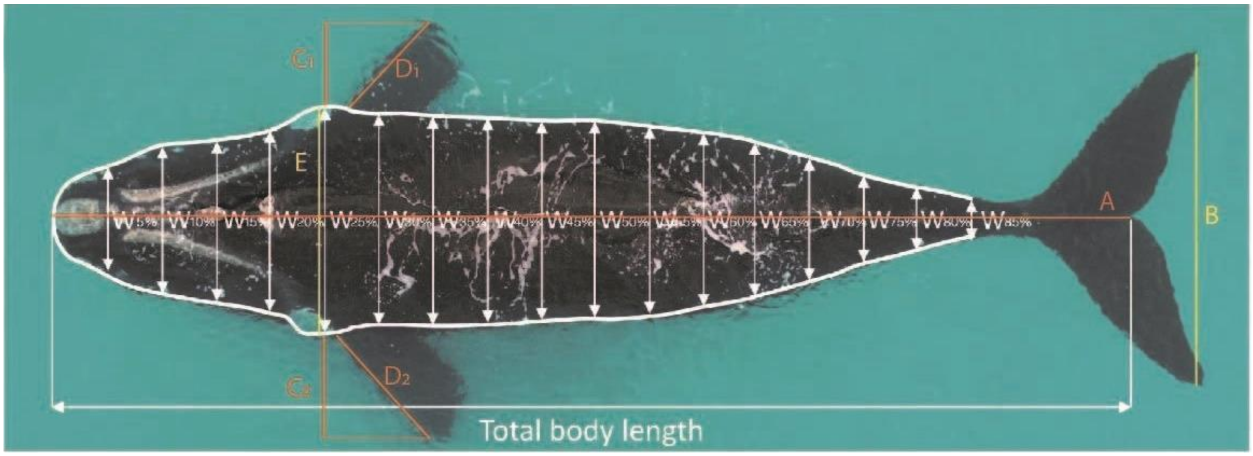

Figure 21. Diagram of the photogrammetry method for calculating the relevant dimensions of a North Atlantic right whale (*Eubalaena glacialis*). A planar photograph adapted from Christiansen et al. (2020) was used to determine A) total body length, B) fluke width, C) flipper extension (distance from axial to farthest reaching point perpendicular to the body), D) flipper length (distance from axial to tip), E) body diameter at max girth, and F) total width (C_1 + E + C_2) measurements used to calculate whale dimensions.

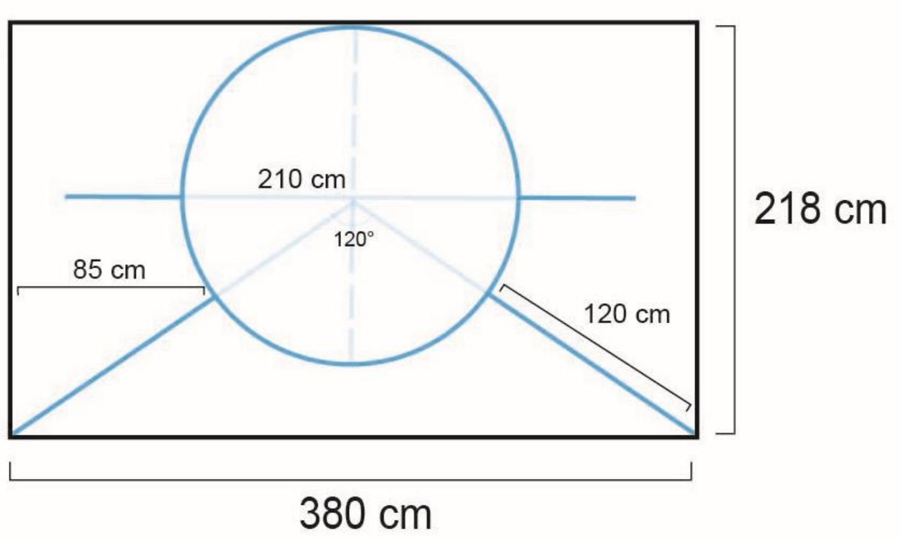

Figure 22. A cross-section diagram of whale dimensions was used to determine encounter probability with gillnets.

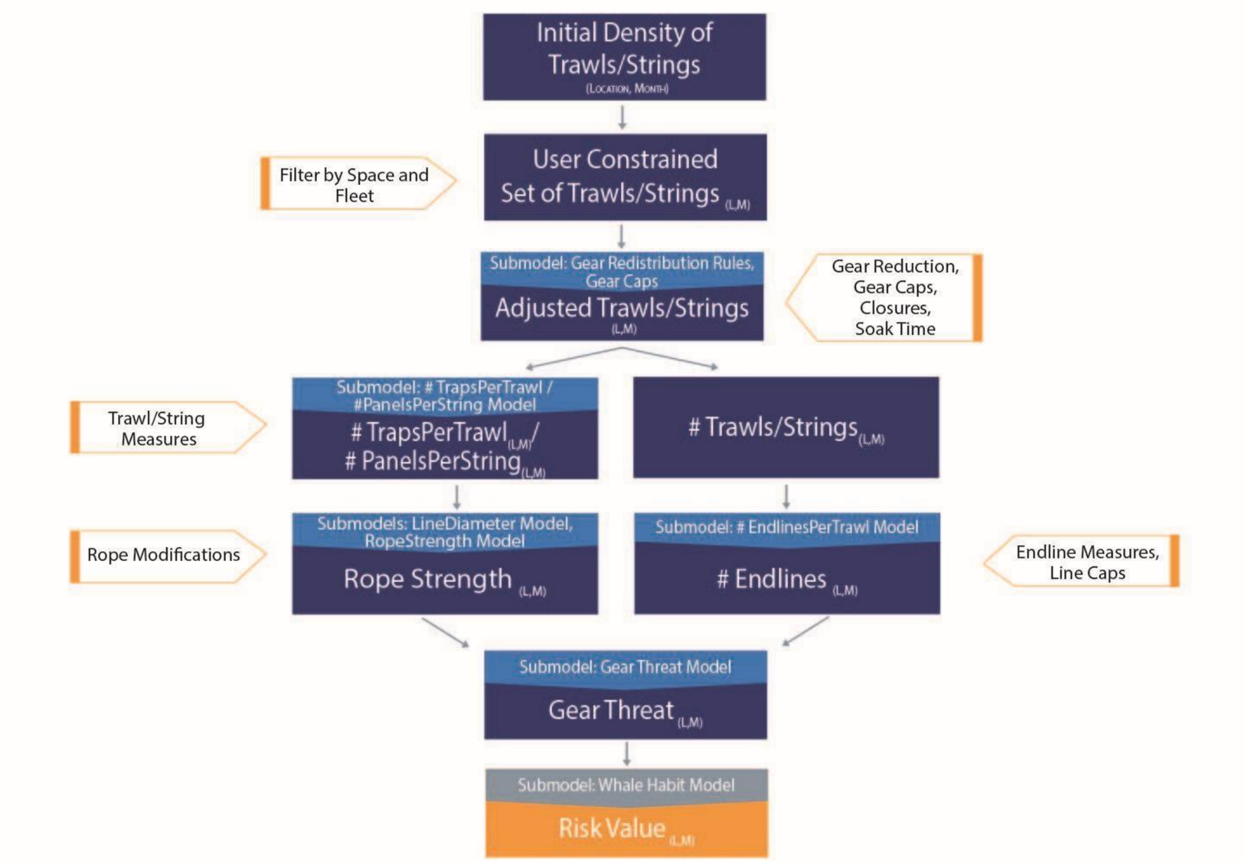

Figure 23. The Decision Support Tool is a function in R with a deterministic series of calculations and a modular design made up of various fishery and whale inputs (in dark blue), with a number of submodels (light blue headers) used to carry out calculations and transformations that are imposed by management actions (white exterior arrows) that eventually lead to resulting risk estimates.

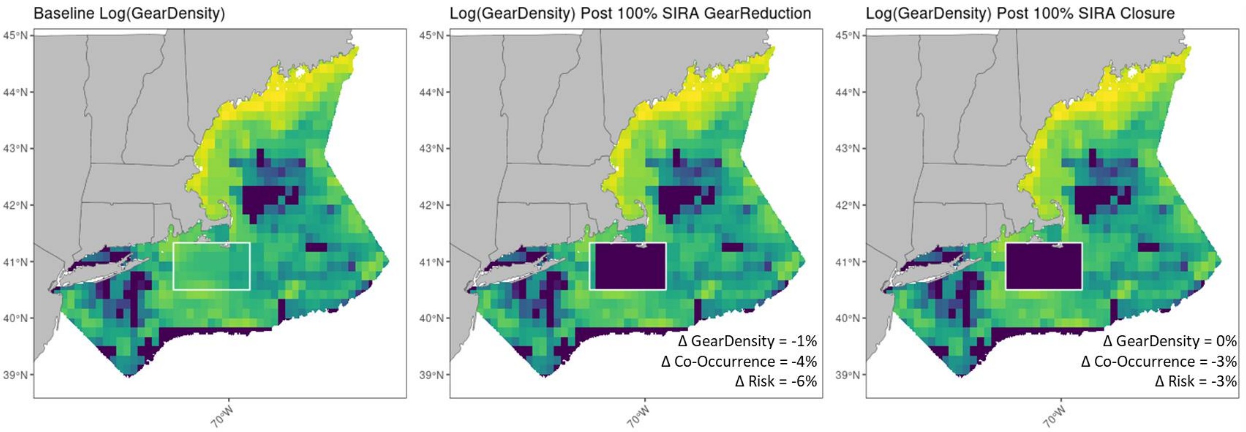

Figure 24. Different results occur when implementing a gear reduction action (center) where gear is removed from the water in the South Island Restricted Area (SIRA; white line) compared to a closure where gear is allowed to move. Change in gear density from the baseline gear density (left) from the100% gear reduction (center) results in 1% decrease in gear density, 4% reduction in co-occurrence, and 6% reduction in risk from baseline values. The closure results in 0% reduction in gear density (all of the gear is successfully displaced), 3% reduction in co-occurrence, and 3% reduction in risk.

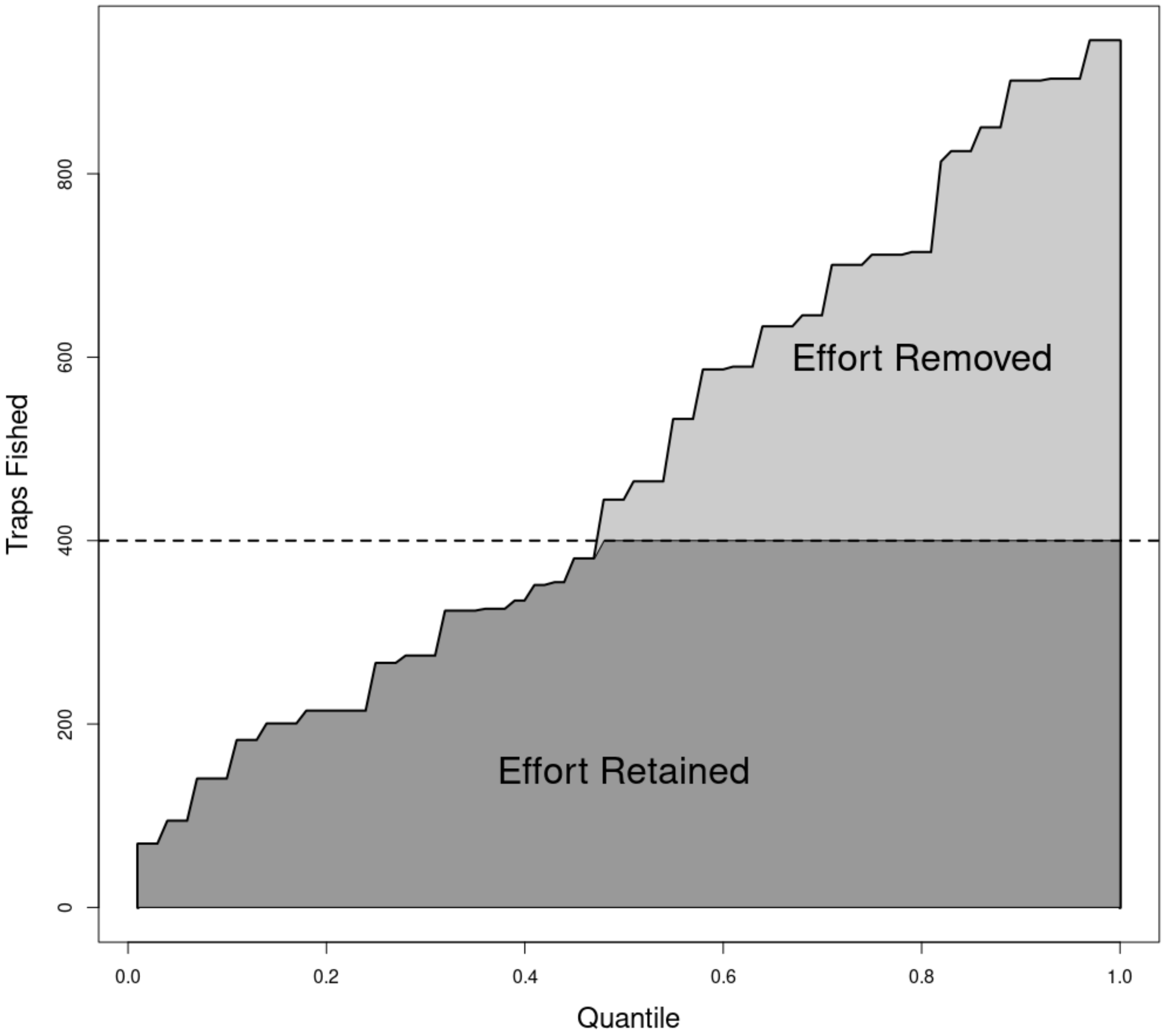

Figure 25. A cumulative quantile curve demonstrates the amount of effort retained and removed from an example 400-trap gear cap. The proportion reduction is calculated as the retained effort divided by both the removed and retained effort (33% reduction in total effort in this example).

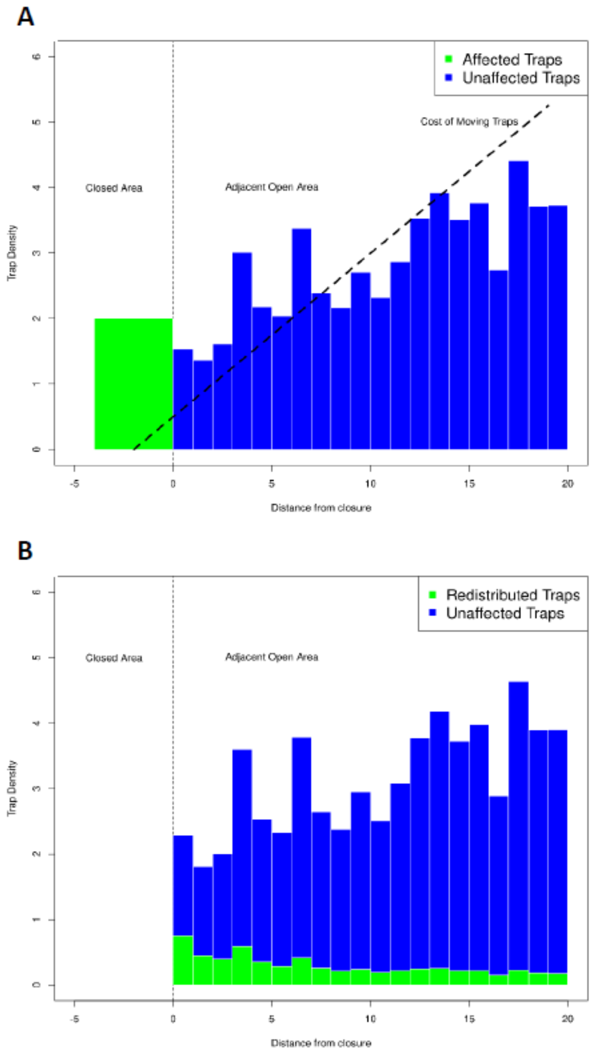

Figure 26. A step-wise illustration describes the process of redistributing traps in a closure scenario. (A) First, affected traps inside the closure to be moved are identified (green) alongside the density of unaffected traps outside the closure (blue), and a linear cost function of moving traps to greater distances (dashed line). (B) Resulting locations of the redistributed traps (green) are a function of the density of adjacent unaffected traps (blue) and cost of redistribution.

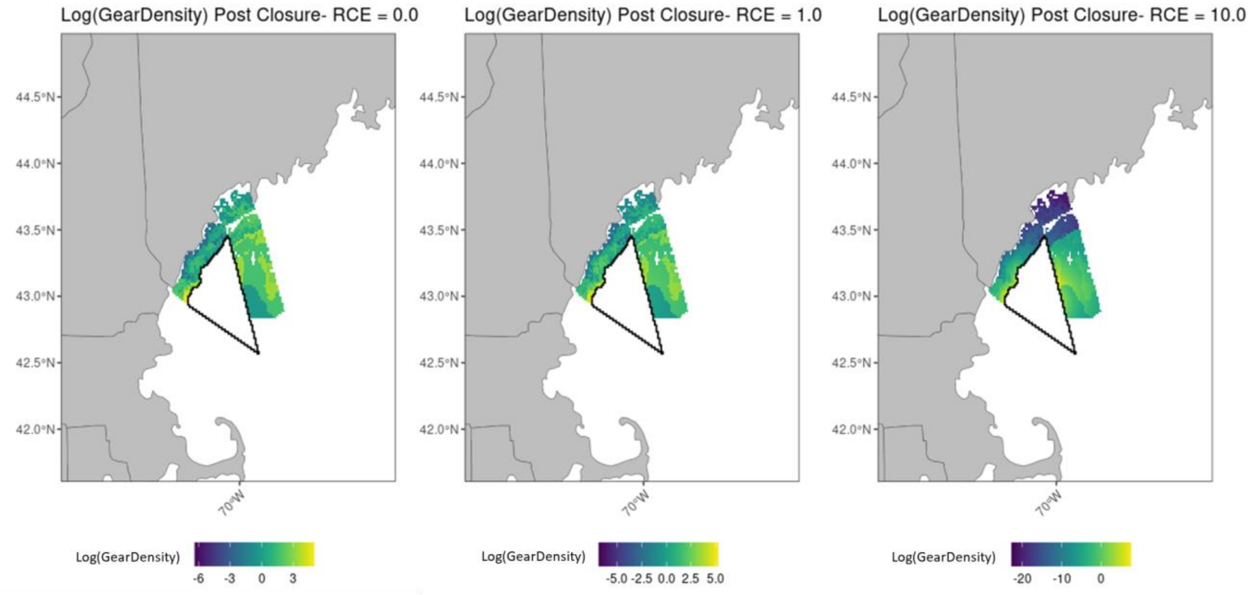

Figure 27. Adjusting the Relocation Cost Exponent (RCE) affects the cost of moving gear when a closure is implemented in the Decision Support Tool. The RCE defaults to 1 (center), making cost of moving gear a linear function, while a value of 0 (left) removes distance as a factor and a value of 10 (right) increases the cost of moving gear greater distances and increases relocated gear around the periphery of the closure.

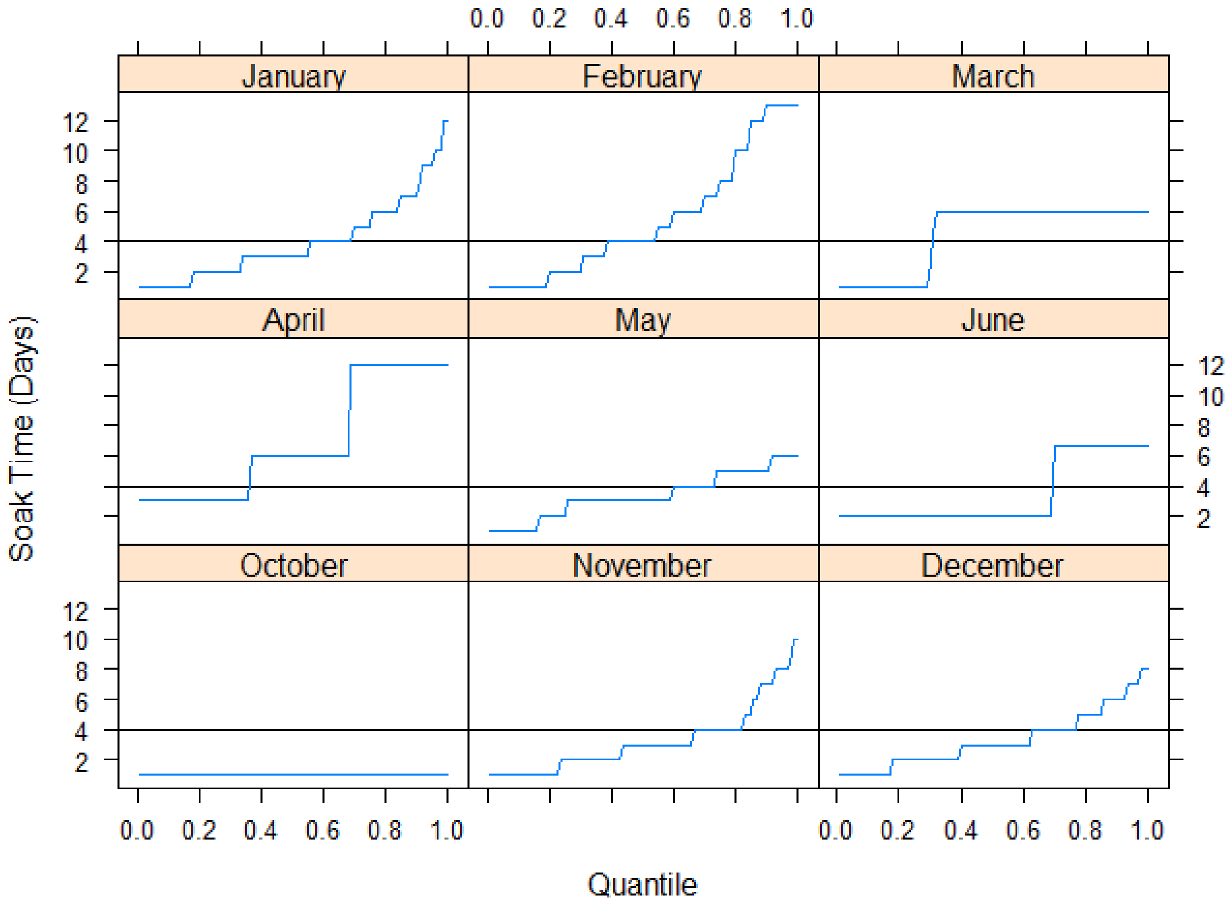

Figure 28. Soak time cumulative effort quantiles for a trap/pot fishery in the Mid-Atlantic by month identify the proportion of trips affected if a soak limit of 4 days were imposed on this fishery.

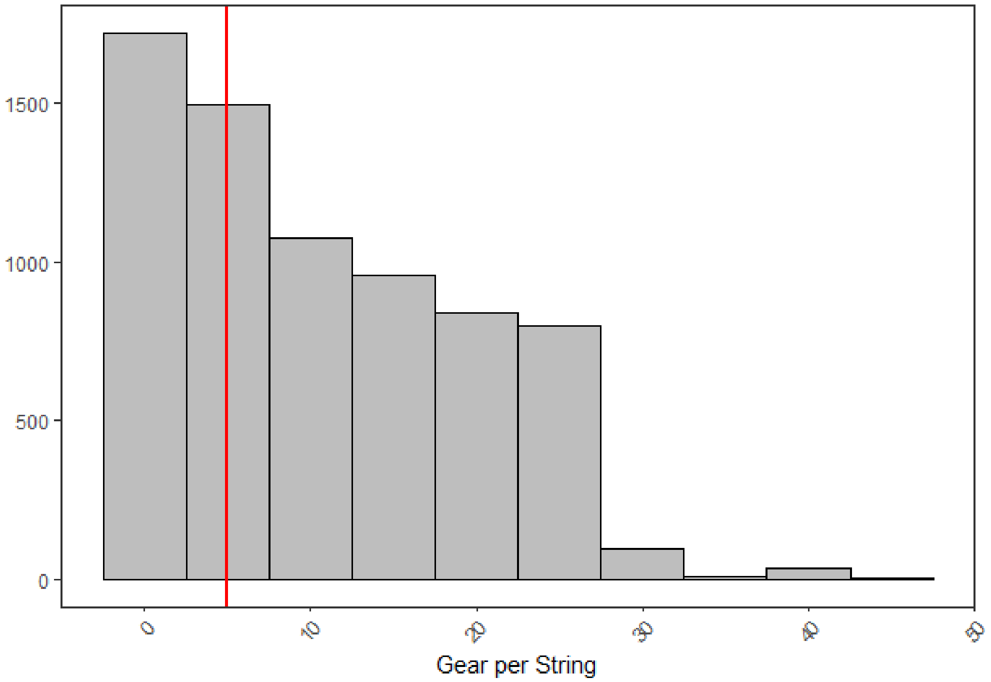

Figure 29. A frequency distribution illustrates the amount of gear per string observed in a group of trap/pot fisheries. In a scenario applying a minimum gear per string action, the red line represents the minimum traps per trawl threshold, with the distribution below representing strings with fewer than 5 traps per trawl that are impacted.

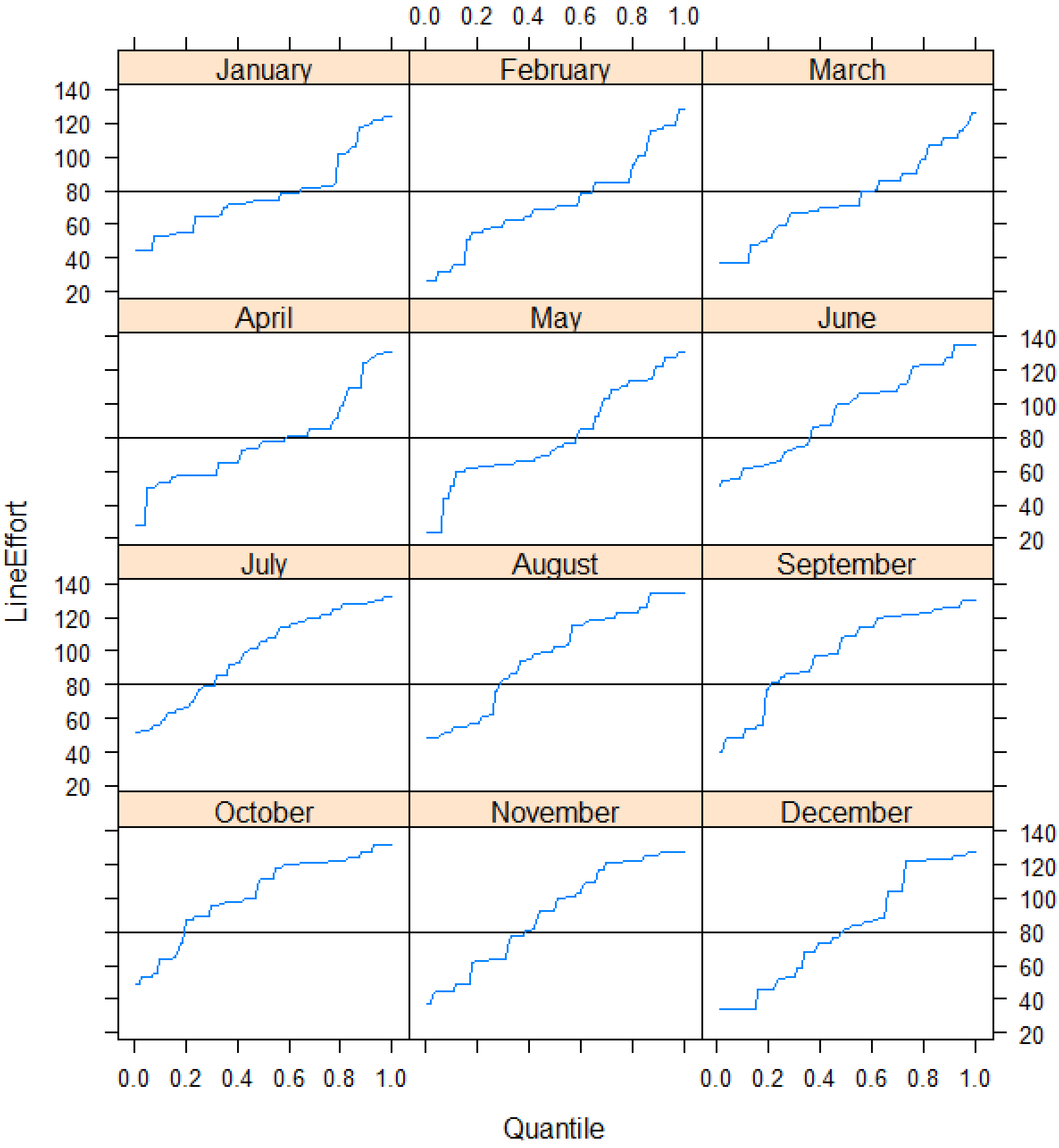

Figure 30. Line effort (number of lines fished by each vessel) cumulative effort quantiles for a subset of the Northeast lobster fishery by month identify the proportion of trips that would be affected if a line cap of 80 lines were imposed on this fishery.

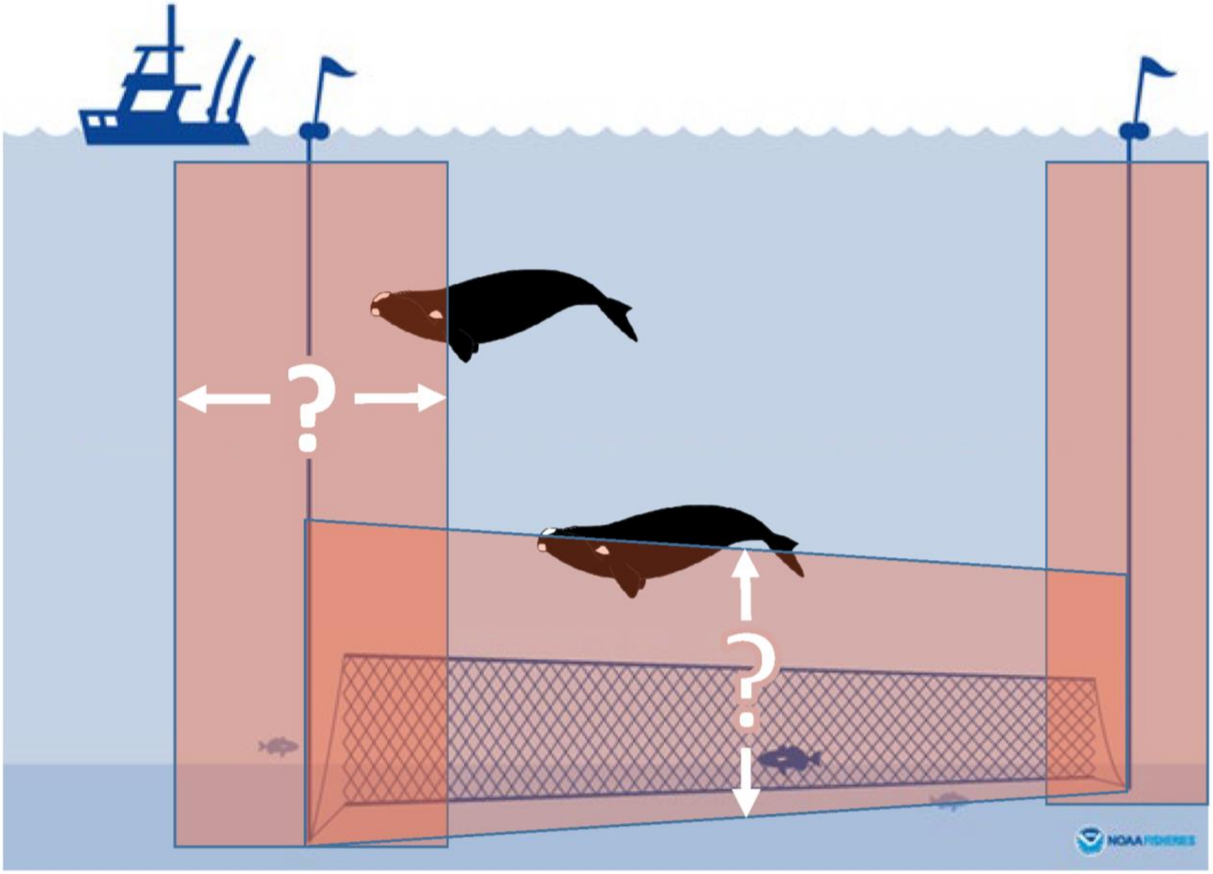

Figure 31. To solve the question of how to quantify the risk of entanglement vertical lines and gillnet panels pose, an understanding of their encounter space available to whales must be considered.

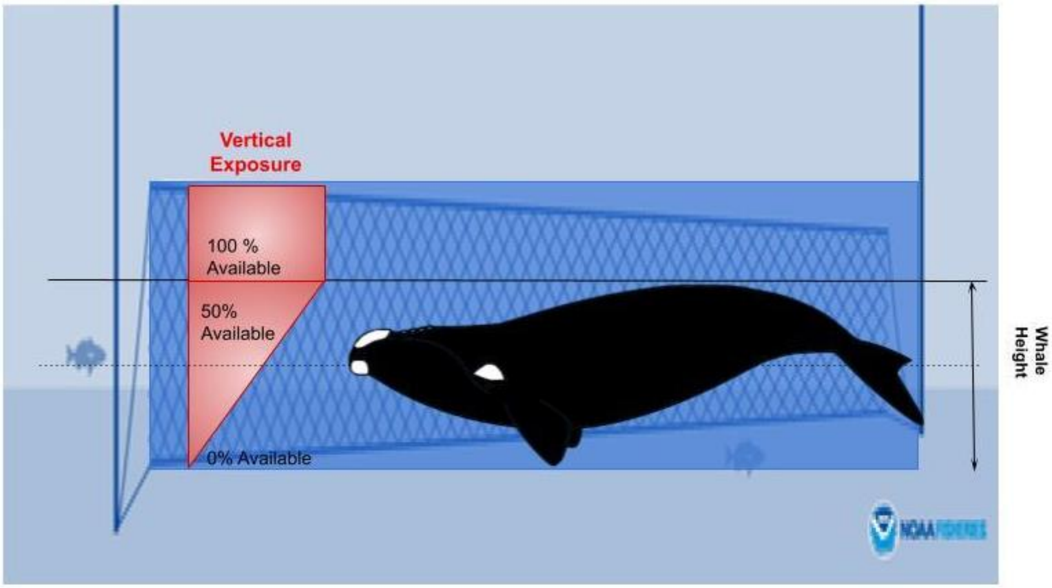

Figure 32. Whale dimensions and gillnet panel height are considered in the calculation of encounter space, where exposure decreases linearly for the portion of the net that is less than a whale height.

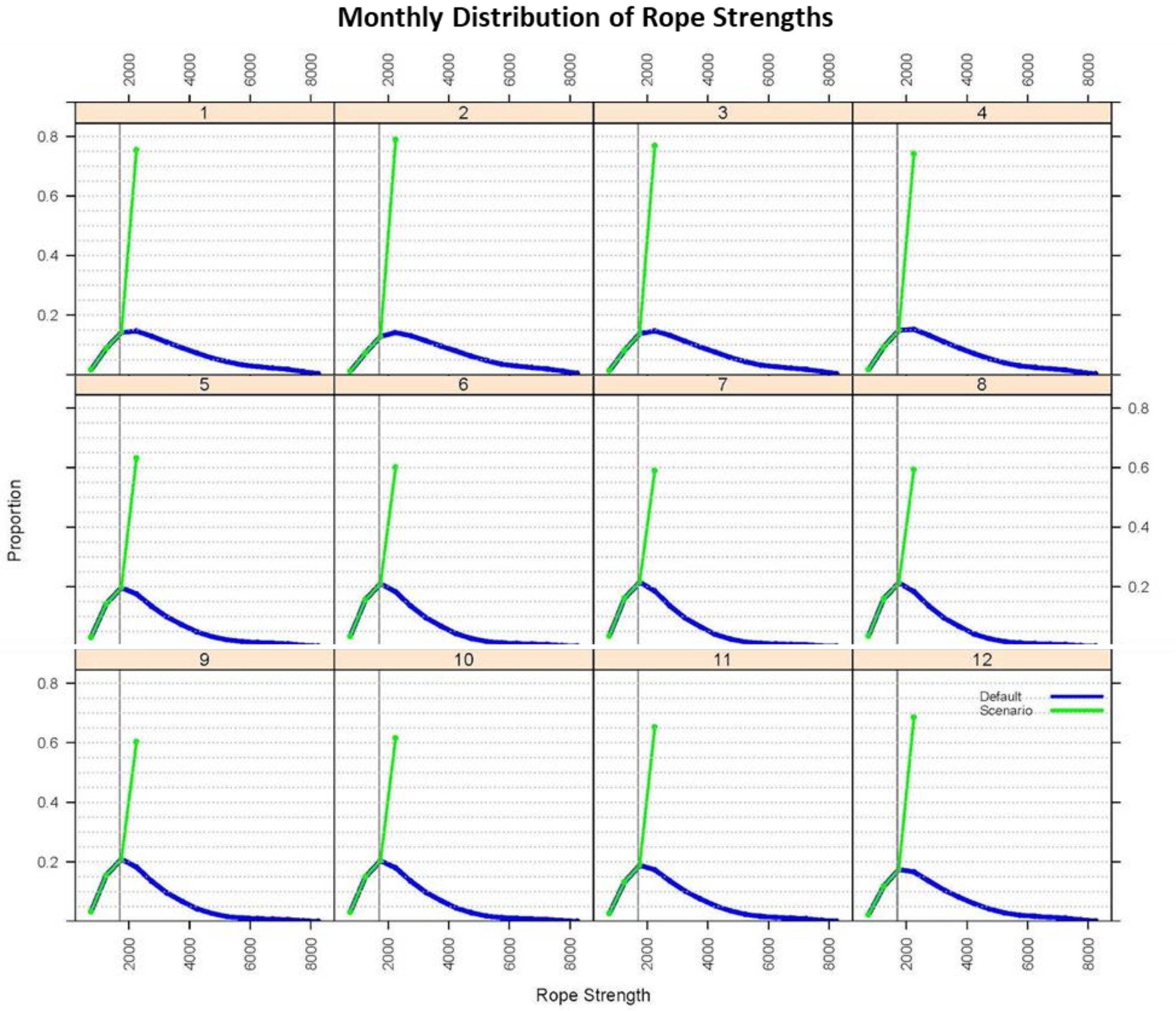

Figure 33. Baseline (blue) monthly distributions of endline rope strength proportions are truncated when a scenario (green) implementing a maximum rope strength of 2,200 lbs. is imposed.

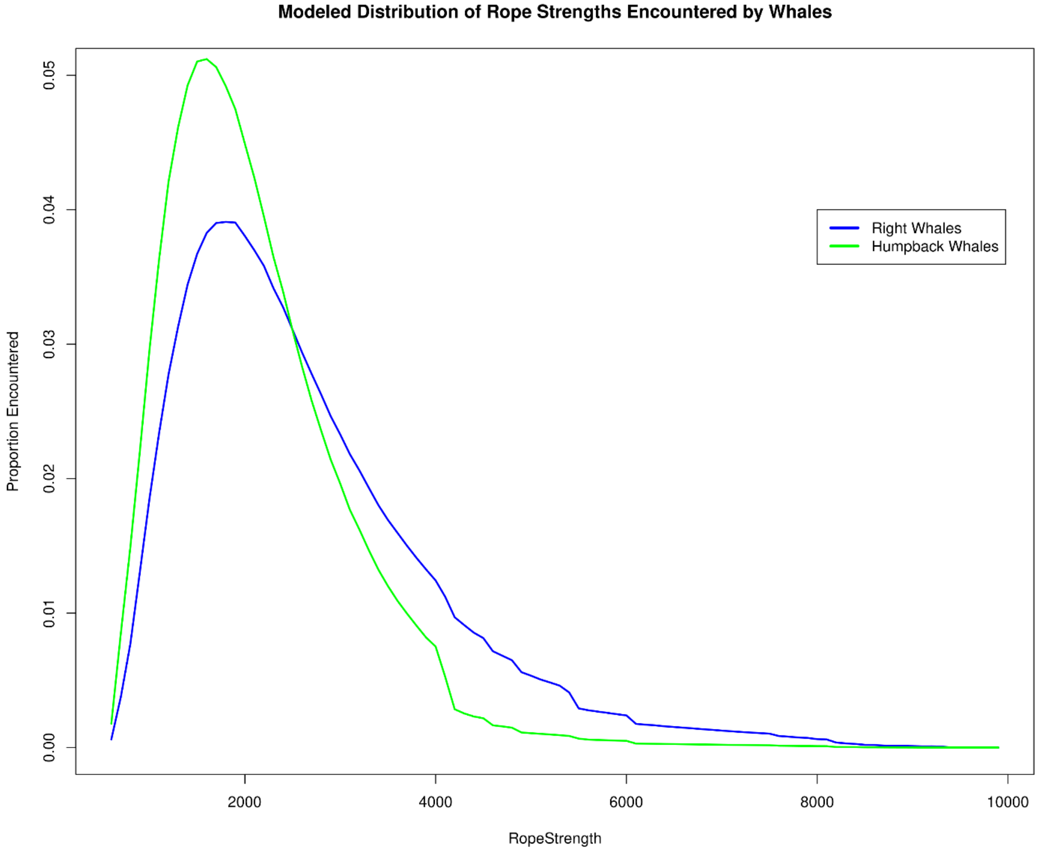

Figure 34. Distributions of endline rope strengths that North Atlantic right whales (*Eubalaena glacialis*) and humpback whales (*Megaptera novaeangliae*) ould be expected to encounter are based on overlap of gear distributions and whale habitat models resulting from baseline runs of the Decision Support Tool.

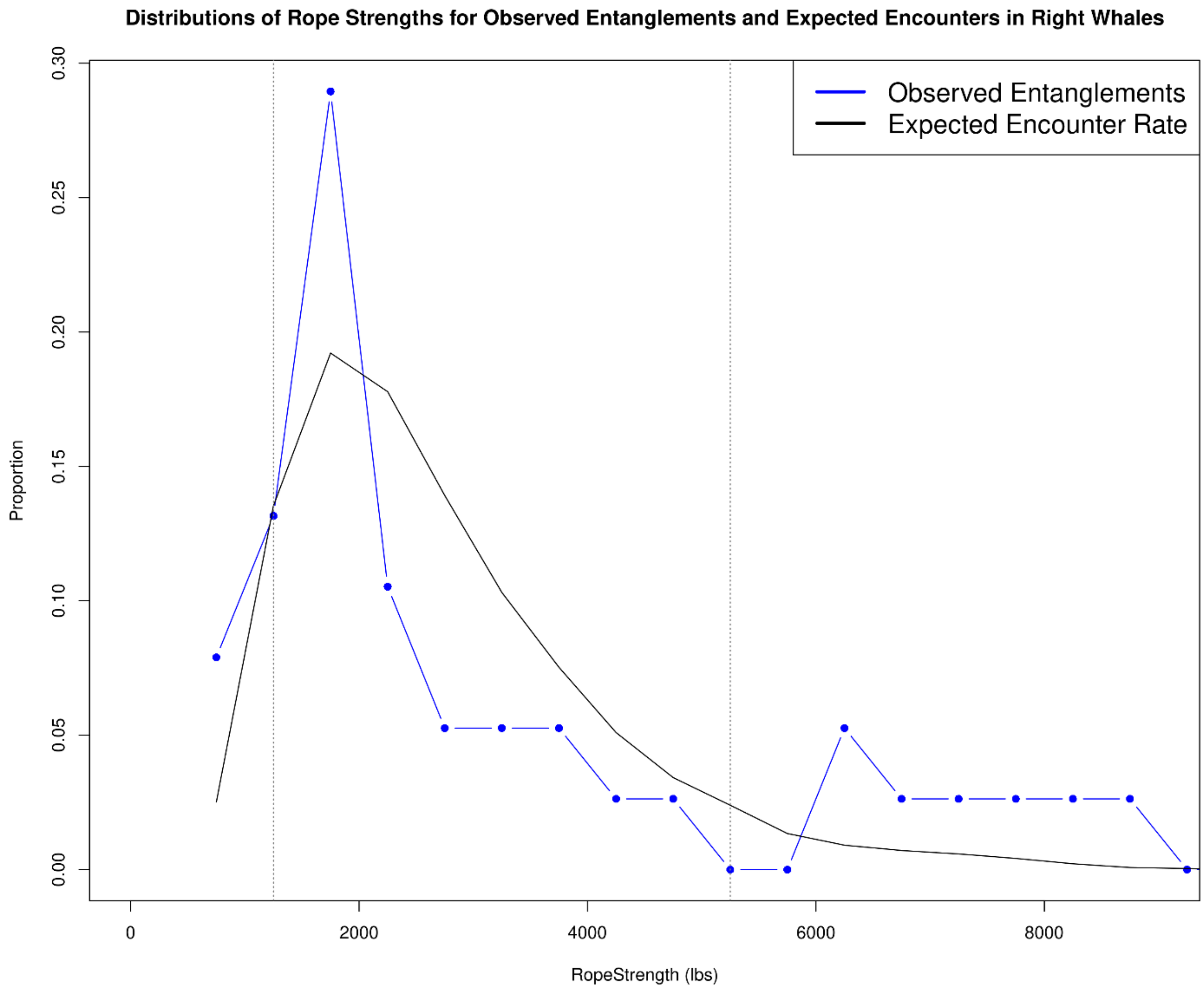

Figure 35. Distributions of rope strengths expected to be encountered by North Atlantic right whales (*Eubalaena glacialis*) in comparison to observed entanglements shows a similar trend with heaviest ropes more common in entanglements than expected.

Figure 36. Distributions of rope strengths expected to be encountered by humpback whales (*Megaptera novaeangliae*) in comparison to observed entanglements shows a similar trend with heavier ropes (~4000-6000 lbs.) more common in entanglements than expected.

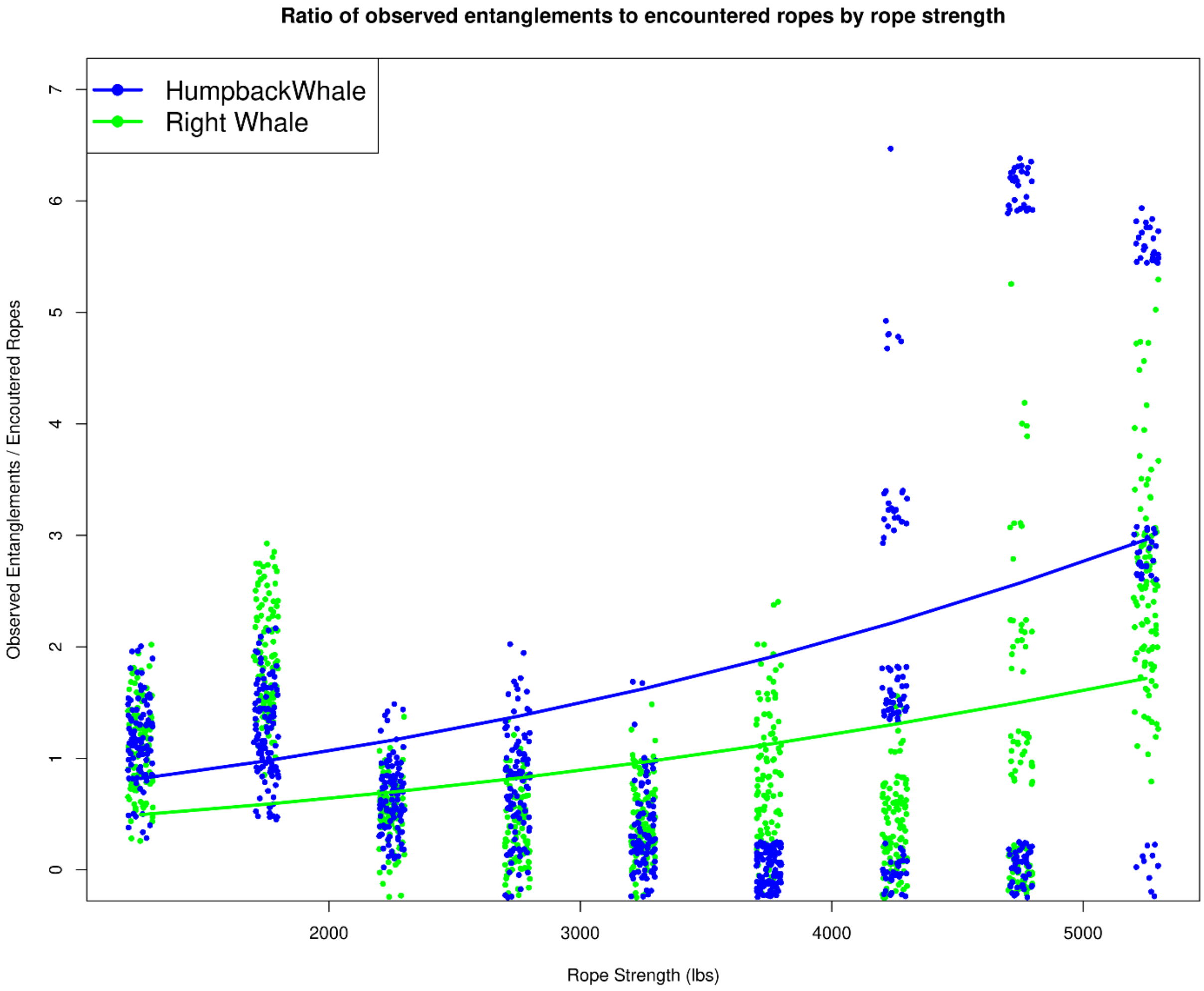

Figure 37. Bootstrapped ratios of observed entanglement rope strength to expected encounter rope strength with fitted lines for North Atlantic right whales (*Eubalaena glacialis*) and humpback whales (*Megaptera novaeangliae*) show an increase with rope strength that is statistically significant, but the species effect is not. A lack of fit at intermediate and high rope strengths is also evident.

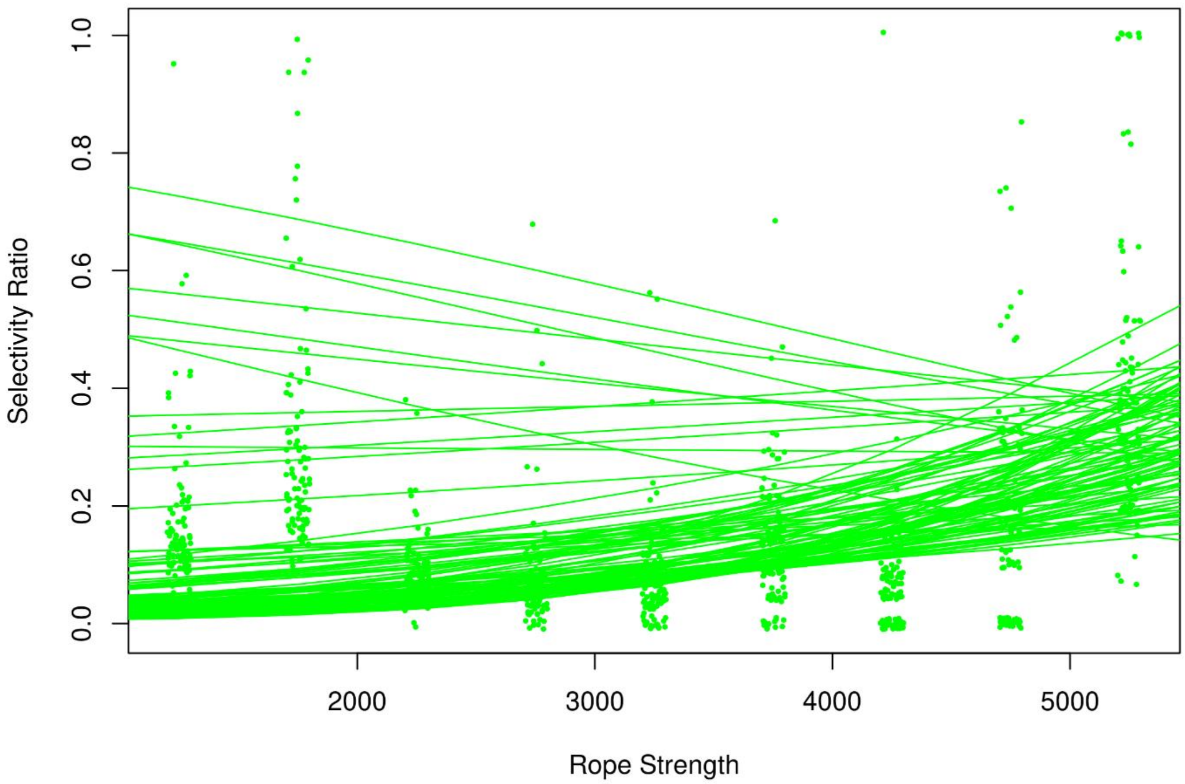

Figure 38. Example bootstrapped threat models show the relationship between rope strength and apparent selectivity ratio for North Atlantic right whales (*Eubalaena glacialis*).

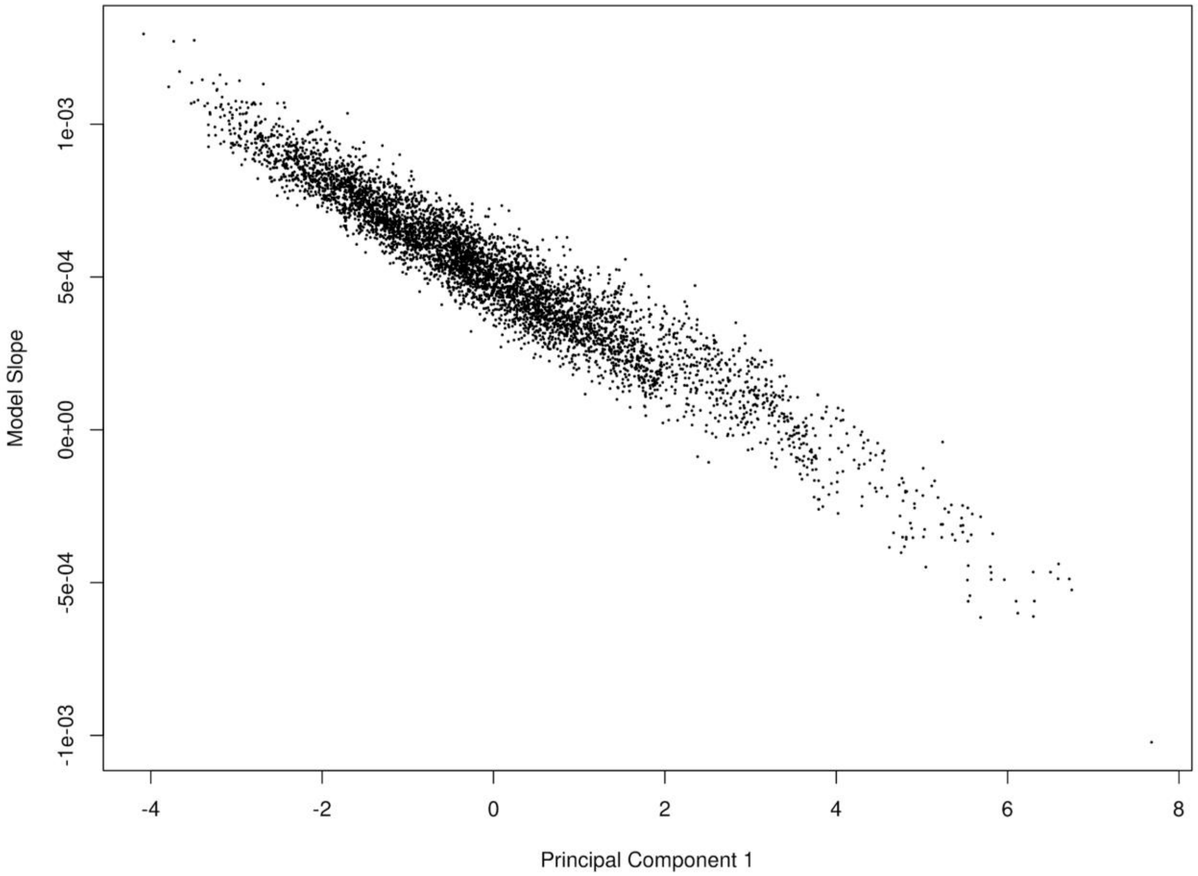

Figure 39. A principal component analysis of parameter estimates from the bootstrapping exercise of threat models (Figure 38) identifies a relationship between threat model slope and Principal Component 1.

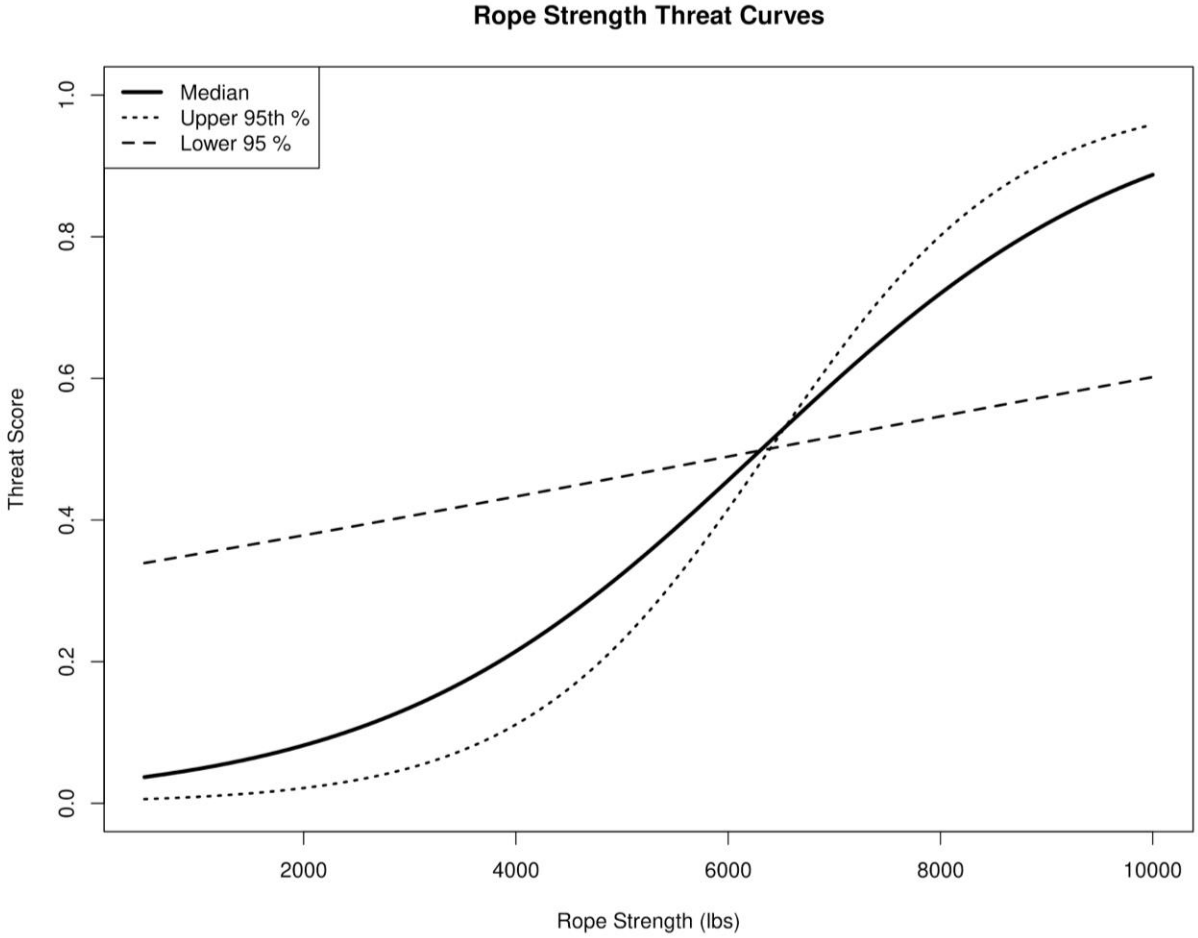

Figure 40. Alternate threat curves representing the median, upper, and lower bounds on the relationship between rope strength and threat provide limits on the relative benefits of decreasing entanglement risk by altering rope strength

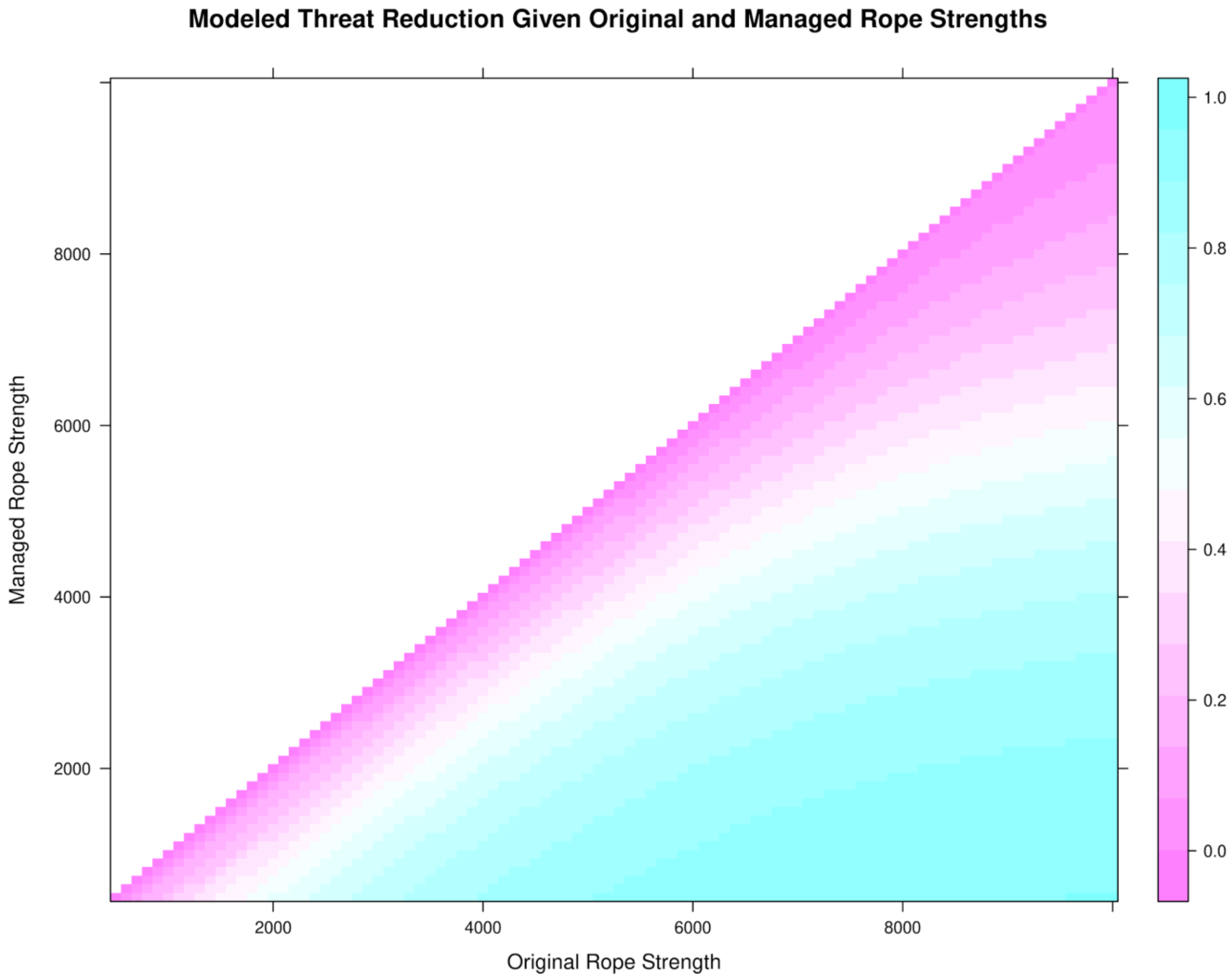

Figure 41. Relative threat surface derived from the median threat curve where surface values represent the reduction in threat based on the ratio of threat scores between pre-management (x-axis) and post-management (y-axis) rope strengths. Thus, values along the diagonal represent no change in rope strength while the area below the diagonal represents decreases in rope strength.

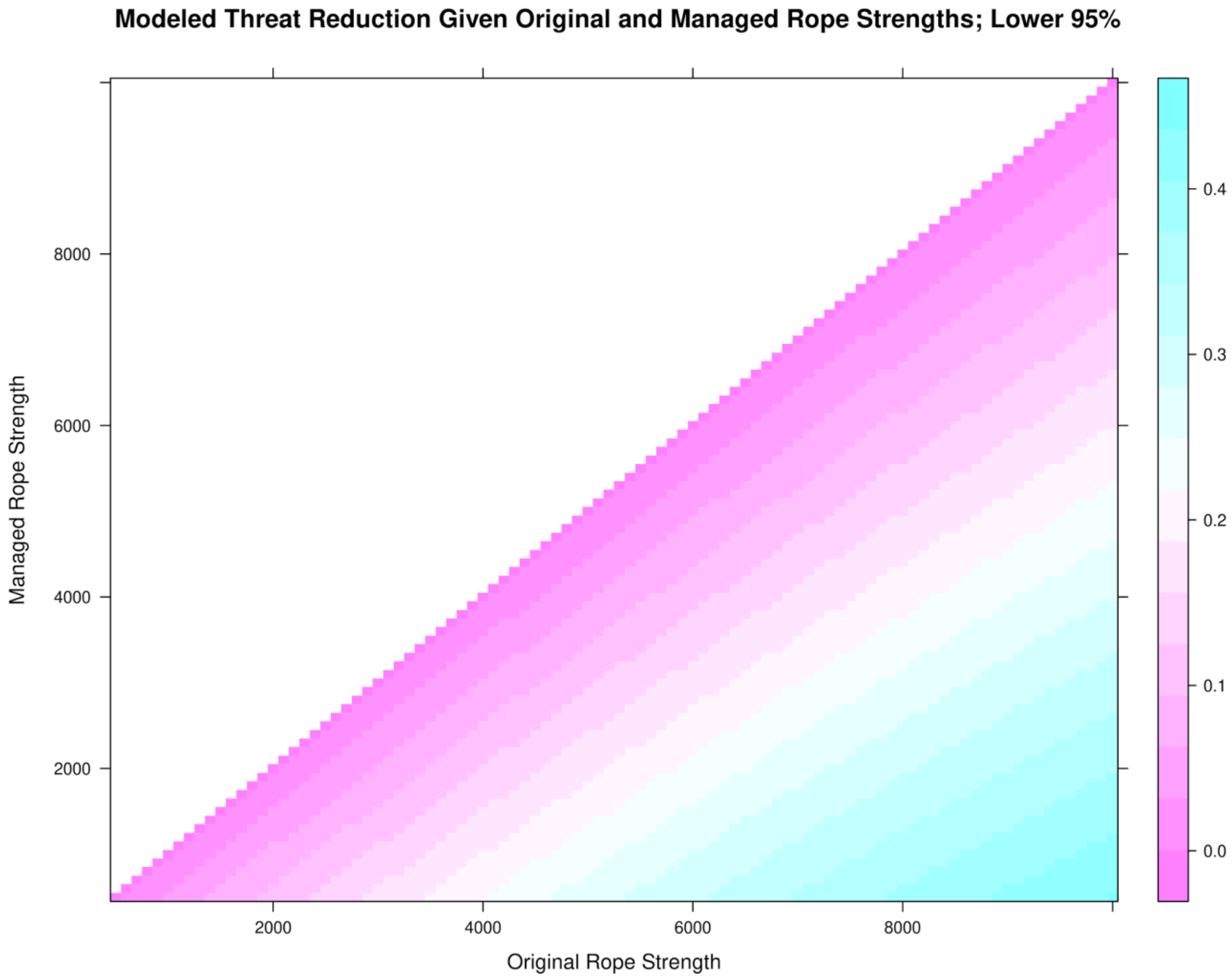

Figure 42. Relative threat surface derived from the lower bound threat curve where surface values represent the reduction in threat based on the ratio of threat scores between pre-management (x-axis) and post-management (y-axis) rope strengths. Thus, values along the diagonal represent no change in rope strength while the area below the diagonal represents decreases in rope strength.

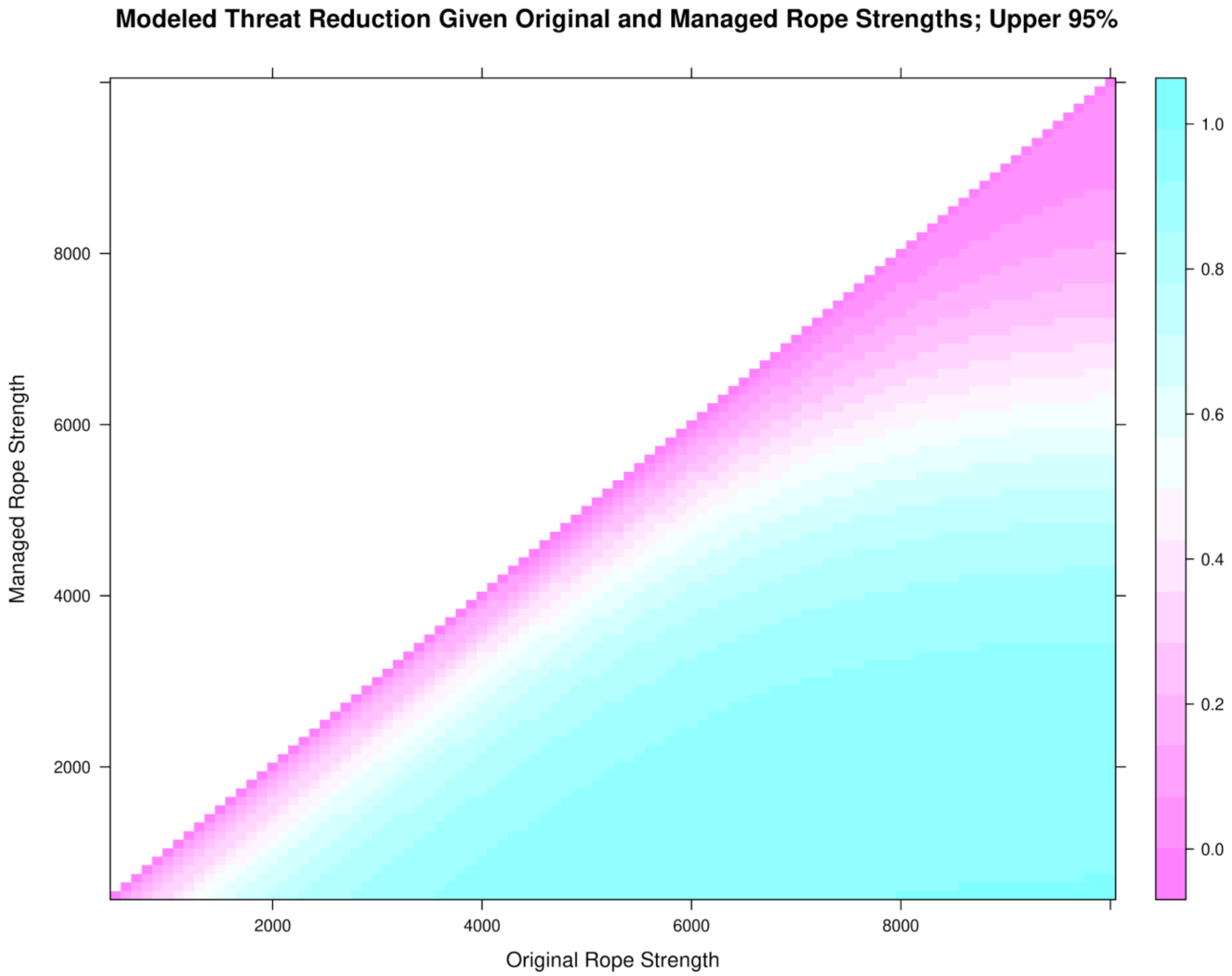

Figure 43. Relative threat surface derived from the upper bound threat curve where surface values represent the reduction in threat based on the ratio of threat scores between pre-management (x-axis) and post-management (y-axis) rope strengths. Thus, values along the diagonal represent no change in rope strength while the area below the diagonal represents decreases in rope strength.

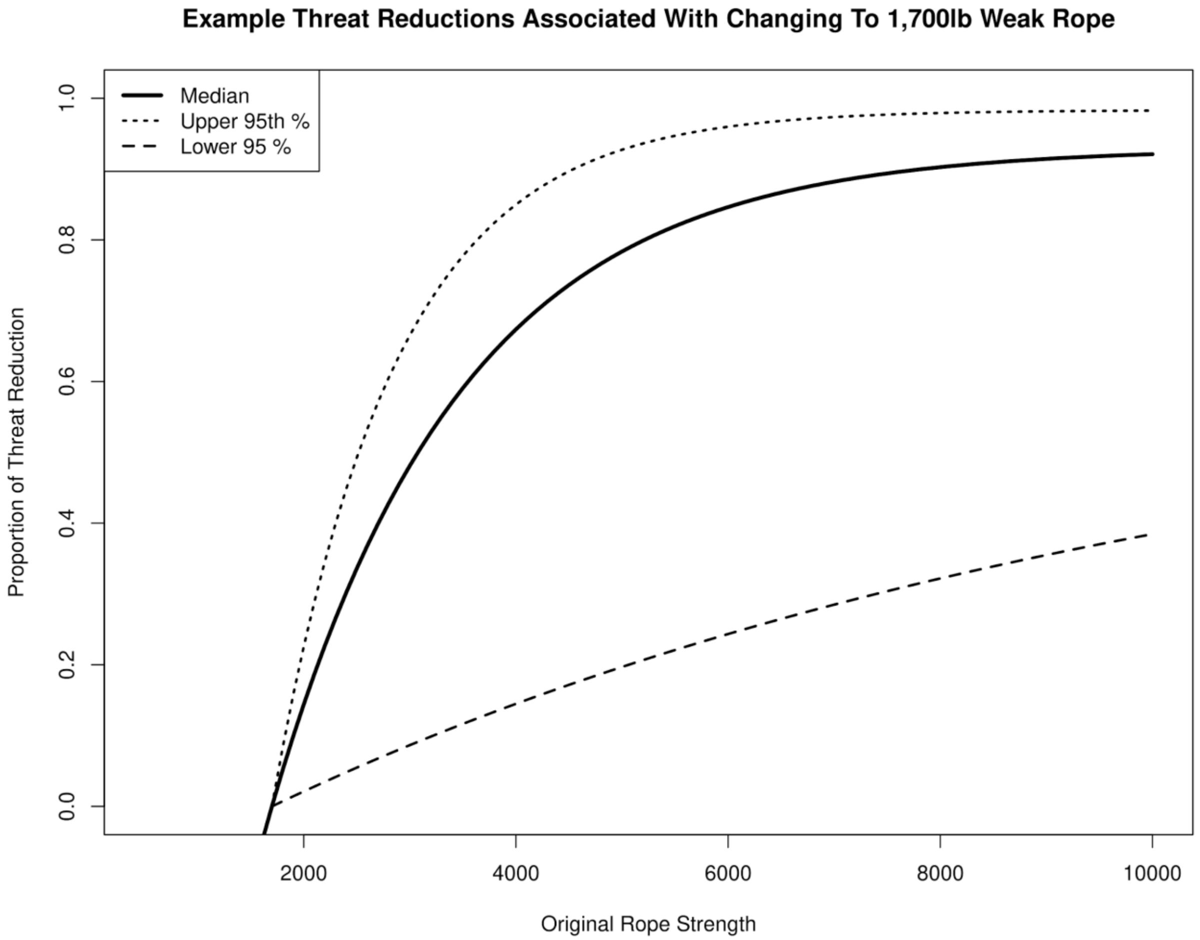

Figure 44. Median, upper bound, and lower bound threat curves provide alternative threat models for decreasing rope strength to 1,700 lbs. within the Decision Support Tool.

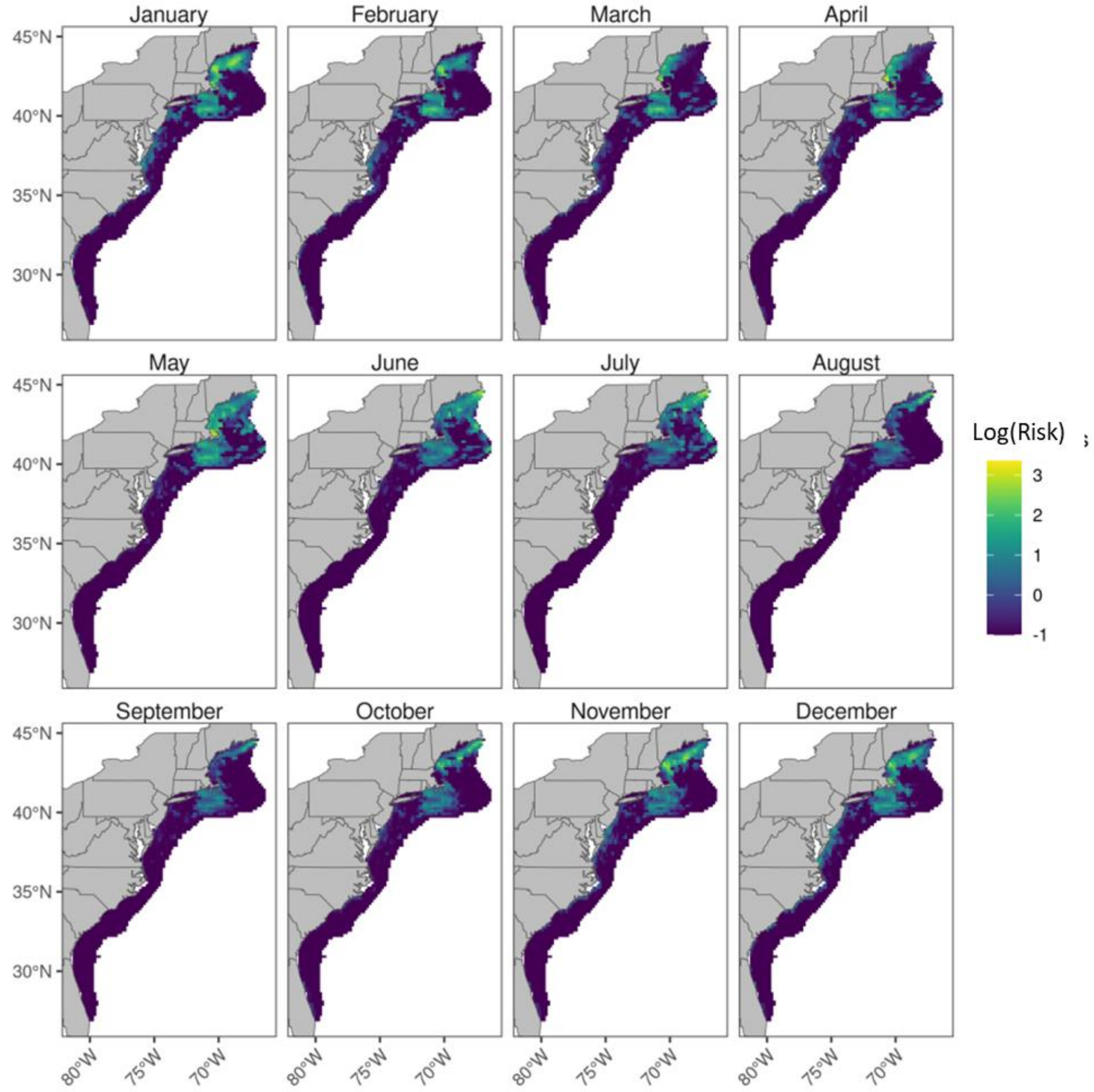

Figure 45. Combining all individual fishery input layers for the entire east coast of the U.S. provides a monthly baseline gear map that identifies areas of high risk for entanglement.

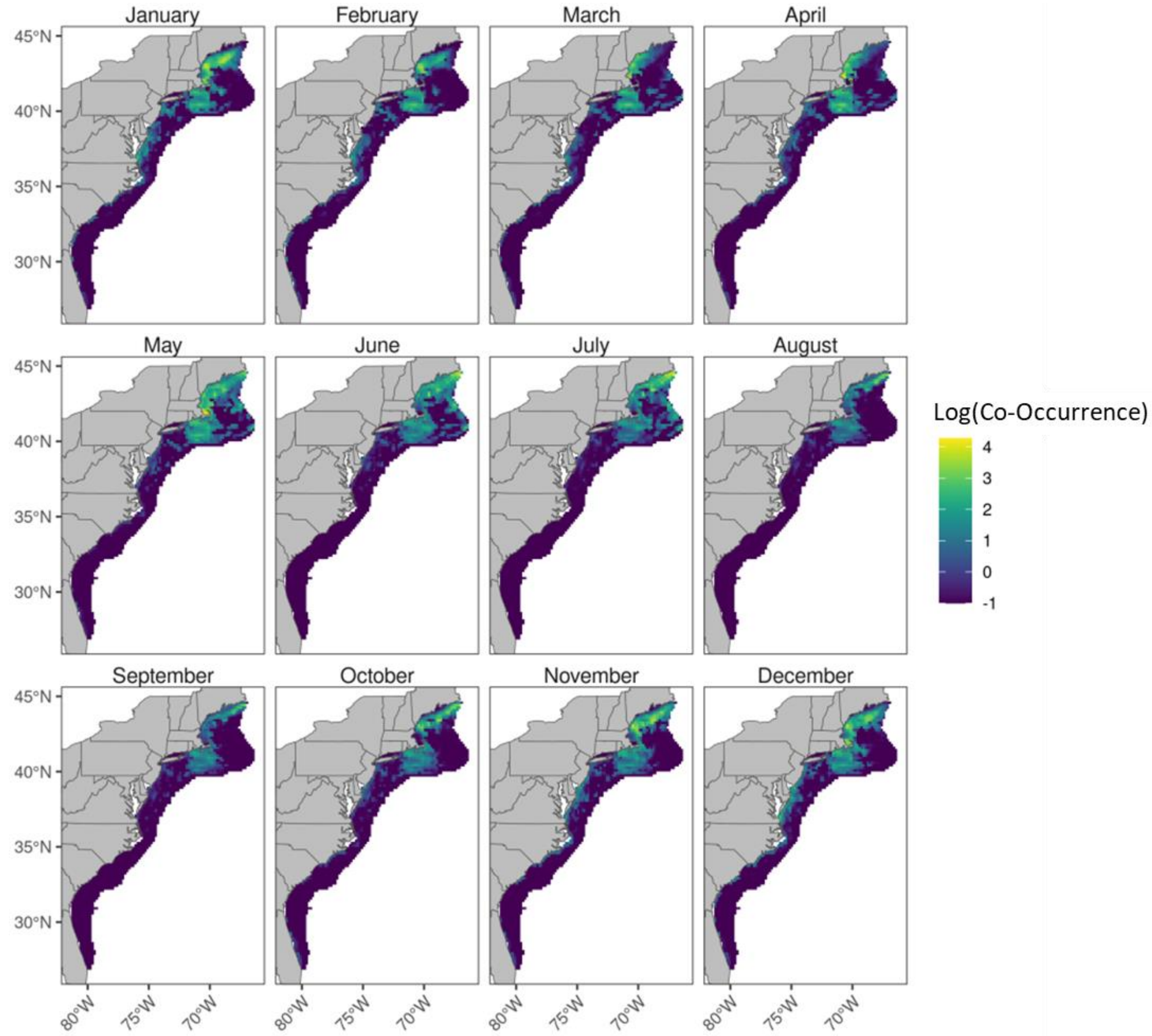

Figure 46. Similar to baseline risk estimates, a co-occurrence baseline combines all individual fishery inputs to determine areas where occurrence of whales and fishing gear are highest without accounting for the threat the gear poses to entanglement.

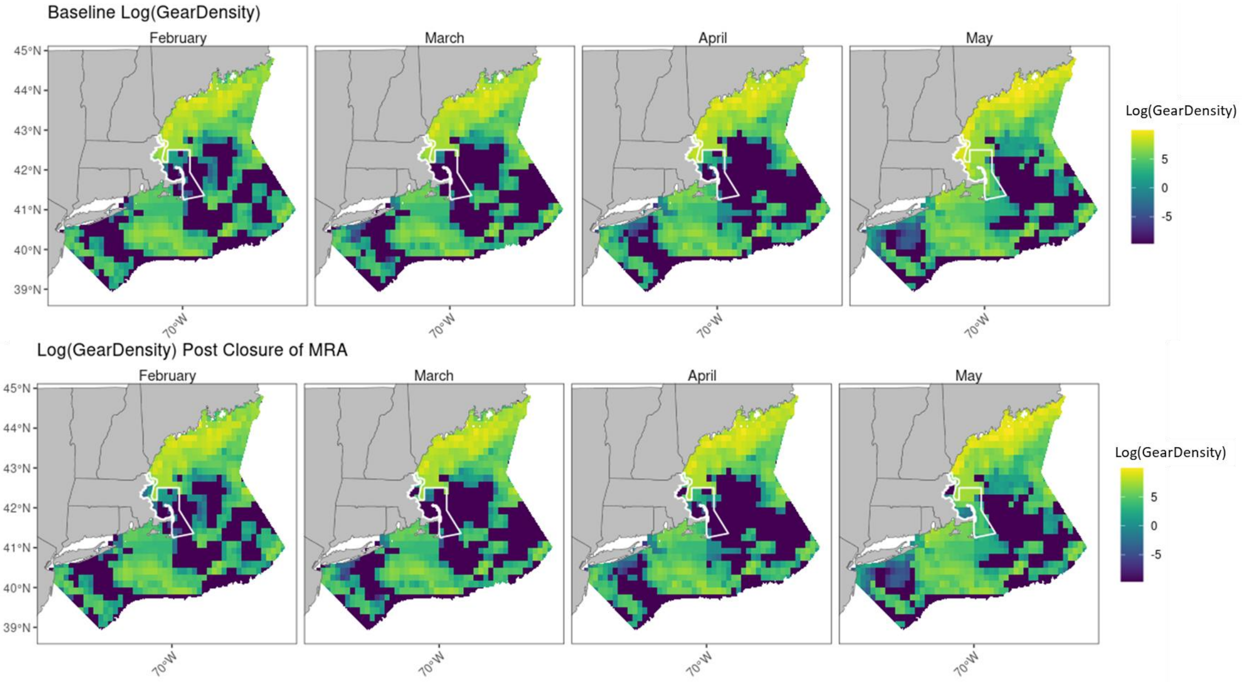

Figure 47. Impacts of closing the Massachusetts Restricted Area from February 1 to May 31 as part of the 2021 final rule management actions can be seen by comparing the baseline gear density (top) to the gear density post closure (bottom). This closure was treated as a gear reduction (gear removed from the water) and only applies to trap/pot gear, leaving any remaining gear density within the closed area attributed to other fisheries.

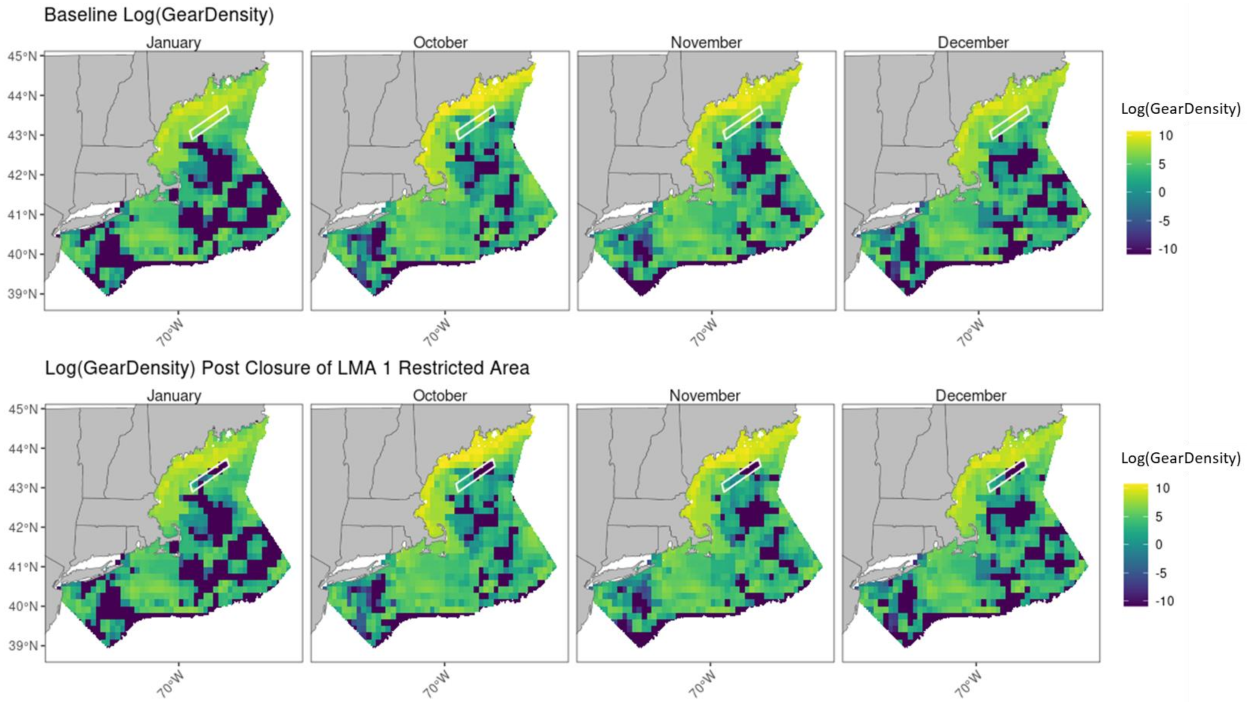

Figure 48. Impacts of closing Lobster Management Area (LMA) 1 Restricted Area from October 1 to January 31 as part of the 2021 final rule management actions can be seen by comparing the baseline gear density (top) to the gear density post closure (bottom). This closure was treated as a true closure (gear may move to adjacent areas) and only applies to lobster gear, leaving any remaining gear density within the closed area attributed to other fisheries.

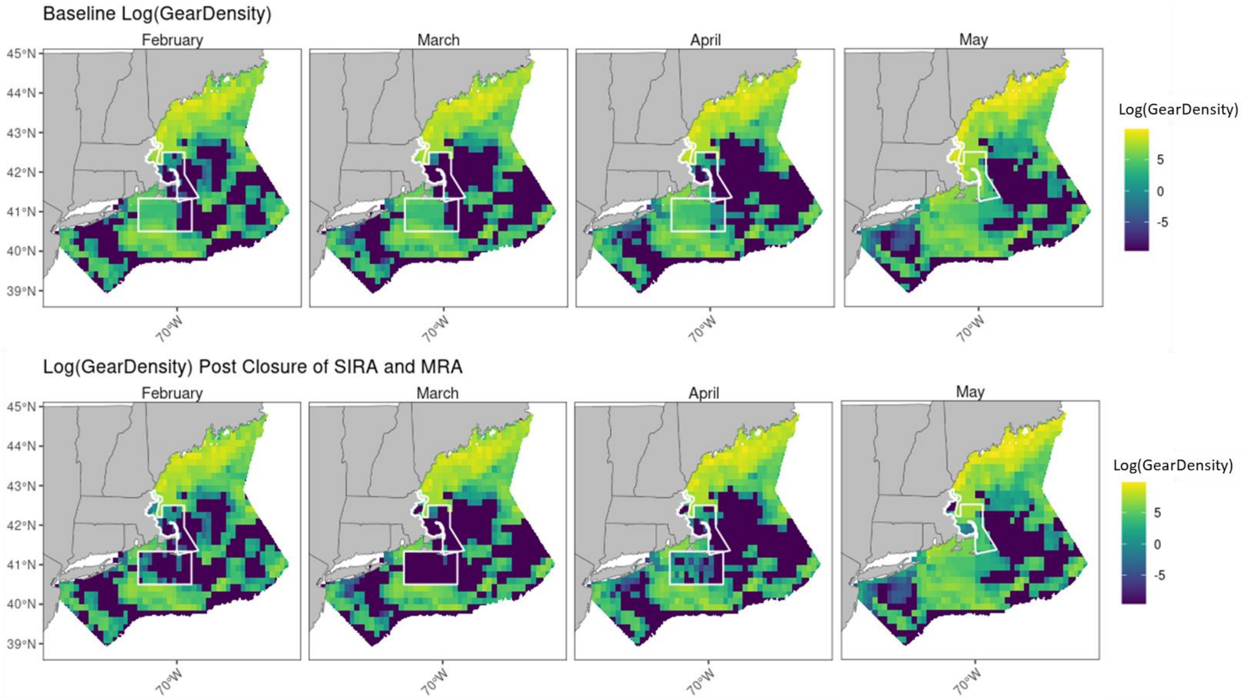

Figure 49. Impacts of closing the South Island Restricted Area (SIRA) and Massachusetts Restricted Area (MRA) in state waters of Lobster Management Area (LMA) 1 and Outer Cape Cod from February 1 to April 30 (the MRA closure also continues through May 31st) as part of the 2021 final rule management actions. These restrictions only apply to lobster gear in SIRA and all trap/pot in the MRA Leaving any remaining gear density within closures attributed to other fisheries.

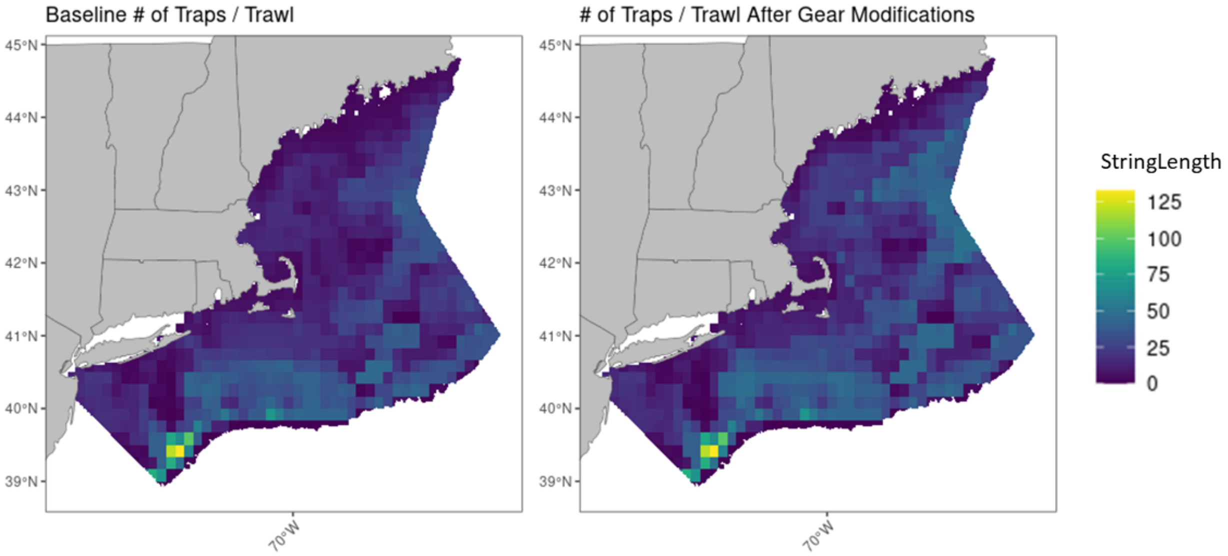

Figure 50. Impacts of the 2021 final rule gear modifications (summarized in Table 10) on string length are compared to the baseline number of traps per trawl (left).

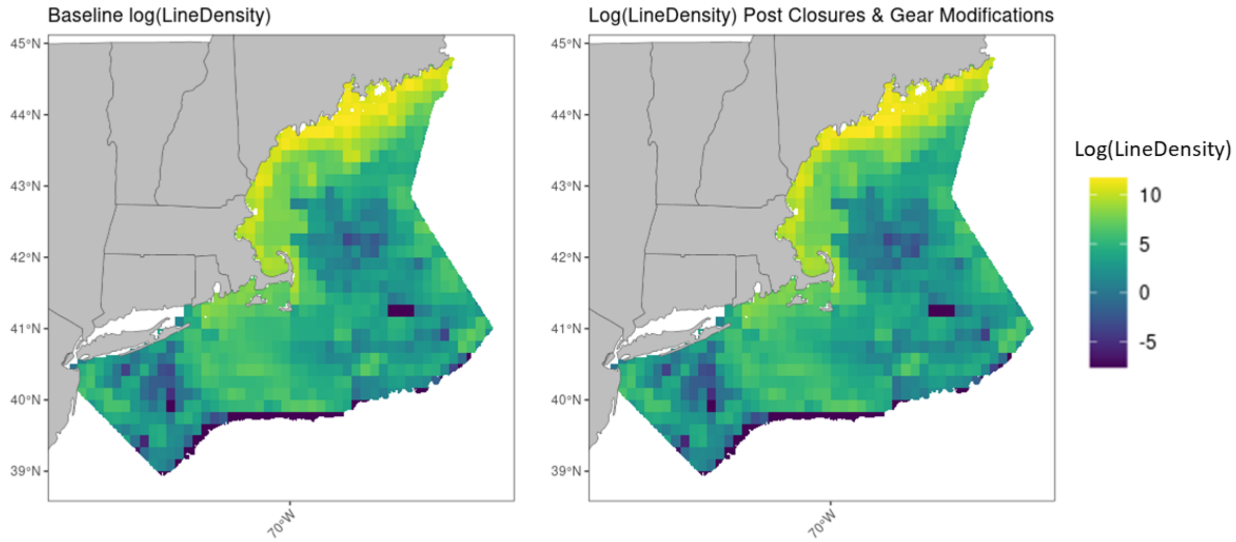

Figure 51. Impacts of the 2021 final rule closures and gear modifications (summarized in Table 9) on line density are compared to the baseline line density (left).

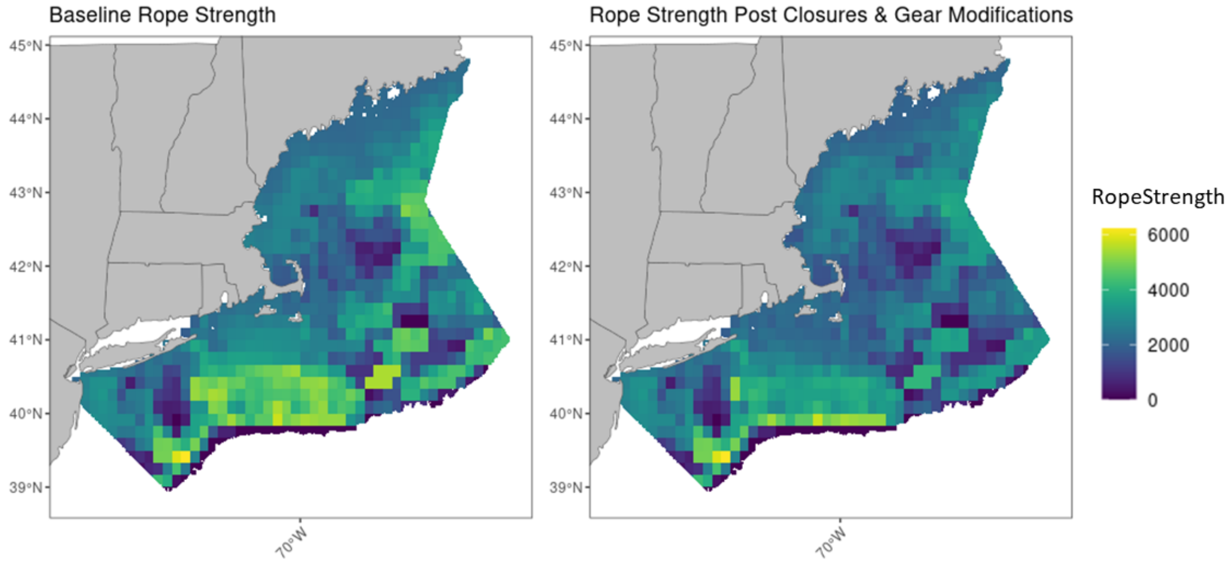

Figure 52. Impacts of the 2021 final rule closures and gear modifications (summarized in Table 9) on rope strength are compared to the baseline rope strength (left).

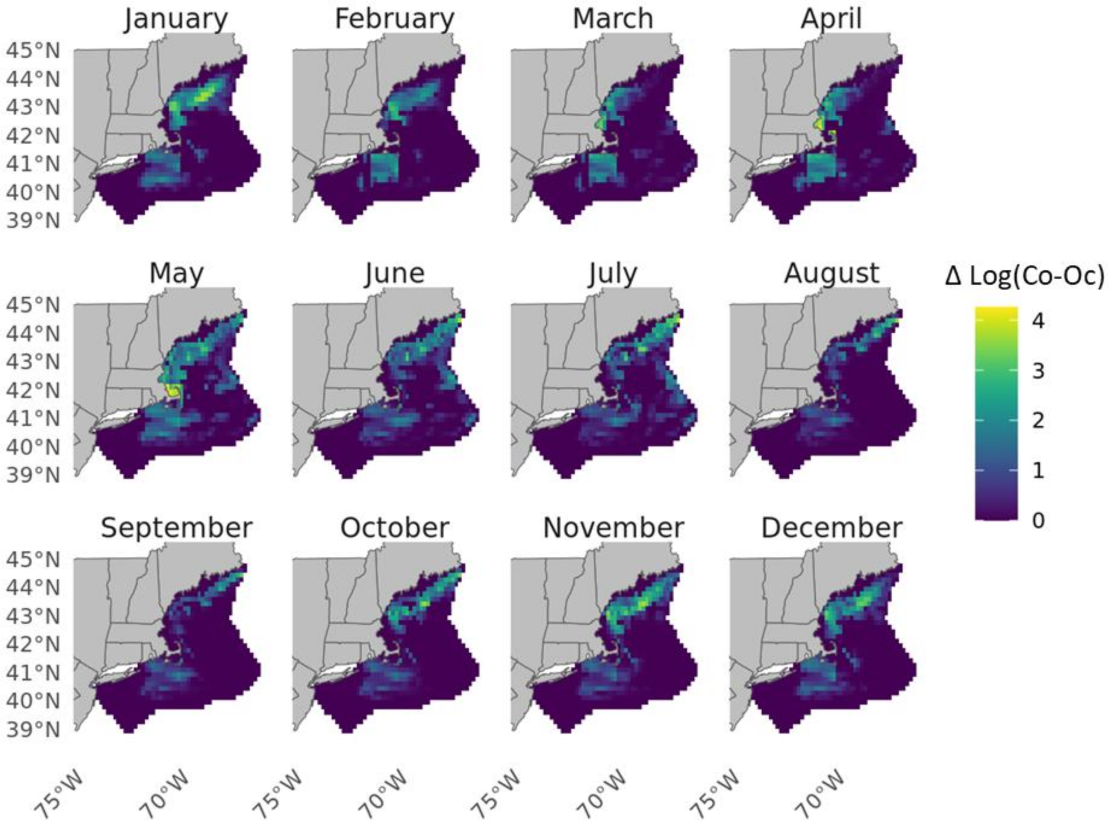

Figure 53. Impacts of the 2021 final rule management actions on monthly co-occurrence of North Atlantic right whales with Northeast lobster (*Homarus americanus*) and Jonah crab (*Cancer borealis*) fisheries are visualized as a change in co-occurrence (Co-Oc) on a log scale.

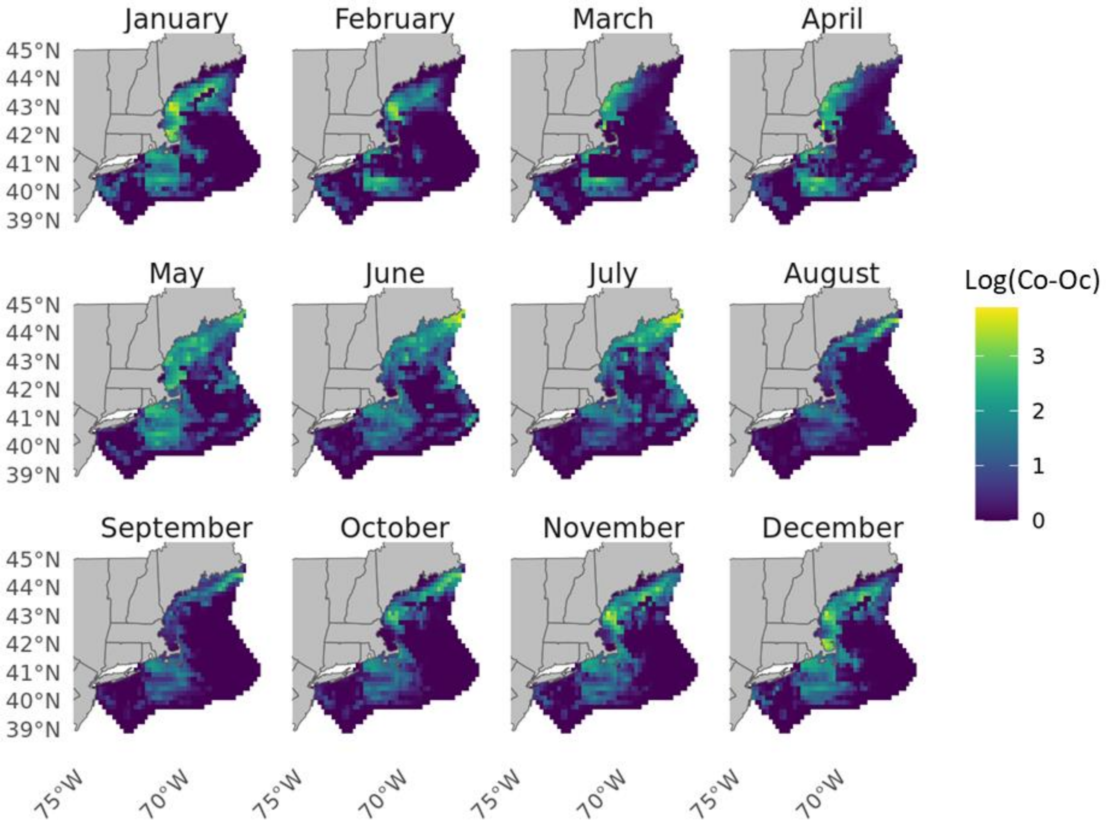

Figure 54. Remaining monthly co-occurrence from in North Atlantic right whale co-occurrence with Northeast lobster (*Homarus americanus*) and Jonah crab (*Cancer borealis*) fisheries following the implementation of the 2021 final rule management actions shows locations where whales and gear still overlap.

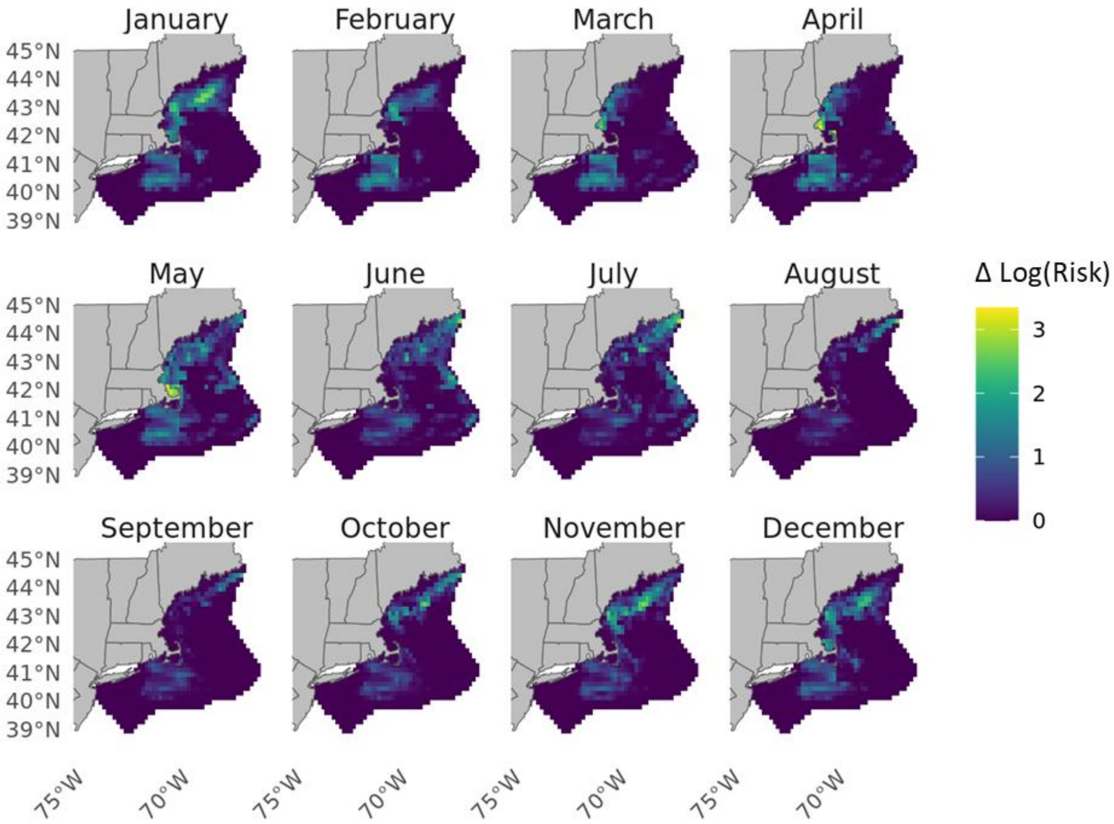

Figure 55. Impacts of the 2021 final rule management actions on monthly total risk values are visualized as a change in risk from the baseline fishery inputs.

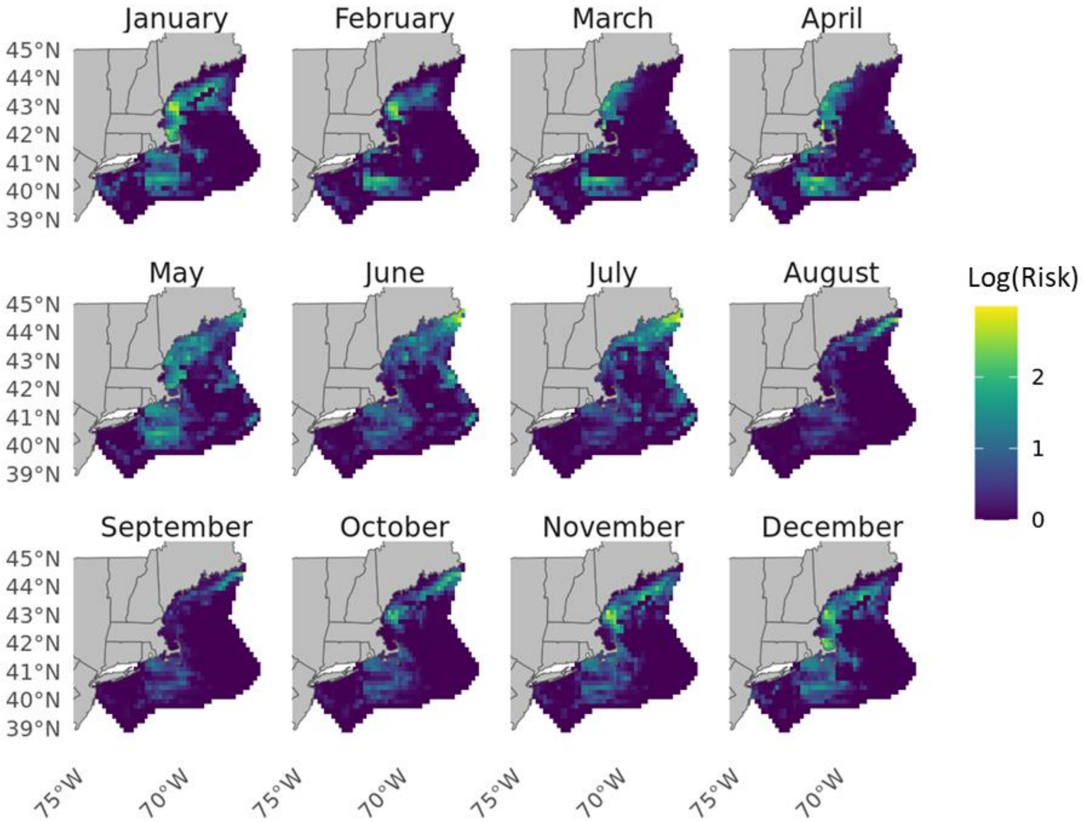

Figure 56. Remaining monthly risk following the implementation of 2021 rule management actions shows locations where entanglement risk to whales still exists.

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