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ARTICLE

Vertical Line Requirements and North Atlantic Right Whale Entanglement Risk Reduction for the Gulf of Maine American Lobster Fishery

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Abstract
In the U.S. western Atlantic Ocean, North Atlantic right whales *Eubalaena glacialis* are subject to gear entanglement in fixed-gear vertical line fisheries, with mortality risk increasing with line strength and spatial density. U.S. federal management agencies have mandated vertical line strength limits (235.033-kg-m [1,700-ft-lb] breaking strength) to curtail the injury and mortality risk that entanglement poses to right whales. Limiting the strength of vertical lines used in the trap fishery for American lobster *Homarus americanus*, however, could negatively impact the economic resilience of New England fishing communities if it forces the purchase of new equipment or increases the incidence of break-offs and lost gear. We provide a novel look at the spatially distinct vertical line strength requirements for the Maine American lobster trap fishery. The hauling load requirements of the fishery were modeled using measurements of strain put on vertical lines used in typical lobster trap operations to determine the minimum strength necessary to fish safely and avoid dangerous line breaks. New regulations on minimum trawl lengths (number of traps fished per vertical line) taking effect in 2022 will cause increases in lobster fishery vertical line loads across all fishing grounds, considerably increasing with depth and distance from shore. Our models indicated that inshore areas can be safely fished with vertical lines within the recommended whale-safe 235.033-kg-m (1,700-ft-lb) breaking strength specification, whereas the offshore lobster fishery will need a suite of measures beyond line strength reductions to reduce entanglement risk and mortality of right whales. We provide guidelines for the minimum line strength necessary for fishery operations, which can be used to inform management goals that balance the need for a sustainable lobster fishery and the conservation of right whales.

Fixed-gear fisheries support some of the most valuable crustacean landings in North America, occurring across the northeastern USA and Atlantic Canada (NMFS 2020). These fisheries also represent the greatest cause of human-induced injury and mortality to the critically endangered North Atlantic right whale (NARW)

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Eubalaena glacialis, with ship strikes being the second most frequent cause (Knowlton et al. 2012; Kraus et al. 2016; Pettis et al. 2021). Right whale entanglement has been linked with several novel, unusual mortality events in Canada resulting from a shifting right whale population distribution; these events killed between 7% and 17% of the total NARW population over a span of 3 years (Meyer-Gutbrod et al. 2021; Pace et al. 2021; Pettis et al. 2021). Right whale entanglement not resulting in mortality is expected to be a major contributor to reduced fitness, reduced size at age, and historically low calving rates (Pettis et al. 2021; Stewart et al. 2021). In 1990–2010, the NARW population experienced a window of recovery from historic lows, but since 2010 it has been in decline, with an estimated current population of 366 individuals (Pace et al. 2014, 2017; Pettis et al. 2021). Considering the current NARW population size and the potential for entanglement events to cause continued injury and mortality, entanglement mitigation efforts are a necessity.

Within the Gulf of Maine (GoM; Figure 1), vertical lines that pose entanglement risk are overwhelmingly represented by the trap fishery for American lobster *Homarus americanus*. The exact risk to NARWs from the variable vertical lines used by the American lobster fishery is understudied. Risk assessments generally try to capture the likelihood of spatial overlap between whales and traps as well as the effects of entanglement severity when they occur (NOAA 2020). Calculated risk assessments using vertical line strength, density, and spatial distribution along with spatial co-occurrence of vertical lines used in trap/pot fisheries and NARWs show a need to reduce entanglement risk by 60% to bring injury and mortality to acceptable levels (Johnson et al. 2005; Knowlton et al. 2016; NOAA 2020). Within the GoM, reductions in

FIGURE 1. Study area in the Gulf of Maine on the East Coast of the USA.

vertical line density and strength constitute a powerful method to reduce risk, as NARW densities are low and their transit paths through the GoM are unpredictable (Davis et al. 2017; Meyer-Gutbrod et al. 2021). The final federal rule to reduce the severity of NARW injuries and the frequency of mortalities that result from entanglement targets the breaking strength and spatial density of vertical lines used by the American lobster fishery (NMFS 2021); however, the line strength requirements for the fishery have not been comprehensively evaluated.

The entanglement problem remains unsolved, partially due to the lack of information on the spatial distribution of entanglement events. The distribution of NARWs is extremely variable, with high variance in seasonal occupancy across the GoM over time (Davis et al. 2017). The frequency of right whale migration is dependent on sex, age, and food availability (Gowan et al. 2019). Right whale distribution is shifting from historic ranges further north in pursuit of ideal prey—calanoid copepods—resulting in shorter residence times within the GoM (Meyer-Gutbrod et al. 2021). Sublethal entanglement events are common, with 82.9% of adult NARWs bearing entanglement scars, while gear is rarely retrieved from whales that are killed by entanglement (Johnson et al. 2005; Knowlton et al. 2012). This shortage of recovered gear makes it difficult to attribute entanglement events to a specific fishery area; attribution may be enhanced by the new gear marking rules, but it is unlikely that NARW mortalities will be discretely attributable in time for any immediate management action. The difficulty in attributing entanglement to a distinct fishery or spatial source has forced risk reduction proposals to take broad action across the range of this animal to reduce entanglement risk. It is difficult to propose effective risk reduction measures across the range of the NARW while fishing practices and gear requirements are not spatially uniform, especially within the diverse American lobster fishery found in the GoM (McCarron and Tetreault 2012).

The American lobster fishery represents the most valuable single-species fishery in the United States (NMFS 2020). Within the GoM, this fishery is uniquely composed of thousands of owner–operator vessels fishing diverse gear configurations (McCarron and Tetreault 2012). Management measures regulating the allowed vertical line strength within this fishery could cost licensed fishers heavily, as new lines or weak links must be purchased to bring gear within specification. The proposed regulations have been the focus of a cost–benefit analysis, with the cost of compliance and lost fishing revenue of US$9.8–19.2 million across affected fisheries (NMFS 2021). Fisher preferences regarding trawl lengths and total trap limits are highly variable, with the fisher response to these management measures being difficult to predict (Acheson 2001). Without spatially explicit knowledge of the gear requirements for fishing in the GoM, proposed regulations may (1) increase the risk of line breaks and make fishing more unsafe, (2) have unforeseen effects on fisher behavior, and (3) result in expensive gear loss in parts of the GoM. Gear lost to parted vertical lines can occasionally be recovered but often result in an expense to fishers and a risk to benthic organisms as "ghost" gear (Goodman et al. 2021). Knowledge about the gear configuration preferences of fishers across the GoM could influence management to consider alternative NARW risk reduction measures that minimize safety risks to fishers, as well as minimizing the economic impact of changes to gear configuration.

The modern fishery for American lobster has low social resilience to cope with extreme changes in landings or potentially strict management changes; extreme or unfeasible requests from management agencies may have outsize effects on this fishery (Henry and Johnson 2015). Modeling the relationship between lobster gear requirements and the oceanographic parameters of the local environment will provide a novel description of the fishing gear landscape in the GoM. This landscape can be used to validate currently untested assumptions about fishing gear and effort, guiding regulations that balance the needs of a sustainable lobster industry with risk reduction for the endangered NARW.

The American lobster fishery operates across large spatial scales, pursuing a shifting lobster distribution that changes seasonally—and, more broadly, with climate change (Chen et al. 2005; Tanaka and Chen 2015). Likewise, the fishery operates at variable densities and with a variety of trawl lengths spatially and seasonally to pursue shifting lobster distributions (Kelly 1993; McCarron and Tetreault 2012). We propose that the most effective way to categorize the needs of the fishery is to account for the oceanographic and gear configuration variables that influence the vertical line strength needs of GoM fishers by modeling the load and line requirements for the fishery across the GoM.

Gear specifications are variable across fishers and areas and must be accounted for to accurately forecast industry needs and regulatory impacts. Federal right whale risk reduction rules use a 235.03-kg-m (1,700-ft-lb) breaking strength maximum for all or part of the vertical lines used in these fisheries to limit the potential for serious injury and mortality of NARWs in cases of entanglement (Knowlton et al. 2016; NOAA 2020). The feasibility of implementing these weak links across management zones is untested, and the current breaking strengths of lines used in the fishery are an unknown point of assumption, as identified by the Atlantic Large Whale Take Reduction Team (ALWTRT 2017).

In this study, we assess the typical loads to which modern lobster gear is subjected across the GoM as the gear is hauled. Using load cells, we captured the actual load as different gear configurations were fished across multiple fishing and geographic conditions. This method of quantifying local fishing practices can support regional gear modification regulations rather than blanket regulation. Using generalized additive models (GAMs), we predicted the minimum vertical line strength requirements spatially across the GoM. We also generated recommendations for (1) areas that can safely fish with vertical lines that are within the recommended breaking strength specifications and (2) areas that need a suite of measures beyond line strength reductions to reduce entanglement risk and mortality.

METHODS

This study used data collected by volunteer fishers across Maine, New Hampshire, Massachusetts, and Rhode Island (Figure 1). Volunteers were solicited by the University of Maine, FB Environmental, the Maine Department of Marine Resources (DMR), and local stakeholder organizations from 2018 to 2020. Volunteers were solicited by a mixture of local management meetings, cold calls, event outreach, and stakeholder group involvement, relying on local industry knowledge to direct our efforts. Outreach was directed to best represent the gear variety seen within the American lobster fishery in the GoM, fishing at variable depths with a variety of gear configurations. Volunteers were chosen opportunistically based on (1) availability to adapt their fishing methods to the use of a load cell and (2) willingness to participate. The final data set included 635 hauls worth of data from 16 different lobster fisher volunteers. This selection of fishers and representative hauls covered a wide range of trawl lengths, depths, and spatial areas (Supplementary Table 1 available separately online). Since the relationship between load and gear parameters is a physical correlation, encompassing the full variety of trap configurations across spatial scales is an important data consideration.

For effective model outputs, we required quantitative data on the actual load to which fixed gear is subjected while being fished in the GoM. This load data must be collated with appropriate environmental variables to quantify their effects on load. Volunteer fishermen were asked to complete a load cell characterization sheet and to provide data on vessel size, hauler size, sea state, the management zone in which they were operating, distance from shore, depth fished, average number of traps fished per trawl, groundline spacing between traps, weight of traps, anchor weight (if used), vertical line rope (diameter, type, and brand), and scope (the additional length of line beyond depth, used to account for tidal pull), as well as the presence of knots and splices in the vertical line. Distance from shore was binned into commonly used state-recognized management zone bins of 0−5.556 km (0–3 nautical miles [nm]), 5.556−22.22 km (3–12 nm), and 22.22 or more kilometers (12+ nm) from shore. These generalized bins were chosen rather than specific latitude–longitude coordinates to reduce the burden of data recording on fishers and encourage participation in a fishery where fishing spots are well guarded (Acheson 2001). The line 11.11 km (6 nm) from shore was developed with the new federal regulations to provide additional specificity to trawl minimum areas. The 11.11-km (6-nm) line was not commonly used as a management tool during the period of data collection and was not used to bin data until the incorporation of the new trawl rules.

Load cells were fixed to the vessel at the point where the davit joins the hauling block. The davit acts as an arm and supports the hauling block over the water, where the load cell can accurately represent the downward pull of the line over the hauling block (pulley). The load cell continuously recorded the actual load as gear was hauled over the block, giving an output of the total force load on the line in foot-pounds at time intervals of approximately 3 readings/s over the course of the haul. Data were transmitted through a receiver onto an onboard laptop via software provided by the load cell manufacturer (Load Cell Central, Milan, Pennsylvania). Fishers were encouraged to run as many hauls as possible with the load cell; however, the increase in hauling block length resulting from the load cell restricted the efficiency of some hauling operations and reduced the volume of hauls possible for many fishers. When use of the load cell was completed, data were pulled from the computer and forwarded to the University of Maine for quality control and analysis.

Load cell data arrived as CSV (comma-separated values) files with time stamps. Individual CSV files were analyzed to ensure that no partial hauls or corrupted data were included. Load cell run time was then edited into discrete individual haul sessions. R programming language code developed by the Maine DMR was used to build plots of load across haul length. The position of the vertical line was identified as all lines between the surface buoy and the first trap to come aboard the fishing vessel. Trap positioning was identified on load plots as dips following spikes in the smoothed load rating. To ground-truth our data analysis process, observers from our research partner, FB Environmental, accompanied the load cell users and took notes on hauling methodology, trap timing, hang-up events, and snarl events, with precise spatial coordinates. These observer ground-truthing data were used to validate our methods. Time stamps indicating when the first trap came aboard found the dip-and-peak trap identification method to be effective for identifying the approximate end of the vertical line.

The point of maximum load on the vertical line varies with hauling factors like depth and the occurrence of hang-ups and snags on the seafloor. Load on the line was calculated by applying a conversion factor to the load cell output, allowing us to account for the multiplication of force as the line is hauled over the hauling block. Although the angle of the line over the block is variable depending on gear and vessel positioning and is influenced by wave and tidal action, we assumed an average of 90° when applying the conversion to these data. This angle conversion choice was validated by onboard observers as representative of typical hauling behavior. The conversion represented the physical formula (hauling stress/angle factor = true load). Conversion was performed with a multiplication factor of 0.7092, representing an angle factor of 1.41 that was taken from published block load multiplier engineering tables (Crosby Group 2013). Data were converted to metric units postanalysis.

Once identified, the maximum load experienced on the vertical line per haul was collated with other hauling information provided by the fishermen. These variables represent spatial identifiers (state, management area, and distance from shore), oceanographic parameters (weather, sea state, and depth), and fisher gear configuration data (vessel size, hauler size, traps per trawl, groundline spacing, scope, use of anchors, trap weight, rope diameter, presence of knots and splices, percent floating line, and additional room for individual comments). Due to the independent deployment of load cells with fishers, accuracy and fulfillment of these gear configuration data varied between fishers and between hauls. Additional quality control and follow-up with fisher volunteers to ensure the accuracy of these data were required, and some fields did not receive sufficient responses for meaningful analysis.

To supplement the spatial coverage of our load cell data and to account for variable fisher trawl length configurations across the GoM, observer data from the Maine DMR lobster survey program were sourced. These data represent the effort of Maine DMR observers sampling biological data across the fishery. For our modeling purposes, depth, trawl length, and latitude–longitude positioning were taken from this data set. Incorporating this data set gave us the typical trawl lengths in Maine waters fished at a higher spatial resolution than the distance-from-shore bins used for the load cell data. We used a data subset that included the time frame of 2009–2019 to best represent modern fishing trends. Additional quality control was performed after data reception; trawl lengths over 40 traps, or long trawl lengths in atypically shallow water (e.g., 40 traps in 9.14 m [5 fathoms]), were assumed to be sampling error and removed as they did not match the known behavior of the fishery.

This study assumed that the relationship between gear and oceanographic parameters remains relatively constant over time and space. This is reasonable due to the relatively static nature of fixed-gear lobster fishery methods (Chen et al. 2005), as lobster traps have not functionally changed within the past two decades, and fishers set variable amounts of the same gear—not different gear—across spatial scales (McCarron and Tetreault 2012). For discussion purposes, this study also uses the Maine state and federally designated lobster management zones and distance-from-shore bins to make results more easily comparable to state and federal proposed rules.

Although data were collected with industry partners from coastal states across New England, we have limited the scale of this article to the Maine coastline. This decision was made to ensure that our assumptions would reflect the behavior of the fishing fleet. Data and products were routinely presented to lobster zone council meetings to solicit fisher feedback, which was incorporated into model decision making as much as possible. Zone council meetings are composed of fishers, management staff, nonfisher lobster industry members, and the public. These meetings exist to advise state management and settle issues within the fishery. Zone council members and meeting attendees were asked to describe whether they felt that the samples were representative of their fishing effort. Although we were restricted to the fishers that attended these meetings, those in attendance felt comfortable with the representation of our sampling distribution. This scientist–fisher relationship was not as available for states other than Maine.

Due to differences in state fisheries, some of the assumptions made about gear configuration in trawl length modeling were inappropriate for areas outside of Maine waters. The relationship between inshore and offshore fishing effort for states like Massachusetts is influenced by productive but distant offshore grounds like Georges Bank (NOAA 2020). Although all states have inshore fisheries, the variability in total number of fishers, as well as the ratio of inshore to offshore fishers, varies widely across states and may have unique impacts on territoriality and fishing methodology that we were unable to quantify. Other New England states have large-scale seasonal closures driven by variable rates of NARW residency (NOAA 2021), and these closures influence fisher behavior. Results may be applied across the scale of the American lobster fishery if spatial fishery behavior changes are later proven to be inconsequential.

Maps of management zones were sourced from the Maine DMR. Bathymetric data for the GoM were sourced from the National Oceanic and Atmospheric Administration (NOAA) ETOPO1 Global Relief Model (NOAA National Geophysical Data Center 2009) to provide high-resolution depth data. Whale safety regulations were taken from the NOAA amendment to the take reduction plan published in 2021 (NMFS 2021).

Data were analyzed within R version 4.0.2. Multicollinearity tests were used to identify collinear variables. Variables were plotted into correlation matrices to show the level of collinearity between variables (Picard and Cook

1984). In this study, collinearity was found across a large proportion of variables (Supplementary Figure 1 available separately online). This is expected, as fishers tailor their gear type to the environment in which they fish. Fishers seemed to naturally settle into binned groups across variables, fishing unified tiers of trap weights, anchor weights, hauler sizes, traps per trawl, and groundline spacings depending on the spatial area they fished. Variance inflation factors show a corollary effect, and the vessel size, anchor size, anchor use, and groundline spacing variables were shown to have high collinearity with other variables. Anchor use and groundline spacing were excluded from the final model due to collinearity with other chosen variables as well as difficulty in modeling these data spatially at a meaningful scale.

Vessel and hauler sizes were highly correlated with depth. Larger vessels are better suited to fish offshore waters and long trawl lengths due to increased deck space and fuel capacity. It is intuitive that these vessels fishing long trawls would be subject to higher load requirements; due to the collinear nature of these variables, vessel size and hauler size were not used in the model so as to preserve depth as a highly explanatory variable. If there are significant changes to fishing methods, this assumption should be re-evaluated. Groundline spacing (i.e., the distance between traps on a trawl) and the use of anchors were so closely tied to depth and trawl length that these variables were also excluded from model training. The remaining variables were tested for outliers via histogram comparison and were groomed appropriately. Variables were tested for the reaction of residuals and fitted values to judge their contribution to model fit and model-specific Akaike's information criterion (AIC) and were eliminated by a backward approach (Figure 2; Supplementary Figure 2).

The mgcv package in R was used to run a series of models based on explanatory variables described by fishermen, with load being the response (Wood 2011). The mgcv package's default parameters were selected, and thin-plate splines were used for automatic smoothing of model terms (Wood 2011). Generalized additive models were applied due to their ability to incorporate nonlinear relationships (Guisan et al. 2002). Likewise, GAMs exhibit robustness to random effects (Guisan et al. 2002), which we may consider as differences between hauling speed and fishing methodology occurring on a small scale between individual fishers. Generalized additive mixed models were used to capture this difference, but the result was nonsignificant when tested with the study data.

Although lobster fishing effort is known to vary spatially with year and season, trawl length is poorly represented in many historical effort surveys. To best represent the modern distribution of gear configurations within the GoM, or the "as-is" case, sampling data from the annual Maine DMR observer lobster survey for the years 2009–2019 were used in a GAM to predict a continuous spatial grid of trawl length. Since the American lobster fishery is considered a pursuit fishery (Chen et al. 2005), the fishing behavior of the fleet is variable with lobster distribution and season. This 10-year period was chosen to best represent the recent actions of the fleet averaged annually. A GAM,

$$\text{Trawl length} \sim S(\text{Depth}) + S(\text{Latitude}) + S(\text{Longitude}),$$

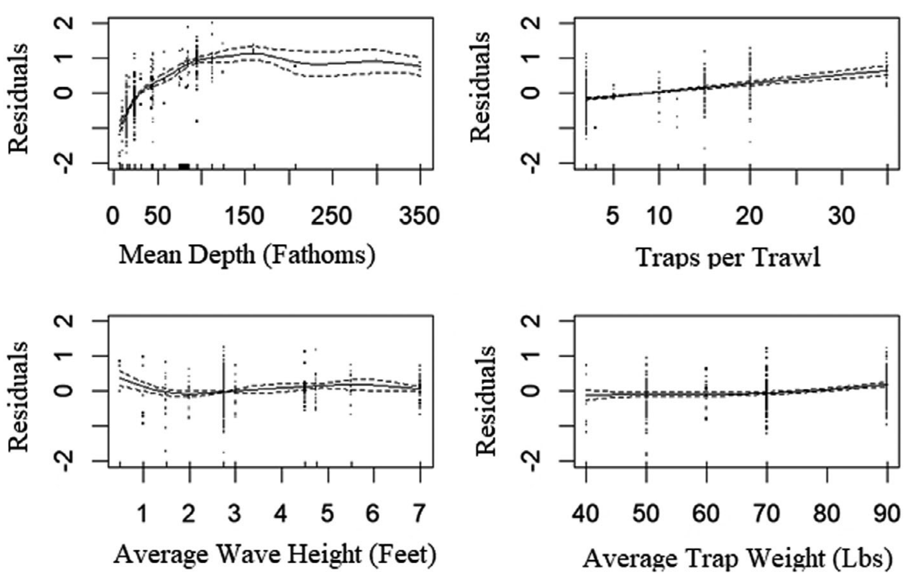

FIGURE 2. Residual distribution plots for smoother terms of the most explanatory covariates. The residuals for mean depth (fathoms), traps per trawl, average wave height (ft), and average trap weight (lb) are displayed.

was used to predict the number of trawls fished at a given location based on depth and spatial association using the Maine DMR survey data, applying a predicted trawl length for every depth point within the GoM study area based on smoothed input data. The predicted trawl lengths were capped at a 40-trap trawl maximum to give reasonable bounds to the predictions, which included some deep areas off the continental shelf that are poorly exploited by the fishery and may not hold to the previous assumptions of the fishery if heavy exploitation begins there.

A Tweedie family GAM was chosen to best describe the distribution of the response between the variables chosen and load when compared to Gaussian and Poisson distribution families. Shapiro–Wilk and AIC testing were used to determine the normality and compare alternative variable GAM combinations. Model fitness was validated against the data by using root mean-square error (RMSE) to gauge the fit of the model to resampled test data. The spatial traps per trawl modeled output from the previous model was used as an input to describe fisher trawl length behavior in this overall predictive model using the following GAM:

$$\begin{aligned}\text{Vertical line load} \sim S(\text{Depth}) + S(\text{Traps per trawl}) \\ + S(\text{Wave height}) + S(\text{Trap weight}),\end{aligned}$$

and vertical line load according to these trawl length distribution data was predicted over space. Different outputs were produced for the baseline trawl length model output as well as the new NOAA rule-making trawl length minima.

To explore the results of implementing the new trawl length minima across the GoM management areas, we overlapped management area delineation spatial polygons on bathymetry maps, applying the NOAA trawl rules to their prescribed regions. The new rule differs from the proposed rule by having greater variation in trap minima across management areas. These rules enact a trawl length limit of 2–3 traps/trawl from the exemption line to within 5.556 km (3 nm) of shore, 5–10 traps/trawl from 5.556 to 11.11 km (3 to 6 nm) offshore, and 10–20 traps/trawl from 11.11 to 22.22 km (6 to 12 nm) offshore (NOAA 2020; NMFS 2021). The remainder of Lobster Management Area 1 (LMA1) occurring outside of Maine state waters (≥22.22 km [≥12 nm]) had the proposed 25-trap trawl minimum applied (Supplementary Figure 3). This analysis was contained to LMA1 to restrict our analysis to the location of most industry activity and likewise our highest fidelity data. These maps were created using the sp, tidyverse, and rgdal packages within the R programming language. Using the proposed trawl length rules, vertical line load was predicted with the best model. The predicted loads under the new trawl length scenario were compared to the "as-is" loads to demonstrate potential changes in fishing gear configuration and experienced loads within state management areas resulting from rule implementation.

Some of the variables could not be predicted as a continuous spatial grid. We were unable to effectively map the distribution of trap weights across the GoM with the data available; therefore, we used a fixed standard 31.75-kg (70-lb) trap weight across space. This represented the trap weight most commonly fished by our volunteers.

Industry volunteers reported hauling in sea heights from 0.3 to 2.13 m (1 to 7 ft), with 0.91−1.22 m (3–4 ft) being the most common. Given the difficulty in preparing models that were inclusive of all possible weather outcomes, we applied a standard 0.91-m (3-ft) wave height across space. Model testing showed an increase in load of approximately 5.5% across all load predictions with a wave height of 2.13 m (7 ft) relative to the 0.91-m (3-ft) average. We did not have any volunteers recording haul data in extreme weather conditions, thus restricting us from making assumptions about hauling loads in extreme weather.

RESULTS

Although lobster fishing effort varies spatially with year and season, trawl length is poorly represented in many historical effort surveys. The model responsible for predicting trawl lengths represents our best knowledge of current trap distribution trends as typically fished by the lobster industry over the past 12 years based on observer data (Figure 3). The relationship between trawl length, distance from shore, and depth is intuitive and was representative of industry behavior based on fisher feedback. The trawl length model predictions were useful for projecting the current load landscape across the GoM; when this information is combined with a high-resolution spatial image of trawl length from observer data (Figure 4), we can perform analysis on spatial gear requirements. There were no significant differences between loads across management areas outstanding from differences in oceanographic parameters. Depth fished, traps per trawl, wave height, and trap weight were determined as the most important variables for explaining the response variable (load on the vertical line). This subset of variables was confirmed by AIC comparison. This combination of variables produced a predictive model with the lowest comparative AIC while maintaining a variance inflation factor below 3 for all chosen variables. The RMSE for all models ranged from 800 to 900. Testing the models with training resampled data showed a minor change in RMSE, indicating that the model was neither underfit nor overfit but was constrained by the data. Shapiro–Wilk normality testing of the residuals revealed a P-value of 1.168×10^{-5}, which is extremely low and suggests a nonnormal distribution. The vertical

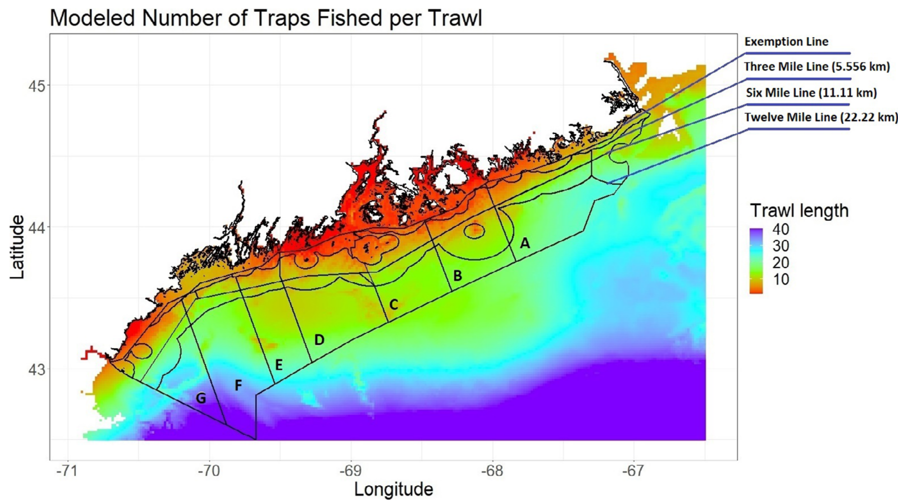

FIGURE 3. Distribution of trawl lengths (number of traps per vertical line) fished across the Gulf of Maine, predicted by a generalized additive model based on Maine Division of Marine Resources observer data. Lines represent management zones (lettered in black text) and distance from shore at the exemption line to 5.556 km (3 nm), 5.556–11.11 km (3–6 nm), and 11.11–22.22 km (6–12 nm) offshore (as labeled). The modeled result shows a highly variable trawl length distribution, with an increasing trend moving offshore.

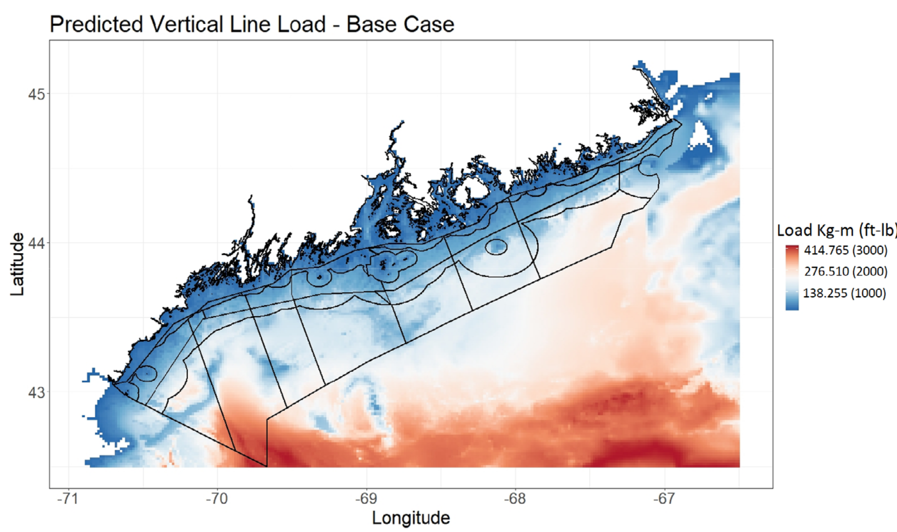

FIGURE 4. Predicted vertical line load (kg-m and ft-lb) for the base case trawl length scenario. Black lines represent the management zones depicted in Figure 3. The predicted loads follow the prescribed trawl lengths at depth. The color scale is based on the proposed 235.033-kg-m (1,700-ft-lb) line strength limit for reducing whale entanglement risk, with areas in shades of red exceeding 235.033 kg-m (1,700 ft-lb) during typical hauling behavior, increasing with color intensity.

line load GAM explained 95.2% of the variation in line load using trap count, depth fished, wave height, and trap weight (Table 1). This high level of deviance explained is reasonable given the physics-based nature of the model. This combination of variables presents the best relationship that offers precision while also making the model robust for predicting across different gear configurations and depth range.

We used generalized additive mixed models to test the variation between fishing styles/fishers as a meaningful contributor to load; however, these models failed to capture any individual variation across fishers. This suggests that the homogeneity of fisher hauling behavior is sufficient to avoid contributing significantly to load differences across fishers.

We used a model to predict vertical line load spatially by using the spatially explicit trawl lengths from Maine DMR

TABLE 1. Comparison of *P*-values, CIs, R^2 values, and Akaike's information criterion (AIC) for the three tested predictive models of vertical line load. Model complexity beyond model A did not meaningfully improve AIC or R^2. Model A was chosen to best represent the contributors to load.

	Model A		Model B		Model C	
Predictor or statistic	Estimate	*P*	Estimate	*P*	Estimate	*P*
Intercept	512.01	<0.001	530.34	<0.001	486.49	<0.001
Depth		<0.001		<0.001		<0.001
Trawl length		<0.001		<0.001		<0.001
Wave height		<0.001		<0.001		
Trap weight		<0.001				
CI	503.4–520.77		521.32–539.51		478.270–494.86	
Observations	441		462		557	
R^2	0.952		0.944		0.916	
AIC	5,259.744		5,571.917		6,713.81	

observer data (Figure 3). Overall, we observed an increase in load with increasing trawl length (weight) across depths. Trawl lengths were highly variable by depth as well as management area, reflecting fisher conformity to oceanographic variables as well as fisher choice. Using the modeled trawl lengths from Figure 3, we predicted the vertical line load maxima spatially to produce the map in Figure 4. The color gradient accentuates the difference between areas fishing within the 235.03-kg-m (1,700-ft-lb) safety margin and areas where that load allowance is exceeded. Far below the 235.03-kg-m (1,700-ft-lb) threshold, the low loads inshore pose no serious problem from a shift to weaker lines. The shift from white to red area in Figure 4 occurred where hauling loads exceeded the widely accepted 235.03-kg-m (1,700-ft-lb) safety margin for whales. From the 11.11-km (6-nm) line to the extent of the LMA1 zone, loads commonly remained around the 235.03-kg-m (1,700-ft-lb) mark or went well over that weight threshold, and those areas will have trouble conforming to 235.03-kg-m (1,700-ft-lb) line regulations without compromises in trawl length from the base case.

Vertical line reduction plan trawl minima were applied to the modeled trawl lengths to present areas of load increase under the new management scheme (Supplementary Figure 3). A direct comparison of current and post-proposed rule implementation showed significant areas of load increase (Figure 5). To highlight the variation between rule implementation and the "as-is" case, the difference between these scenarios was isolated as well. The consistent increase in load from the 5.556-km (3-nm) line and further offshore suggested that these new trawl minima will require stronger lines. The management tactic of reducing the total volume of lines in the water will have the trade-off of fewer, albeit stronger, lines.

DISCUSSION

Given the high fit of this model, predictions about the load requirements for fishery operation in a variety of trawl length configurations across depth strata can be considered accurate to fishery behavior. This load study has been used to ground-truth some assumptions within the different NARW risk reduction plans of what loads are feasible for different areas.

Increasing the number of traps per trawl allows fishers to utilize the same number of traps with fewer vertical lines. While hauling the gear, the increasing load with increased trap count would suggest that there is an anchoring or drag effect from having more traps on a string. Previous dialogue with fishers had suggested that while hauling gear at the same depth, no matter the trawl length, there should be a relatively fixed number of traps suspended in the water column, supplying most of the resistance and driving the variation in line load. Although the number of traps suspended is fixed by depth and trawl length, traps on the ground provide resistance when dragged toward the hauling vessel. The presence of dragged gear was much more pronounced than anticipated and increased load significantly on longer trawls at any depth.

The presence of a substantial drag factor when hauling longer trawls creates the need for stronger vertical lines when considering "trawling up" to reduce the total amount of rope in the water. This presents some risk to NARWs, as regions with increased trawl minima will have fewer but stronger vertical lines. The subsequent increase in load and need for stronger lines must be considered when calculating the total risk reduction. Some alternative gear configurations have been proposed during Atlantic Large Whale Take Reduction Team meetings, such as increased lengths of groundline between the first and subsequent traps to reduce the dependency on strong vertical lines for increased trawl lengths (NOAA 2021). These increased groundline length proposals could become a critical component of reducing vertical line strength in offshore, high-trawl-length areas.

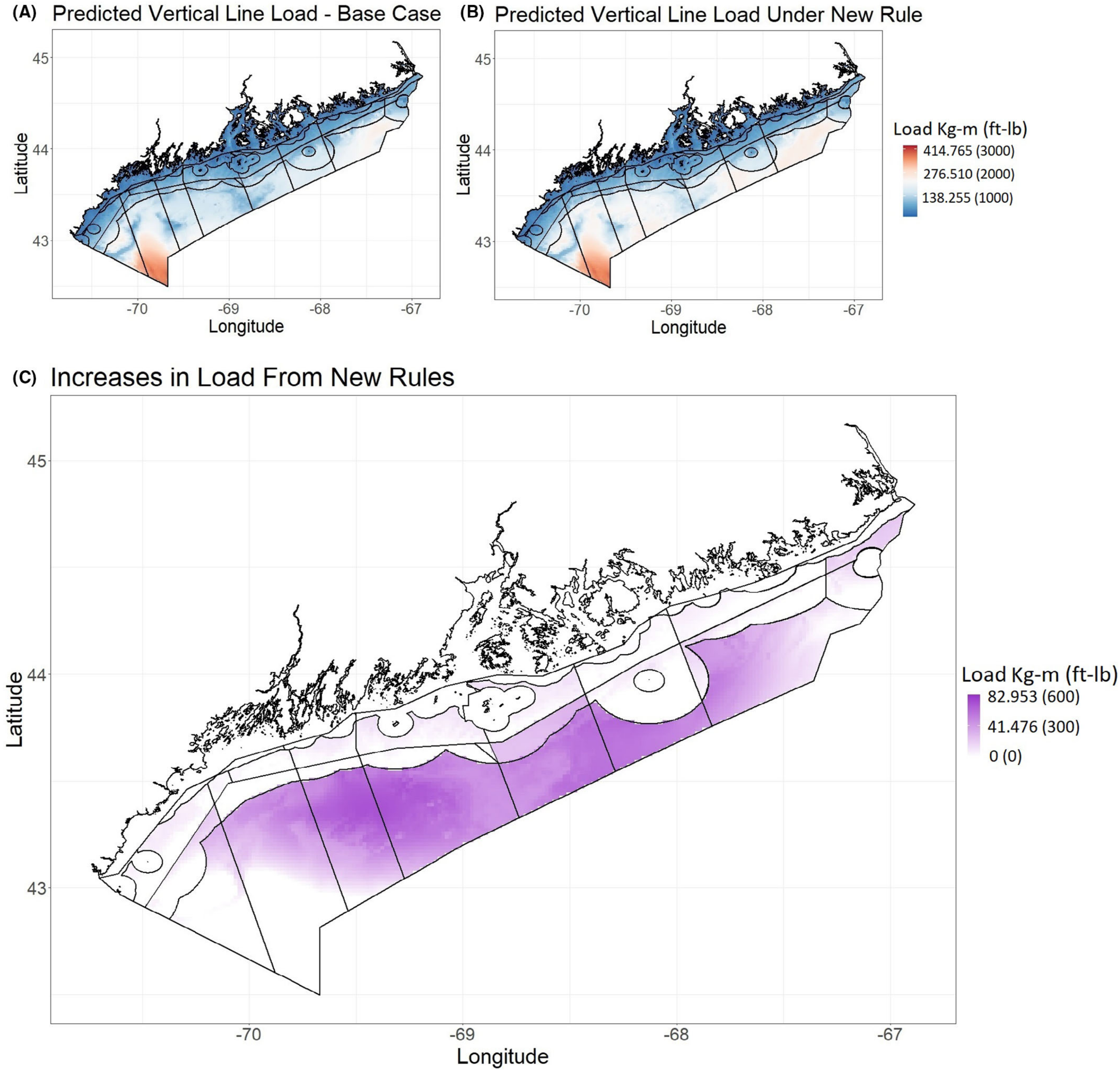

FIGURE 5. Predicted vertical line load (ft-lb) under **(A)** an "as-is" (base case) scenario and **(B)** proposed trawl length rule implementation of whale-safe rules. The color scale is based on the proposed 235.033-kg-m (1,700-ft-lb) line strength limit for reducing whale entanglement risk, with areas in shades of red exceeding 235.033 kg-m (1,700 ft-lb) during typical hauling behavior. **(C)** The increase in load from the base case scenario is isolated to the new trawl minima; only the increase in load resulting from the new rule implementation is shown, increasing with color intensity. The black lines represent the lobster management delineations presented in Figure 3.

The area closest to shore in Maine is exempt from Atlantic Large Whale Take Reduction Plan regulations. When this exemption area was created, the National Marine Fisheries Service determined that NARWs were unlikely to utilize this rocky habitat close to the coastline. The Maine exemption area exists almost entirely inside of the state's statutory 5.556-km (3-nm) line and encompasses about 70% of those state waters. The areas outside of the exemption zone but within the 5.556-km (3-nm) line have new trawl minima; however, the minima do not exceed the trawl lengths already fished there. We do not expect any significant change in hauling loads for those areas. Hauling load largely stays below 138.26 kg-m (1,000 ft-lb) within the Maine exemption line and in the area between the exemption line and the 5.556-km (3-nm) demarcation.

Within the areas 5.556–11.11 km (3–6 nm) from shore (the 11.11-km [6-nm] line is defined within the Atlantic Large Whale Take Reduction Plan), loads started to approach the 235.033-kg-m (1,700-ft-lb) limit in deeper waters. These are the first areas that show pronounced increases in load under the new trawl minimum rule, with loads increasing by 13.83–41.48 kg-m (100–300 ft-lb) consistently from the base case. Hauling strain could approach or exceed the 235.033-kg-m (1,700-ft-lb) limit when the loads under new trawl minima combine with unusual circumstances, such as gear hang-ups, setovers with other fishing gear, or extreme weather conditions. This is most pronounced in the 5.556–11.11-km (3–6-nm) section of zone A (Figure 3)—a direct result of the specialized higher trawl minimum in that area.

The 11.11–22.22-km (6–12-nm) fishery routinely experiences hauling loads over 235.033 kg-m (1,700 ft-lb) and likely would be unable to come within that specification given current fishing gear configurations and practices. Zone C (Figure 3) is likely to experience increased loads across the board, as the specialized rule for this area would involve a 20-trap minimum—much higher than our modeled trawl length base case for this zone. Other than zone C and some areas of zones A and G, there will be little change from the base case to fishers operating in the 11.11–22.22-km (6–12-nm) area.

Offshore fishers (≥22.22 km [≥12 nm] offshore) within LMA1 would likely have to use a suite of measures to come within desired NOAA suggestions for risk reduction rather than just a switch to weaker rope. This offshore area will have the most pronounced increases in load unders the implementation of a blanket 25-trap minimum, with massively increased vertical line loads everywhere except the Wilkinson Basin. Although this may reduce risk to NARWs by reducing the total number of vertical lines in areas where the use of a weak, 235.033-kg-m (1,700-ft-lb) line is impossible, the increases in load there may exceed the breaking strength of the lines and gear currently in use by fishers in this area.

To reduce the break-off risk to fishers, the NOAA rule allows approximately half the trawl minimum per area to be fished if only using a singular vertical line. This provision may help fishers who cannot fish the new trawl minimums due to vessel size or gear strength constraints. The decreased trawl length should decrease loads and help reduce vertical line break-offs; however, without a secondary vertical line, break-offs will then have to be recovered by dragging for gear.

Recommendations must be considered in light of our model's gear homogeneity assumptions. Given the fixed values for wave height and trap weight, these load values should be considered a best-case scenario, as loads exceeding these values are likely in inclement weather. We noted an approximately 5.5% increase in predicted load force on the vertical line when fishing in 2.13-m (7-ft) seas from the original 0.91-m (3-ft) predictions. Dialogue with fishers suggested that weather-forced vessel rolling caused this increase. Vessel rolling, combined with additional difficulty in maintaining best-hauling practices (e.g., maintaining an even angle of approach to minimize dragging gear in heavy seas), was difficult to fully capture with fair-weather volunteer data. We recommend extra caution for safety when making line strength recommendations for zones that are close to the 235.033-kg-m (1,700-ft-lb) load limit, such as between the 11.11–22.22-km (6–12-nm) line and further offshore. An increase in load during an extreme weather event may cause line parting and mid-haul gear failure, carrying the potential for fisher injury. Fishers or management personnel examining these results must assume that larger loads will result from the use of heavier traps, foul weather, or changes in the relationship between anchor use and depth beyond the typical operational parameters used in the lobster fishery outlined above.

Hauling methodology was consistent across fishers, with vessels striving to maintain an even rate of haul while positioned vertically above the trawl. There was typically an even increase in load as the vertical line was brought aboard, although this was highly variable depending on gear hang-ups, fishing conditions, and trawl length. The NOAA rule includes provisions for either weak-link inserts or a 50% vertical line "topper" that increases in strength from surface to seafloor, which may capitalize on this relationship to provide some reduced risk to whales. This could be of particular benefit to risk reduction in inshore areas, where we have shown a low total load and little increase in load as a result of new trawl minimum implementation.

The more drastic changes resulting from longer trawl lengths at great depth may pose a challenge to fishers implementing these rules. Implementation of weak rope or weak links in these deep offshore areas is likely to pose a high break-off risk, as we predicted loads commonly exceeding 235.033 kg-m (1,700 ft-lb) in these areas. Implementation of these trawl minima may pose a break-off risk even to current gear since the increase is large when considered both as a flat rate and as a percentage of total previous load (Supplementary Figure 4).

Changes in the load landscape due to implemented trawl length minima were expected, and we saw variable changes across depth within management areas (Figure 5). The previous, somewhat smooth gradient of load change from areas of low load in shallow inshore waters to areas of higher load in deeper offshore waters was replaced with more abrupt cutoffs of increased loads along the distance-from-shore delineations as the new trawl minima were implemented. In practice, load decreases are unlikely to occur, as whale protective plans currently only implement changes to trawl length minima, while fishers may continue to fish trawl lengths greater than the minimum in areas where they already do so. To reflect this, trawl lengths were only changed where they were below the new minima, while areas where fishers currently fish above the minimum were unchanged (Supplemental Figure 3).

Results indicated that under the new rules, many fishers would experience increases in load across the GoM. These changes were particularly pronounced in areas of greater depth. Implementation of these trawl minima in offshore areas will increase the risk of breakaway fishing gear due to higher loads or will force adaptation costs for fishers buying stronger lines. If gear loss is common when fishing the new trawl minima in deep waters, these areas may no longer be cost effective for fishers to target, thereby effectively closing the area to fixed-gear lobster fishing. Fishers shift their effort distribution to seek the highest CPUE outside of closed areas (Hilborn 2018). It is possible that fishers will redistribute their fishing effort to avoid the costs of fishing new trawl minima attributed to historic fishing areas. Displaced effort may change the overall NARW entanglement risk depending on the likelihood of whale occurrence in the preferred fishing area. The potential for a shifting effort distribution ought to be considered as a point of further study when testing the outcomes of the new trawl minima.

Further research in this field should more acutely describe the overlap of fishing effort and NARW distribution in the GoM. The high variability in NARW seasonal and spatial residency and transit pathways through the GoM suggests that management will have to review risk reduction proposals on an annual basis until NARW migration patterns are consistently and accurately described (Wikgren et al. 2014; Meyer-Gutbrod et al. 2021). The American lobster fishery exhibits strong seasonal variation in effort scale and distribution, posing variable risk to NARWs as their temporal residency patterns change. We expect that a comparison of shifting NARW distributions with the load landscape described here could yield information on areas of high entanglement severity as well as areas where lobster fishing and NARWs fail to overlap.

Efforts to describe the overlap of fishing effort and NARWs could utilize the impending mandate for fishing vessel monitoring systems in federal waters to improve the spatial resolution of trawl areas fished. This potential data stream or a modern comprehensive study of gear distribution within the GoM may better inform management decision making on spatial risk for NARWs. With regard to Figure 4, it is important to note that fishing effort is not uniform across the GoM. The majority of the American lobster fishing fleet operates within 5.556 km (3 nm) of shore (McCarron and Tetreault 2012). When quantifying risk to NARWs, it is important to consider the relative high density of low-load lines inshore as well as the lower density but relatively high-load lines in the 5.556–22.22-km (3–12-nm) and offshore areas. The ability of the inshore fishery to comply with the new trawl minima generates a marked reduction in risk to NARWs and, thus, a potential benefit to fishers by avoiding an NARW mortality-induced fishery closure. Areas beyond the 22.22-km (12-nm) boundary overwhelmingly exceed 235.033 kg-m (1,700 ft-lb) under rule implementation, and break-off risk is high if fishers are forced to implement the weak, 235.033-kg-m (1,700-ft-lb) rope under the new trawl minima. Changes in fisher behavior, such as targeting more shallow, low-load-inducing environments, may be required if fishers want to avoid gear loss and maintain entanglement risk reduction goals.

Management decisions that are intended to reduce risk to NARWs by increasing minimum trawl lengths and reducing the overall number of vertical lines in the water must also consider the capacity of the fleet to operate within these new rules. Changes to trawl length minima may cause fishing effort displacement or shifts in fishing methodology, with unforeseen effects on overlap between whales and fishing gear. Inshore vessels fishing historically low-load environments are typically smaller vessels (McCarron and Tetreault 2012) and may not have the deck size to fish the newly mandated trawl length minima safely. Although some flexibility for small vessels is included in the provision allowing half trawl length for a single vertical line, the possibility of lost gear without a secondary vertical line may drive fishers to conform to the higher trawl minima. This study has occurred simultaneously with management proposals calling for sweeping changes to trawl lengths and fishery behavior in the GoM. As management continues to develop and refine risk reduction proposals, the outlined mechanisms between trawl length, depth, and drag force on load should be considered, with the entanglement severity implications of stronger lines balancing the benefit of reduced numbers of lines. Applying these lessons to other fixed-gear or high-bycatch fisheries, it appears prudent to maintain modern fishery gear distribution data so that management can react swiftly and with minimal detriment to fishing communities when crises like endangered species mortality occur.

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REFERENCES

Acheson, J. 2001. Confounding the goals of management: response of the Maine lobster industry to a trap limit. North American Journal of Fisheries Management 21:404–416.

ALWTRT (Atlantic Large Whale Take Reduction Team). 2017. Atlantic Large Whale Take Reduction Team meeting, April 25–27, 2017: Providence, RI: key outcomes. National Oceanic and Atmospheric Administration Fisheries, Silver Spring, Maryland. Available: https://media.fisheries.noaa.gov/dam-migration/alwtrt_kom_april_2017.pdf. (March 2019).

Chen, Y., C. Wilson, K. Scheirer, D. Couture, and J. Wilson. 2005. Spatial dynamics of the lobster fishery and oil spills in the Gulf of Maine: a risk analysis of oil spills on the lobster fishery. University of Maine, Maine Oil Spill Advisory Committee/Department of Environmental Protection/Sea Grant Report, Orono. Available: https://seagrant.umaine.edu/research/projects/mosac-02-01-spatial-dynamics-of-the-lobster-fishery-and-oil-spills-in-the-gulf-of-maine-a-risk-analysis-of-oil-spills-on-the-lobster-fishery/. (September 2018).

Crosby Group. 2013. Loads on blocks. Crosby Group, Tulsa, Oklahoma. Available: http://www.thecrosbygroup.com/html/en-US/pdf/pgs/378.pdf. (March 2019).

Davis, G. E., M. F. Baumgartner, J. M. Bonnell, J. Bell, C. Berchok, J. Bort Thorton, S. Brault, G. Buchanan, R. A. Charif, D. Cholewiak, C. W. Clark, P. Corkeron, J. Delarue, K. Dudzinski, L. Hatch, J. Hildebrand, L. Hodge, H. Klinck, S. Kraus, B. Martin, D. K. Mellinger, H. Moors-Murphy, S. Nieukirk, D. P. Nowacek, S. Parks, A. J. Read, A. N. Rice, D. Risch, A. Širović, M. Soldevilla, K. Stafford, J. E. Stanistreet, E. Summers, S. Todd, A. Warde, and S. M. Van Parijs. 2017. Long term passive acoustic recordings track the changing distribution of North Atlantic right whales (*Eubalaena glacialis*) from 2004–2014. Scientific Reports 7:13460.

Goodman, A., J. McIntyre, A. Smith, L. Fulton, T. Walker, and C. Brown. 2021. Retrieval of abandoned, lost, and discarded fishing gear in southwest Nova Scotia, Canada: preliminary environmental and economic impacts to the commercial lobster industry. Marine Pollution Bulletin 171:112766.

Gowan, T. A., J. G. Ortega-Ortiz, J. A. Hostetler, P. K. Hamilton, A. R. Knowlton, K. A. Jackson, R. C. George, C. R. Taylor, and P. J. Naessig. 2019. Temporal and demographic variation in partial migration of the North Atlantic right whale. Scientific Reports 9: article 353.

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

Henry, A., and T. Johnson. 2015. Understanding social resilience in the Maine lobster industry. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science [online serial] 7:33–43.

Hilborn, R. 2018. Are MPAs effective? ICES (International Council for the Exploration of the Sea) Journal of Marine Science 75:1160–1162.

Johnson, A., G. Salvador, J. Kenney, J. Robbins, S. Kraus, S. Landry, and P. Clapham. 2005. Fishing gear involved in entanglements of right and humpback whales. Marine Mammal Science 21:635–645.

Kelly, K. H. 1993. Determination of lobster trap density near midcoastal Maine by aerial photography. North American Journal of Fisheries Management 13:859–863.

Knowlton, A. R., P. K. Hamilton, M. K. Marx, H. M. Pettis, and S. D. Kraus. 2012. Monitoring North Atlantic right whale *Eubalaena glacialis* entanglement rates: a 30 yr retrospective. Marine Ecology Progress Series 466:293–302.

Knowlton, A. R., J. Robbins, S. Landry, H. A. McKenna, S. D. Kraus, and T. B. Werner. 2016. Effects of fishing rope strength on the severity of large whale entanglements. Conservation Biology 30:318–328.

Kraus, S. D., R. D. Kenney, C. A. Mayo, W. A. McLellan, M. J. Moore, and D. P. Nowacek. 2016. Recent scientific publications cast doubt on North Atlantic right whale future. Frontiers in Marine Science 3:137.

McCarron, P., and H. Tetreault. 2012. Lobster pot gear configurations in the Gulf of Maine. Maine Lobstermen's Association, Kennebunk.

Meyer-Gutbrod, E. L., C. Greene, K. Davies, and D. Johns. 2021. Ocean regime shift is driving collapse of the North Atlantic right whale population. Oceanography 34:22–31.

NMFS (National Marine Fisheries Service). 2020. Landings. NMFS, Silver Spring, Maryland. Available: https://www.fisheries.noaa.gov/foss/f?p=215:200. (January 2021).

NMFS (National Marine Fisheries Service). 2021. Final rule to amend the Atlantic Large Whale Take Reduction Plan to reduce risk of serious injury and mortality to North Atlantic right whales caused by entanglement in Northeast crab and lobster trap/pot fisheries. NMFS, Silver Spring, Maryland.

NOAA (National Oceanic and Atmospheric Administration). 2020. Draft environmental impact statement, regulatory impact statement, regulatory impact review, and initial regulatory flexibility analysis for amending the Atlantic Large Whale Take Reduction Plan: Risk Reduction Rule volume 1. NOAA, Washington, D.C.

NOAA (National Oceanic and Atmospheric Administration) National Geophysical Data Center. 2009. ETOPO1 1 arc-minute global relief model. NOAA, National Centers for Environmental Information, Boulder, Colorado.

Pace, R. M., T. V. Cole, and A. G. Henry. 2014. Incremental fishing gear modifications fail to significantly reduce large whale serious injury rates. Endangered Species Research 26:115–126.

Pace, R. M., P. J. Corkeron, and S. D. Kraus. 2017. State-space mark–recapture estimates reveal a recent decline in abundance of North Atlantic right whales. Ecology and Evolution 7:8730–8741.

Pace, R. M., R. Williams, S. D. Kraus, A. R. Knowlton, and H. M. Pettis. 2021. Cryptic mortality of North Atlantic right whales. Conservation Science and Practice 3:e346.

Pettis, H. M., R. M. Pace, and P. K. Hamilton. 2021. North Atlantic Right Whale Consortium 2020 annual report card. North Atlantic Right Whale Consortium, Boston.

Picard, R. R., and R. D. Cook. 1984. Cross-validation of regression models. Journal of the American Statistical Association 79:575–583.

Stewart, J. D., J. W. Durban, A. R. Knowlton, M. S. Lynn, H. Fearnbach, J. Barbaro, W. L. Perryman, C. A. Miller, and M. J. Moore. 2021. Decreasing body lengths in North Atlantic right whales. Current Biology 31:3174–3179.

Tanaka, K., and Y. Chen. 2015. Spatiotemporal variability of suitable habitat for American lobster (*Homarus americanus*) in the Long Island Sound. Journal of Shellfish Research 34:531–543.

Wikgren, B., H. Kite-Powell, and S. Kraus. 2014. Modeling the distribution of the North Atlantic right whale *Eubalaena glacialis* off coastal Maine by areal co-kriging. Endangered Species Research 24:21–31.

Wood, S. N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. Journal of the Royal Statistical Society Series B: Statistical Methodology 73:3–36.

SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.