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Authors: Roman, Sally, and Rudders, David B.

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EXAMINATION INTO A VESSEL EFFECT FOR A MULTI-VESSEL INDUSTRY-BASED SEA SCALLOP DREDGE SURVEY

SALLY ROMAN* AND DAVID B. RUDDERS

Virginia Institute of Marine Science, William and Mary, 1375 Greate Road Gloucester Point, Virginia, VA 23062-1346

ABSTRACT Generalized linear models (GLM) and generalized additive mixed models (GAMM) were developed to examine for differences in fishing power, also referred to as a vessel effect, for three commercial fishing vessels chartered by the Virginia Institute of Marine Science (VIMS). The vessels conducted a fishery-independent sea scallop dredge survey of the MidAtlantic sea scallop resource in 2015. Surveys have continued since 2015 using a multivessel approach, and understanding the implications of a potential vessel effect on scallop catch is important for management and assessment of the resource. Surveys are conducted yearly to support annual fishery specifications and contribute biological and catch data for stock assessments. Generalized linear models tested for an effect of vessel on the total number of scallops captured and indicated survey strata and rotational area were significant predictors. Generalized additive mixed models tested for a vessel effect on scallop catch-at-length with length, vessel, strata, rotational area, and an interaction of vessel and length as fixed effects and survey station as a random effect. Two preferred GAMM were identified for the catch-at-length analysis. One model indicated that strata and rotational area had significant effects on scallop catch-at-length, whereas the interaction term was not significant. The second model did not include the interaction term or vessel as a predictor. Results presented here are consistent with previous calibration studies conducted for scallop dredge surveys suggesting that scallop catch is robust to the effect of vessel and support the use of a suite of industry vessels in the VIMS sea scallop surveys.

INTRODUCTION

Data obtained via fishery-independent resource surveys support a multitude of fishery stock assessment and management related objectives. These surveys inform stock assessment models by supplying requisite information on trends in abundance, age composition, and other biologically relevant information of marine populations. Survey data also offer guidance for managers in regulating fisheries.

In the United States, broad-scale fishery-independent surveys have traditionally been conducted onboard dedicated research vessels by the federal government, state agencies, or other research/academic organizations. For example, in the Northeast United States, the National Oceanic and Atmospheric Administration's (NOAA) Northeast Fisheries Science Center (NEFSC) has used dedicated research vessels along the northeastern continental shelf to survey the sea scallop (*Placopecten magellanicus*) resource and a multispecies groundfish complex since 1979 and 1963, respectively (NEFSC 2018, Politis et al. 2014). Advantages for this approach include minimizing variance associated with using multiple vessels by maintaining a consistent sampling platform and having a vessel designed to satisfy data collection needs (Helser et al. 2004). Although there are benefits to the deployment of dedicated research vessels, an increasing number of resource surveys are being conducted using a cooperative approach, where commercial fishing vessels are chartered as research platforms (Hanna 1995, Helser et al. 2004, Runnebaum et al. 2018, Thorson & Ward 2014, Wurtzell et al. 2016). This type of approach can decrease research costs and increase stakeholder buy-in to survey, management, and assessment results (Hartley & Robertson 2006, Johnson & van Densen 2007, Wurtzell et al. 2016). An additional benefit is the potential for flexibility in vessel selection afforded by having a large pool of vessels to address issues like mechanical malfunctions or vessel availability. This type of flexibility can rarely be obtained through the use of dedicated research vessels.

A cooperative approach for fishery-independent surveys has been adopted on a larger scale on the West Coast of the United States compared with the East Coast (Cooper et al. 2004, Helser et al. 2004). Although for some fisheries, like the sea scallop fishery in the Northeast United States, this cooperative approach to conducting surveys has been used since 1999 (DuPaul et al. 2000, Stokesbury et al. 2004). The majority of funding for these surveys comes from an innovative funding mechanism administered by the NOAA's Northeast Cooperative Research Sea Scallop Research Set-Aside Program (RSA). The primary objective of this program is to provide funding for applied research to support sea scallop fishery management and assessment. The RSA Program designates a portion of allocated annual catch to support a competitive grant program that funds collaborative, fishery-focused research through the sea scallop fishery management plan (Zuur et al. 2009, "Research Set-Aside Programs" 2016).

The sea scallop fishery is one of the most valuable wild-caught, single-species fisheries in the Northeast United States. In 2019, 27,500 mt of adductor muscles was landed with an ex-vessel value of U.S. $570 million (NOAA 2020). The fishery operates throughout the MidAtlantic Bight (MAB) and Georges Bank (GB) regions at depths ranging from 30 to 100 m. The stock is assessed as two distinct resource areas referred to as the GB and MAB subunits (NEFSC 2018) (Fig. 1). Although historically subject to extreme cycles of productivity, the fishery has benefited from management measures intended to bring stability and sustainability through rotational area management and the creation of rotational access areas (NEFMC 2003).

A benefit of the productivity in the resource has been the continued availability of RSA allocations to fund cooperative fishery-independent surveys. Data collected during these surveys are used to inform stock assessment models, as well as guide annual fishery regulations and catch allocations (i.e., total allowable catch, number of fishing days, access to rotational

*Corresponding author. E-mail: saroman@vims.edu
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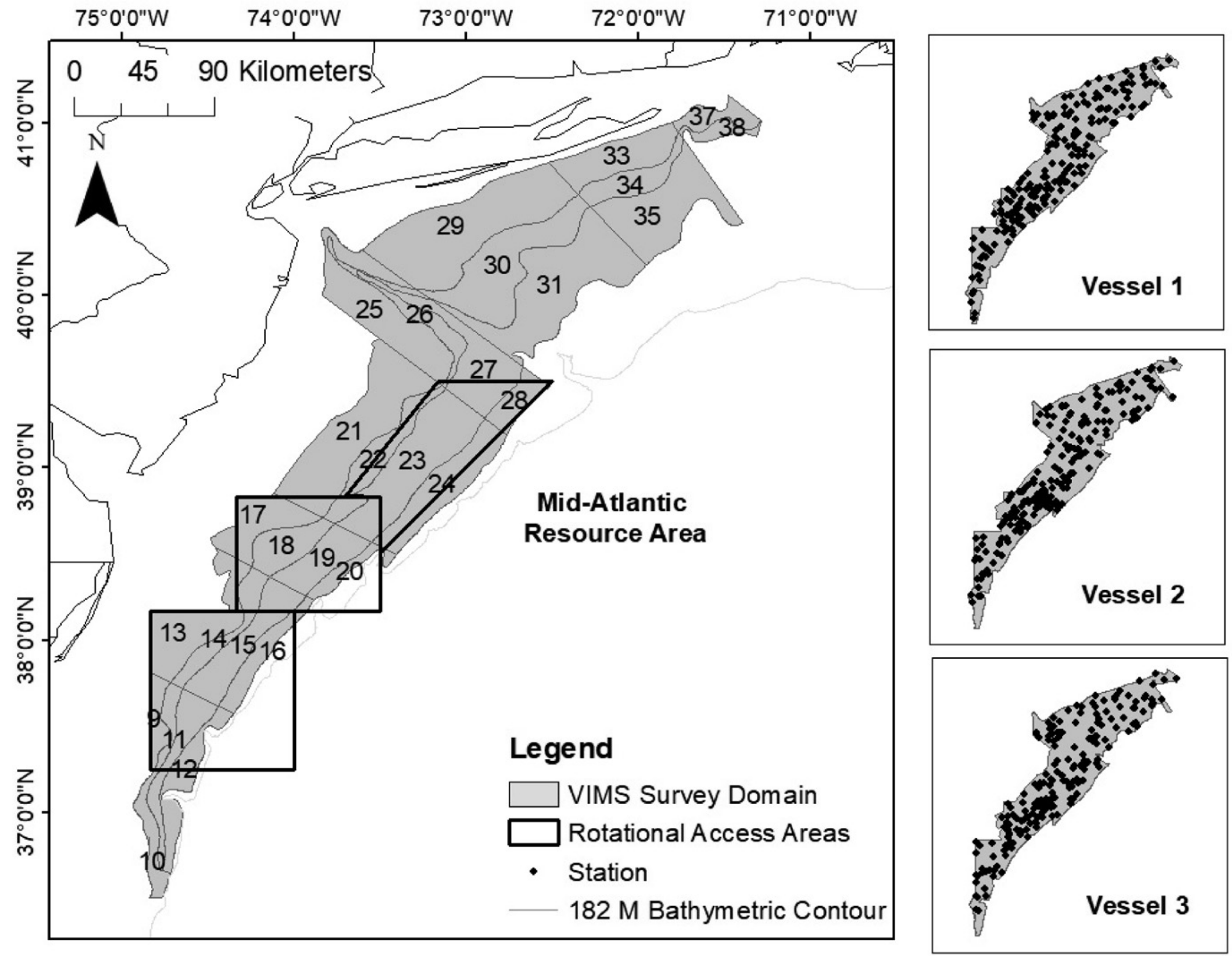

Figure 1. Map of the VIMS 2015 survey domain with strata boundaries and identifiers, and rotational access areas on the left. On the right are the completed stations by vessel overlaid on the survey domain.

areas, etc.). Several organizations have conducted cooperative optical and dredge surveys of the scallop resource, at varying spatial scales, with support from the RSA Program since 2000, whereas the NEFSC has conducted a broad-scale survey of the resource (DuPaul et al. 2000, NEFSC 2018, Stokesbury et al. 2004). Beginning in 2014, the Virginia Institute of Marine Science (VIMS) has been awarded RSA funding to conduct a broad-scale industry-based dredge survey of the MAB resource area (Fig. 1). The Virginia Institute of Marine Science conducts the survey onboard commercial fishing vessels that participate in the sea scallop fishery and hold a limited access sea scallop permit. The survey is conducted onboard multiple commercial vessels both within and among years. The potential for a vessel effect (i.e., differences in fishing power) could result from the use of several vessels for the survey. A vessel effect can manifest itself in the total number of animals caught and the number of scallops caught-at-length (Thorson & Ward 2014). The presence of a vessel effect could bias abundance estimates, as well as other data collected during the surveys such as catch-at-length and maturity information. Bias-related abundance estimates may impact the setting of annual fishery specifications, as well as assessment results, thereby affecting the interpretation of stock status. The direction of the effect would depend on the impact of vessel on catch. This bias would need to be accounted for in biomass estimation by switching from a design-based estimator to a model-based approach, where vessel is accounted for in biomass estimation (Helser et al. 2004, Thorson & Ward 2014) or applying a correction factor to adjust catch estimates (Benoít & Swain 2003). Other adjustments to the survey methodology may also be needed to ensure that biological data are collected without bias. Although standard survey protocols are in place to minimize among vessel variance, a vessel effect may exist as a consequence of differences among vessels (i.e., length or horsepower) (Thorson & Ward 2014).

The objective of this paper is to quantify the effect of vessel on the catch of sea scallops and draw inference related to the vessels used to conduct the dredge survey used within a cooperative survey framework. To address this goal, survey data from 2015 was examined to test whether the number of scallops caught and scallop catch-at-length differed among vessels. Investigating the effect of vessel for the VIMS industry-based fishery-independent dredge survey will assist in understanding the impact of using multiple vessels within a cooperative survey framework and the effect of vessel relative to the scale of abundance estimates generated from the survey.

TABLE 1.

Vessel characteristics (length and horsepower) along with survey leg information: sail date, land date, trip duration, number of days among survey legs, and mean depth (m) with SE in parentheses by vessel for the 2015 VIMS survey.

Vessel	Length (m)	Horsepower	Sail date	Land date	Trip duration	Days among legs	Mean depth (m)
Vessel 1	25	850	May 16, 2015	May 25, 2015	9	–	56.14 (0.95)
Vessel 2	27	1,150	June 5, 2015	June 13, 2015	8	11	54.44 (0.96)
Vessel 3	30	1,500	June 20, 2015	June 28, 2015	8	7	58.23 (0.92)

MATERIALS AND METHODS

Survey Methodology and Data Collection

The 2015 VIMS fishery-independent survey was specifically modified to test for a vessel effect and, thus, differed slightly from normal survey operations. Under normal conditions, two different vessels survey a portion of the survey domain on a survey leg in a given year. The survey generally occurs in May to minimize temporal variability among years and the time among survey legs is minimal (i.e., 2–4 days). A survey leg is defined as the time it takes a vessel to complete the predetermined number of stations and return to port. All vessels participating in the surveys are required to be similar in length, have a minimum horsepower of 800, and have sufficient space to complete the required sampling. In 2015, three vessels were selected to participate in the survey to test for a vessel effect. Vessel characteristics are provided in Table 1. Three consecutive survey legs were completed by the vessels, with each vessel sampling the entire survey domain. For a balanced design, each vessel surveyed a similar number of stations per strata and for the entire domain (Table 2, Fig. 1).

The 2015 survey was conducted from the Virginia/North Carolina border to Block Island, RI, in May and June of 2015

TABLE 2.

Number of stations and percentage of stations with at least one sea scallop caught included in all analyses by strata and vessel for the 2015 VIMS survey.

	Number of stations occupied			Percent positive stations		
Stratum	Vessel 1	Vessel 2	Vessel 3	Vessel 1	Vessel 2	Vessel 3
9	3	3	3	100	100	100
10	4	4	4	100	100	100
11	6	6	6	100	100	83
13	7	7	7	100	71	42
14	6	6	6	100	100	100
15	8	8	8	100	100	100
17	5	5	5	100	100	100
18	7	7	7	100	100	100
19	10	10	10	100	100	100
21	14	14	14	100	100	100
22	15	15	15	100	100	100
23	23	23	24	100	100	95
24	7	7	7	57	71	85
25	11	10	10	91	90	90
26	6	5	6	83	100	100
27	8	8	8	100	100	100
29	13	13	13	92	92	85
30	8	8	8	100	100	100
31	14	14	14	100	100	100
33	6	6	5	100	100	100
34	4	4	4	100	100	75
35	9	9	9	100	67	67
Total/Average	197	195	196	96	95	92

The total number of stations by vessel and the average number of positive tows by vessel is the last row.

(Fig. 1, Table 1). The survey domain consisted of a combination of NEFSC core scallop survey strata within the MAB resource area and additional strata that have been identified as important scallop habitat (NEFSC 2018). Sea scallop strata are delineated by depth and latitude (NEFSC 2018). The sampling framework was a stratified-random design. Stations were randomly allocated to strata using a hybrid approach consisting of both proportional (station allocation based on stratum area) and Neyman allocation techniques using the prior year's scallop survey catch data in weight and number of animals (Cochran 1977).

One of the contemporary approaches used to examine for the effect of vessel is a paired vessel field study, where vessels fish in close proximity using identical fishing gear to reduce spatial heterogeneity in catch rates (Cadigan & Dowden 2010, Cadigan et al. 2006, Fowler & Showell 2009, Miller 2013, Rudders & DuPaul 2010). Several constraints, such as limited staff and equipment, as well as the financial burden associated with deploying multiple vessels during a survey leg precluded the use of this approach for the survey. The assumption with a stratified-random sampling design is that catch within a stratum is more homogenous, reducing within strata variability (Cochran 1977, Helser et al. 2004). With the theory of homogeneity within strata in mind, having each vessel sample a similar number of randomly selected stations within each stratum was deemed as a valid approach to test for vessel effect. Scallops are also generally considered to be sessile animals, which minimized concerns regarding changes in scallop distribution and abundance associated with migration among strata during the survey (Smith & Rago 2004). Ehrich (1991) diverged from the paired vessel design to determine whether a vessel effect existed for haddock (*Melanogrammus aeglefinus*) catch between two research vessels. Vessels in Ehrich's (1991) study completed randomly selected stations within predetermined areas with known concentrations of haddock to deal with the high variability in haddock catch rates that had been observed in the survey.

At each station, vessels towed a NEFSC standard survey dredge with a 2.4 m dredge frame equipped with 5 cm rings, 10.2 cm diamond twine top, and 3.8 cm diamond mesh liner. Survey tows followed a standard protocol with a 15 min tow time at a speed-over-ground of approximately 1.9–2 m/sec (3.9–4 kts). A standard tow distance following speed and time protocols is approximately 1.8 km, although variability in tow distance can occur due to environmental conditions (i.e., wave height, wind speed, wind direction, and tide), as well as vessel speed, which can also be affected by the same environmental conditions. Starting and end coordinates of a tow were recorded by the chief scientist in the bridge using a GPS. Vessel speed and location were also automatically recorded every 3 sec during a tow from the GPS data string. A Star Oddi™ inclinometer was placed on the dredge to record dredge angle and was used to determine realized bottom contact time. Tow distance was calculated after completion of a survey using bottom contact time, vessel speed, and coordinate data. Captains were instructed by the chief scientist to set the survey dredge at approximately 0.9 km ahead of the station location and tow through the station on the same course. The direction of a tow was generally made in the direction of the next station to be sampled. Deviations from where and what direction a tow was completed were due to a number of factors including navigational hazards (i.e., ship wrecks or hangs that would damage the survey gear), weather conditions that made sampling on deck difficult, and the presence of fixed fishing gear. All modifications to how a station was sampled were done in consultation with the chief scientist and the vessel remained in the strata, where the station was originally allocated for the entirety of a tow.

Standardized catch sampling was conducted in the same manner as described by DuPaul and Kirkley (1995). All scallop catch was placed into bushel baskets and counted to quantify total catch at a given station. This included all sizes of live scallops, including damaged scallops (i.e., the shell was punctured, crushed, or broken). To obtain an estimate of the number and size of scallops caught at each station, either the total scallop catch or a subsample, depending on catch volume, was measured from the umbo to the shell margin to the nearest millimeter (mm). If a subsample was selected for length measurements, one to three baskets were randomly selected from the total catch after being placed in bushel baskets. The number of baskets selected for subsampling was scaled to the total scallop catch at a station: all scallops were measured if scallop catch was 1 basket or less, 1–5 baskets of total scallop catch equaled one basket selected for subsampling, 5–20 baskets equaled 2 baskets selected for subsampling, and more than 20 baskets equaled 3 baskets selected for subsampling. The size frequency of the entire catch at a station was determined by applying an expansion factor (number of baskets caught/number of baskets measured in a subsample) to the sampled number caught-at-length. The number of scallops caught-at-length measured in a subsample without applying an expansion factor is referred to as the unexpanded catch-at-length.

Data

Station-level catch data for all successful survey tows were queried for sea scallop catch (number of animals) and length data (number-at-length) for 28 strata. A successful tow is defined as a tow, where the survey dredge fished correctly, the dredge did not flip over, there were no hangs with the gear as it was hauled in, and no fixed fishing gear was caught on the dredge. Successful tows included stations, where zero scallops were caught in the survey dredge. Strata with less than three valid survey tows were excluded from analysis (n = 6), leaving station-level data from 22 strata for analysis. The unexpanded number-at-length data were summed to obtain the total number of scallops at each station by vessel for the pooled catch analysis. This resulted in 588 station-level observations for analysis (Table 2). The unexpanded number-at-length data in 1 mm length bins were used for the catch-at-length analysis (Fig. 2). Stations with zero catch were removed for length analysis (n = 525 stations). The number of length bins for each vessel was relatively similar, with 156 length bins for Vessel 1, 149 for Vessel 2 and 146 for Vessel 3. Using the unexpanded scallop data with an offset to account for differences in subsampling rates is the recommended approach for analyzing count data, where variability exists in sampling at the observation level (Cadigan & Dowden 2010; Cadigan et al. 2006, Holst & Revill 2009, Maunder & Punt 2004, Zhang & Chen 2015, Zuur et al. 2009).

Survey stations were assigned to rotational access areas to account for commercial effort and removals by the fishery, as well as growth. Fishery removals may impact the catch and catch-at-length of vessels completing later survey legs as

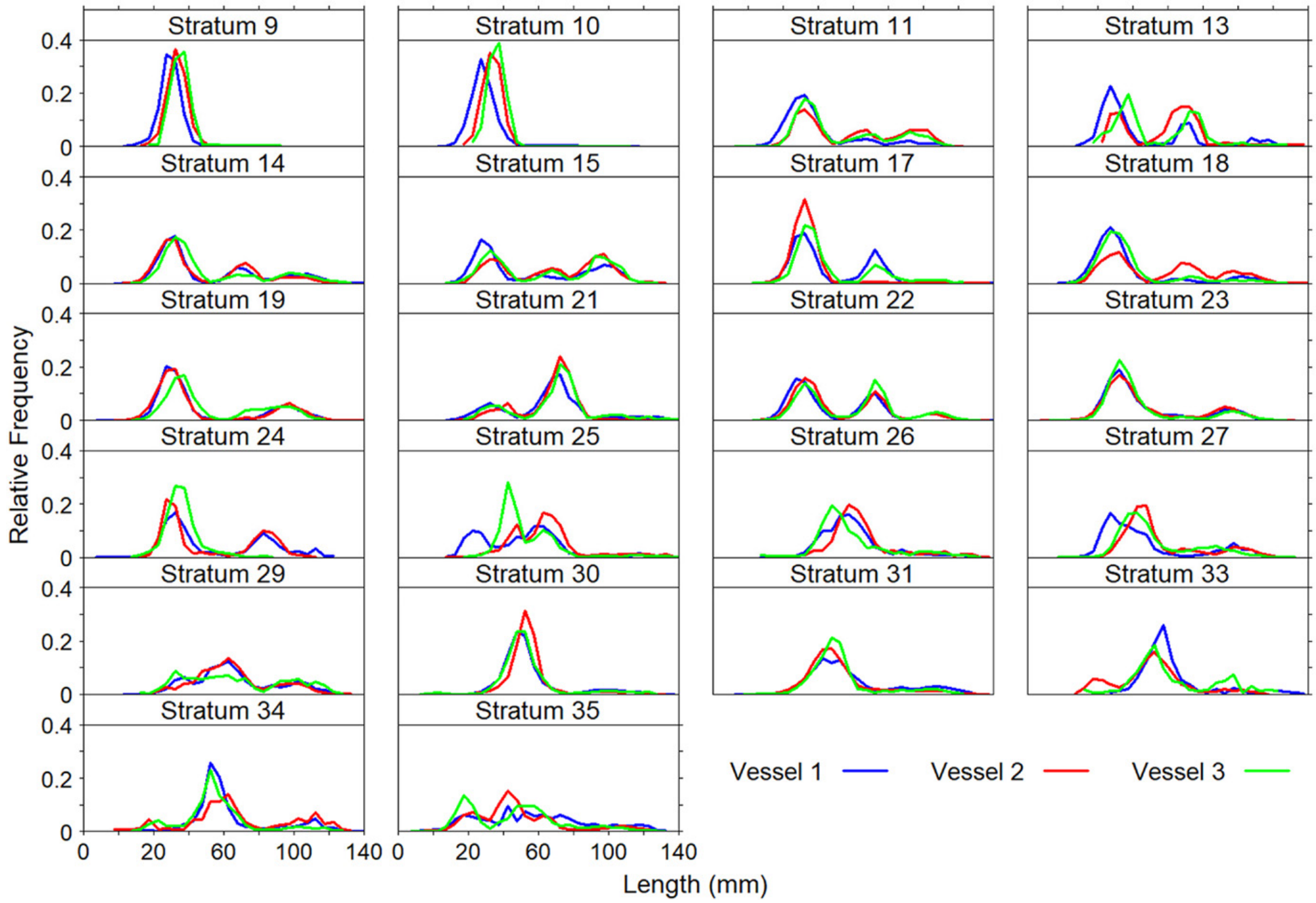

Figure 2. Sea scallop relative length frequency distributions by strata and vessel for the 2015 VIMS survey.

scallops were removed from the population that would have been available to the survey if the rotational access area was not open to the fishery. Scallops also exhibit faster growth in rotational access areas compared with scallops outside of these areas (Hart & Chute 2009, NEFSC 2018). Rotational area designation is illustrated in Figure 1. Stations within a rotational area were coded as a 1 and stations outside rotational access areas were coded as 0 for analysis.

Although standard survey protocols control for tow distance, variability in tow distance can occur for several reasons, as stated previously. Significant differences in the mean tow distance among vessels was detected with a one way ANOVA ($P < 0.01$). An additional offset term was included in analyses to account for this, as these differences may affect scallop catch and variability existed at the station-level (Cadigan and Dowden 2009, Cadigan et al. 2006, Helser et al. 2004, Moriarty et al. 2020, Zuur et al. 2009).

Pooled Catch Analysis

Generalized linear models were developed to determine whether there was a significant difference in the total catch of scallops among vessels. Modeling approaches to estimate a vessel effect for cooperative research surveys have been conducted via generalized linear mixed models, where models were developed with vessel as a fixed and random effect (Cooper et al. 2004, Helser et al. 2004, Thorson & Ward 2014). Results from these studies indicated that modeling vessel, as a random effect, was preferred and vessel was a source random variation when estimating biomass. The data precluded considering vessel as a random effect because three vessels participated in the survey and the threshold for including a variable as a random effect is to have a minimum of five levels of a variable (Bolker 2008, Zuur et al. 2009). For analysis, models were developed treating vessel as a fixed effect to test for the effect of vessel. Generalized linear models allow for flexibility in specifying the error structure of the response variable, which, in this case, was count data, and allow for the incorporation of additional variables beyond vessel that may also impact scallop catch like rotational area and strata (Zuur et al. 2009).

The response variable was the unexpanded number of scallops caught. Predictor variables considered were: vessel (a categorical variable with 3 factor levels), strata (a categorical variable with 22 factor levels), and rotational area (a categorical variable with 2 factor levels). An offset term to account for subsampling of catch and tow distance at the station-level was also included the following methods from Millar (1992), Cadigan et al. (1996), and Cadigan and Dowden (2010). The general GLM was:

$$g\left(u_{v,s,a}\right) = \alpha + \beta_1 * v + \beta_2 * s + \beta_3 * a + x_i \qquad (1)$$
$$y_{v,s,a \sim NB\left(u_{v,s,a},\, k\right)}$$

where, g is the log link function, $u_{v,s,a}$ is the expected mean number of scallops caught by vessel v in strata s and rotational area a. α is the intercept, and x_i is an offset term In(*towdistance*$_i$ • *subsampling fraction*$_i$) at station i. The negative binomial error distribution was chosen after preliminary analysis with a Poisson error distribution indicated the data were overdispersed (Zuur et al. 2009). The negative binomial distribution is also shown in Eq. 1, where $y_{v,s,a}$ is the number of scallops caught by vessel v in strata s and rotational area a, and k is the overdispersion parameter.

All combinations of covariate candidate models were developed using the MuMIn R package (Barton 2009) and the glm.nb function in the MASS R package with maximum likelihood for parameter estimation (Venables & Ripley 2002). A manual forward model selection process was also completed to confirm modeling results and identify any other potentially useful models. Models were compared with the Bayesian information criterion (BIC) and confirmed with the Akaike information criterion (AIC) due to the tendency of AIC based model selection to favor more complicated models (Burnham & Anderson 2002). The model with the lowest BIC was selected as the best fitting model (Burnham & Anderson 2002). Models with a BIC within three units of the BIC_{min} and an AIC within three units of the AIC_{min} were considered equally plausible as preferred models (Bolker 2008, Raftery 1995). Overall significance of model terms was determined with the ANOVA function in the car R package by applying a Wald's test (Fox & Weisberg 2019). Model goodness-of-fit was assessed with residual diagnostics including a Q–Q plot, residuals against fitted model values, and residuals against all explanatory variables.

Tukey's honest significance test (HSD) was used to conduct *post hoc* pairwise comparisons to test for significant differences among vessel factor levels for the preferred model(s), if the vessel term was included in the preferred model(s) (Major et al. 2017, Miller 1981, Nanda et al. 2021, Roop et al. 2018, Zuur et al. 2009). The null hypothesis for this test is that there are no differences between parameter mean estimates and the test uses confidence intervals to determine significance among specific pairs of factor levels. This approach can be preferred over a significance value from an ANOVA for categorical variables (Nanda et al. 2021). The glht function in the multcomp R package was used to carry out the tests (Hothorn et al. 2008). All analyses were completed with the statistical program R (R Core Team 2020). Statistical significance (α) was equal to 0.05 for all analyses.

Catch-At-Length Analysis

Generalized additive mixed models were developed to test for differences in the number of scallops caught-at-length among vessels. This family of models allow for flexibility in modeling nonlinear relationships between a response variable and predictor variables through the use of smoothing functions (Hastie & Tibshirani 1990, Pedersen et al. 2019, Wood 2017). Generalized additive mixed models can also incorporate categorical and continuous predictor variables and various error distributions. The response variable for these models was the unexpanded number of scallops-at-length caught in 1 mm length bins. Predictor variables considered were: length (mm), stratum, rotational area, vessel, and an interaction of length and vessel. Thin plate regression smoothers were used for both the length and interaction terms. The interaction term was modeled as a factor smooth interaction following examples from Wood (2017) and Pedersen et al. (2019), where the smoother of length was modeled by the vessel term (length, by = vessel) to allow for smoothers to be estimated for each vessel level. The vessel term was also included as a categorical predictor to allow for parametric parameter estimates for Vessels 2 and 3, and to test for significance differences between the reference vessel level (Vessel 1) and the other two vessel levels. All other terms entered into the models as categorical variables with the same number of factor levels as described for the GLM. A random effect smoother was used for the random effect term of station, as this approach allows for the significance of the random effect to be determined (Pedersen et al. 2019). Station was included as a random intercept to account for the spatial autocorrelation of scallops caught at a given station (Pinheiro & Bates 2000, Zuur et al. 2009). The same offset term applied in the GLM was also used for the GAMMs to account for differences in subsampling of catch and tow distance at the station level. Generalized additive mixed models were developed with a negative binomial error structure. The general GAMM was:

$$g\left(\mu_{l,v,s,a}\right) = \alpha + s(l) + s\left(l, by = v\right) + \beta_1 * v + \beta_2 * s + \beta_3 * a + x_i + \gamma_i \qquad (2)$$
$$y_{l,v,s,a} \sim NB\left(u_{l,v,s,a}, k\right)$$

where, g, i, v, s, a, x_i, and α have the same notation as in Eq. 1. $\mu_{l,v,s,a,}$ is the expected mean number of scallops-at-length as a function of the smooth term s for length l and the smooth terms for the interaction of length by vessel ($s(l, by = v)$), strata s, and rotational area a. γ_i is the random effect of station i that is assumed to be independent and identically distributed with a mean of 0 and variance of σ_i^2. The negative binomial distribution is also shown in Eq. 2, where $y_{l,v,s,a}$ is the number of scallops caught by length l and vessel v, in strata s and rotational area a, and k is the overdispersion parameter.

Candidate models were developed with manual forward and backward selection procedures for all combinations of variables. Model selection procedures were also similar to those used for the GLM, where preferred models were determined based BIC values and confirmed by AIC. Model fit was also examined with residual diagnostics, similar to the GLM. Models were fit with restricted maximum likelihood using the mgcv R package and the gam function (Wood 2011). Overall significance of both smooth and parametric model terms was determined with the ANOVA function in the mgcv R package by applying a Wald's test (Wood 2011). A Tukey's HSD test was also completed for the preferred model(s) to test for significant differences among vessel factors parametric estimates following the same approach outline for the GLM. The predicted number of scallops at-length was estimated with 95% confidence intervals for the preferred model(s) and plotted to assess the length frequency distributions by vessel.

RESULTS

Survey Characteristics

The entire survey was completed over the course of 43 days from May 16, 2015 to June 28, 2015 (Table 1). There

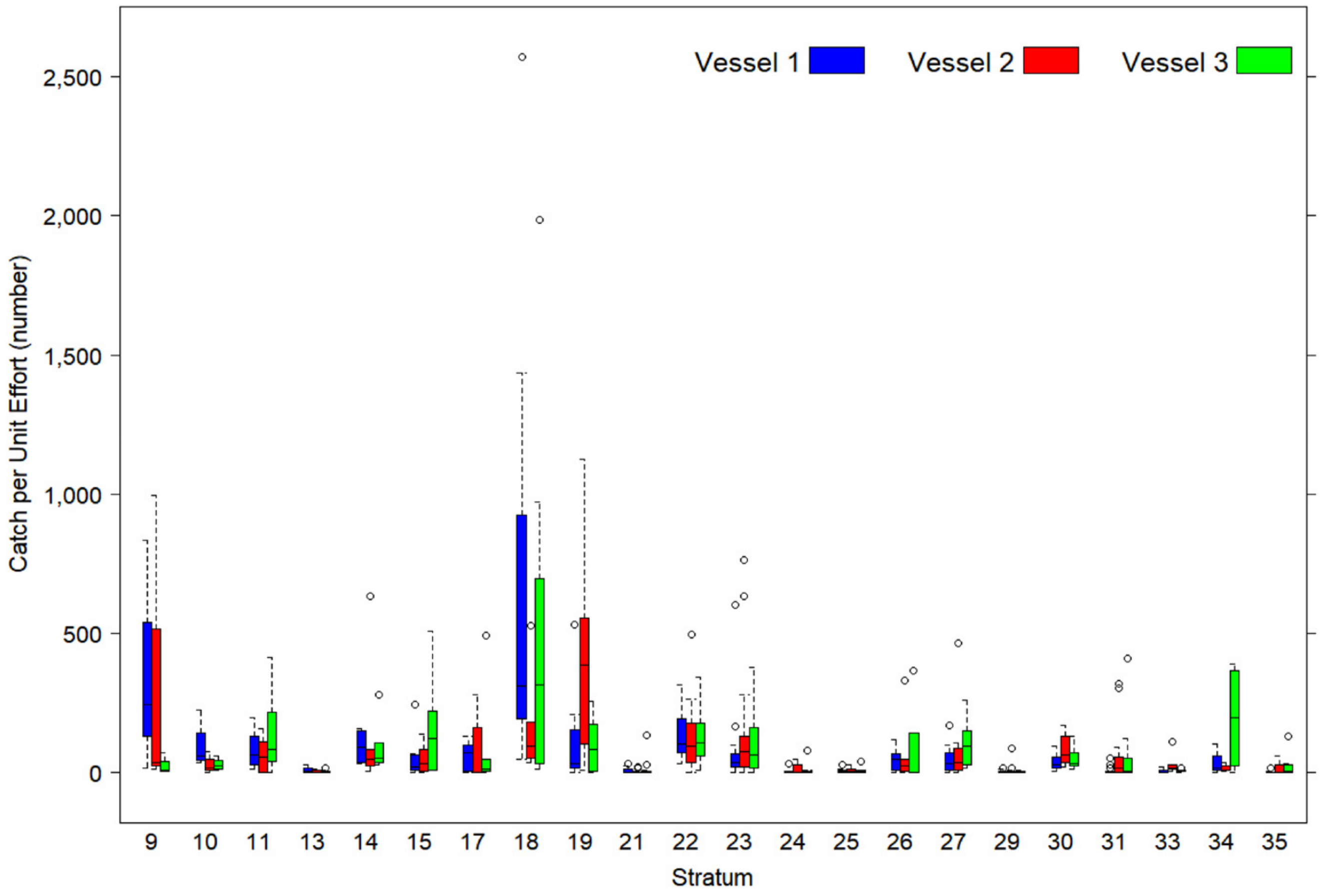

Figure 3. Catch per unit effort (standard survey tow) in number of sea scallops by strata and vessel with 95% confidence intervals.

was an 11-day delay between legs 1 and 2, and leg 3 departed after a 7-day hiatus (Table 1). Trip duration was similar among vessels (Table 1). The average number of stations with positive scallop catch rates ranged from 92% to 96% and the percentage of positive catches was generally consistent across strata (Table 2). Catch per unit effort was variable among strata, whereas relatively consistent across vessels within strata, and 95% confidence intervals overlapped for all strata (Fig. 3). Four strata showed variability in catch per unit effort among vessels. Strata 9 and 34 tend to have more variable catch rates due to the patchy distribution of scallops and being located at northern and southern extents of the MAB resource. Strata 18 and 19 are located within rotational access areas that were open to fishing activity in 2015 during the course of the survey.

Pooled Catch Analysis

Seven candidate GLM were developed for the pooled catch analysis (Table 3). Model glm6 was the preferred model based on BIC, whereas model glm7 had a similar AIC value (ΔAIC = 1.6) compared with the preferred model. For the

TABLE 3.

Candidate generalized linear models for the pooled scallop catch analysis ranked by BIC.

Model	Predictors	BIC	ΔBIC	AIC	ΔAIC
glm6	**Stratum, Rotational Area**	**7,542.4**	–	**7,433.0**	–
glm7	Stratum, Rotational Area, Vessel	7,552.8	10.4	7,434.6	1.6
glm2	Stratum	7,576.0	33.6	7,471.0	38.0
glm4	Stratum, Vessel	7,584.5	42.1	7,470.7	37.7
glm3	Rotational Area	7,589.3	46.9	7,576.2	143.2
glm5	Rotational Area, Vessel	7,599.7	57.3	7,577.8	144.8
glm1	Vessel	7,756.3	213.9	7,738.8	305.8

Predictors included in each model, along with the BIC, ΔBIC ($BIC_i - BIC_{min}$), AIC, and ΔAIC ($AIC_i - AIC_{min}$) are provided. The preferred model based on model selection criteria is identified in bold.

preferred model, predictors of scallop catch were rotational area and stratum (Table 4); both terms were significant ($P < 0.01$ for both terms). Although model glm7 was not considered a preferred model based on selection criteria, summary information for this model is included because AIC values were comparable to model glm6. In model glm7, both stratum and rotational area were again significant predictors of scallop catch ($P < 0.01$ for both terms), whereas vessel was not a significant predictor ($P = 0.30$). There were also no significant differences among the reference vessel factor level, Vessel 1, and either of the other two vessel factor levels (Vessel 2 $P = 0.11$ and Vessel 3 $P = 0.57$). Tukey's HSD test was completed for model glm7, where vessel was included as a predictor. There was no significant difference in mean scallop catch among all combinations of vessels (all $P > 0.24$). The manual forward selection procedure produced similar model results. Model diagnostics and partial effect plots for predictors in model glm6 indicated an acceptable goodness-of-fit (Fig. 4).

Catch-At-Length Analysis

In total, 10 GAMM were developed for the catch-at-length analysis (Table 5). Models gam7 and gam9 were identified as preferred models based on BIC model selection criteria, although model gam9 had a significantly higher AIC compared with model gam7 (ΔAIC = 204.8). Predictors in model gam7 included stratum, rotational area, and the length:vessel interaction term. All smooth interaction terms were significant (all $P < 0.01$), indicating the smoothers were significantly different from zero (Table 6, Fig. 5). Both stratum and rotational area were significant predictors of scallop catch-at-length ($P < 0.01$ for both terms), whereas the vessel length interaction term was not significant ($P = 0.58$). Parametric vessel term estimates indicated the effect size for Vessels 2 and 3 were small and there was no significant difference between the reference vessel (Vessel 1) and either Vessel 2 or Vessel 3 (Table 6). The overall shape and effective degrees of freedom for each vessel specific smoother were similar (Fig. 5). The summed effects plots with 95% confidence intervals by vessel indicated no differences in catch-at-length across the length range as confidence intervals for all three vessels overlapped across the entire length range (Fig. 6). The predicted catch-at-length plots by vessel and strata also confirmed no differences in catch-at-length, with 95% confidence intervals overlapping across the length range sampled for all vessels (Fig. 7). The random effect of station was significant ($P < 0.01$) and the estimated variance was 1.43 (SD 0.004). A Tukey's HSD test was completed for model gam7. There was no significant difference between the mean scallop catch-at-length and all combinations of vessel factor levels (all $P > 0.90$). The other preferred model, gam9, did not have the length:vessel interaction term or the vessel term as predictors and indicted stratum, length, and rotational area effected scallop catch-at-length. Model diagnostics for both preferred model were acceptable.

TABLE 4.

Parameter estimates and *P* values for predictors of stratum and rotational area from the preferred GLM (glm6) for the pooled scallop catch analysis.

Parameter	Estimate	SE	*P*-value
Intercept	−2.48	0.51	<0.01
Stratum 10	−0.57	0.60	0.34
Stratum 11	−0.13	0.55	0.81
Stratum 13	−2.65	0.53	<0.01
Stratum 14	−0.27	0.54	0.62
Stratum 15	−0.31	0.52	0.55
Stratum 16	−0.68	0.62	0.28
Stratum 17	−0.81	0.56	0.15
Stratum 18	1.06	0.53	0.05
Stratum 19	0.62	0.50	0.22
Stratum 21	−1.12	0.53	0.03
Stratum 22	0.72	0.48	0.13
Stratum 23	0.74	0.47	0.11
Stratum 24	−2.12	0.54	<0.01
Stratum 25	−0.65	0.56	0.25
Stratum 26	0.63	0.60	0.29
Stratum 27	0.48	0.53	0.37
Stratum 29	−0.64	0.55	0.24
Stratum 30	1.09	0.57	0.06
Stratum 31	0.59	0.55	0.28
Stratum 33	−0.52	0.60	0.39
Stratum 34	0.38	0.64	0.55
Stratum 35	−0.28	0.57	0.62
Rotational Area 1	1.59	0.25	< 0.01

DISCUSSION

Vessel was not found to be a significant predictor of scallops caught for either pooled scallop catch or catch-at-length. Vessel was not included as a predictor of scallop catch for the preferred pooled catch model. For the competing pooled catch model, with an AIC value similar to the preferred model, no difference in catch among vessels was detected. For the catch-at-length analysis, the interaction of length and vessel was retained in one of the preferred models, but was not significant and ultimately no differences were detected among vessels when comparing predicted catch-at-length or smoother fits. For the second preferred catch-at-length model, vessel was not included as a predictor and therefore did not affect catch-at-length.

The main predictors of scallop catch were strata, rotational area, and length. The inclusion and significance of all three predictors in the preferred models should be expected. The sea scallop resource has been stratified based on depth and latitude since 1979 (NEFSC 2018) and dredge surveys use a stratified-random survey design to assess the sea scallop resource. As such stratum should be expected to be a significant indicator of scallop catch rates. The expectation that length impacts catch-at-length follows a similar logic in that the length distribution of a scallop bed or population would determine catch-at-length. Rotational area management was implemented to maximize

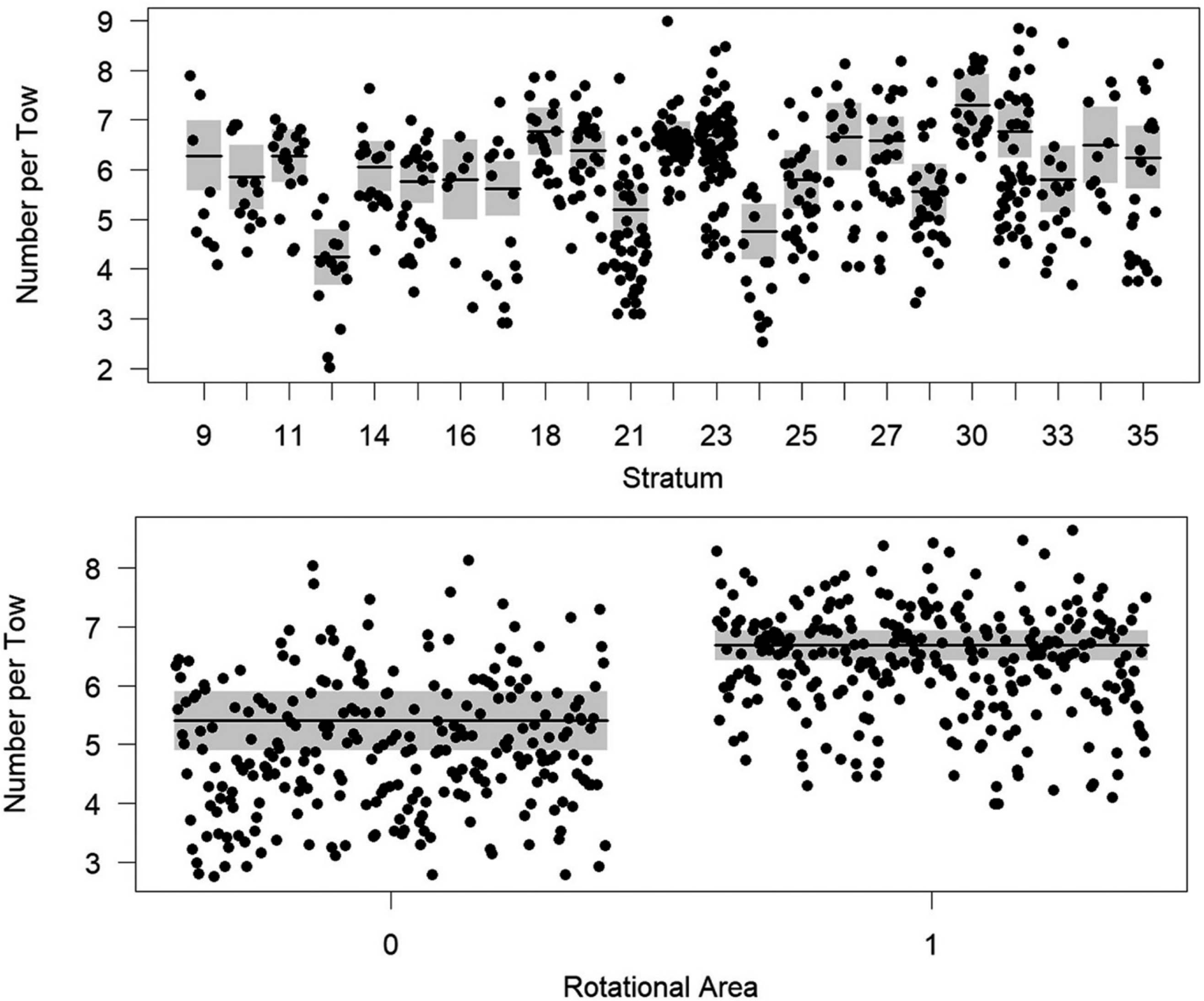

Figure 4. Partial effect plots from the preferred pooled catch GLM (glm6) for the predictors of stratum and rotational area.

TABLE 5.

Candidate generalized additive mixed effect models for the scallop catch-at-length analysis ranked by BIC.

Model	Predictors	BIC	ΔBIC	AIC	ΔAIC
gam7	**Stratum, Length:Vessel, Rotational Area**	**131,402.3**	**–**	**127,079.6**	**–**
gam9	**Stratum, Length, Rotational Area**	**131,404.3**	**2**	**127,284.4**	**204.8**
gam6	Stratum, Length:Vessel	131,415.8	13.5	127,083.2	3.6
gam4	Length:Vessel	131,523.4	121.1	127,101.6	22.0
gam10	Stratum, Length, Vessel, Rotational Area	131,525.5	123.2	127,284.7	205.1
gam1	Stratum	131,537.3	135.0	127,288.0	208.4
gam5	Stratum, Length	131,537.3	135.0	127,288.0	208.4
gam8	Stratum, Length, Vessel	131,538.8	136.5	127,288.3	208.7
gam2	Length	131,645.8	243.5	127,307.1	227.5
gam3	Vessel	131,646.8	244.5	127,307.1	227.5

Predictors included in each model, along with the BIC, ΔBIC ($BIC_i - BIC_{min}$), AIC, and ΔAIC ($AIC_i - AIC_{min}$) are provided. The preferred models based on model selection criteria are identified in bold. Length:Vessel indicates an interaction term.

TABLE 6.

Parameter estimates, standard errors, and *P* values for the parametric predictors of stratum, rotational area, and vessel in the preferred GAMM (gam7) for the scallop catch-at-length analysis.

Predictor type	Parameter	Estimate	SE	*P*-value
Parametric predictors	Intercept	−6.81	0.34	<0.01
	Stratum 10	−0.06	0.39	0.87
	Stratum 11	0.17	0.36	0.63
	Stratum 13	−0.88	0.37	0.02
	Stratum 14	0.03	0.35	0.93
	Stratum 15	0.02	0.34	0.96
	Stratum 17	−0.41	0.37	0.27
	Stratum 18	0.94	0.34	0.01
	Stratum 19	0.72	0.33	0.03
	Stratum 21	−0.09	0.35	0.79
	Stratum 22	1.00	0.31	<0.01
	Stratum 23	0.71	0.30	0.02
	Stratum 24	−0.77	0.37	0.04
	Stratum 25	−0.03	0.37	0.93
	Stratum 26	0.67	0.40	0.10
	Stratum 27	0.41	0.35	0.24
	Stratum 29	−0.25	0.37	0.50
	Stratum 30	0.92	0.38	0.02
	Stratum 31	0.23	0.36	0.52
	Stratum 33	−0.24	0.40	0.54
	Stratum 34	0.37	0.42	0.39
	Stratum 35	0.01	0.39	0.98
	Rotational Area 1	0.84	0.17	<0.01
	Vessel 2	0.09	0.09	0.30
	Vessel 3	0.06	0.09	0.54
	Parameter	**Effective degrees of freedom**		***P*-value**
Smooth predictors	s(length:Vessel 1)	4.99		<0.01
	s(length:Vessel 2)	4.98		<0.01
	s(length:Vessel 3)	4.97		<0.01
	s(Station)	524		<0.01

Smooth term predictors of length:vessel and the random effect of station along with effective degrees of freedom and *P* values are in the lower section of the table.

yield per recruit and provide protection for smaller scallops observed in high abundance, so having a significant effect of this predictor is an indication that this approach is meeting management objectives (NEFMC 2003). The application of GAMM and the significance of the smooth terms for the catch-at-length analysis indicate this approach captured the nonlinear nature of the scallop length distribution in the MAB. The significance of rotational area in both the pooled catch and catch-at-length analysis, as well as the smooth terms in the catch-at-length analysis indicate a wide range of predictor variables should be considered when developing models to estimate differences in fishing power among a group of vessels. This issue may be especially relevant when deviating from a traditional paired calibration study and using an experimental design that occurs over an extended time period.

Although this study did not detect a vessel effect on scallop catch, when comparing the three vessel specific smoothers and predicted catch-at-length some minor differences were observed. Vessel 1 caught fewer scallops from 6.5 to 16 mm and 60 to 90 mm. Vessel 1 also caught slightly more of the largest size classes of scallops (<160 mm) compared with Vessels 2 and 3. The smoothers and predicted catch for Vessels 2 and 3 were almost identical. Vessel 1 was the smallest out of the three vessels in terms of both length and horsepower (Table 1). For scallops at either end of the length distribution the difference in catch may be a result of sample size, where few small or large scallops are in the population and encountered by the survey.

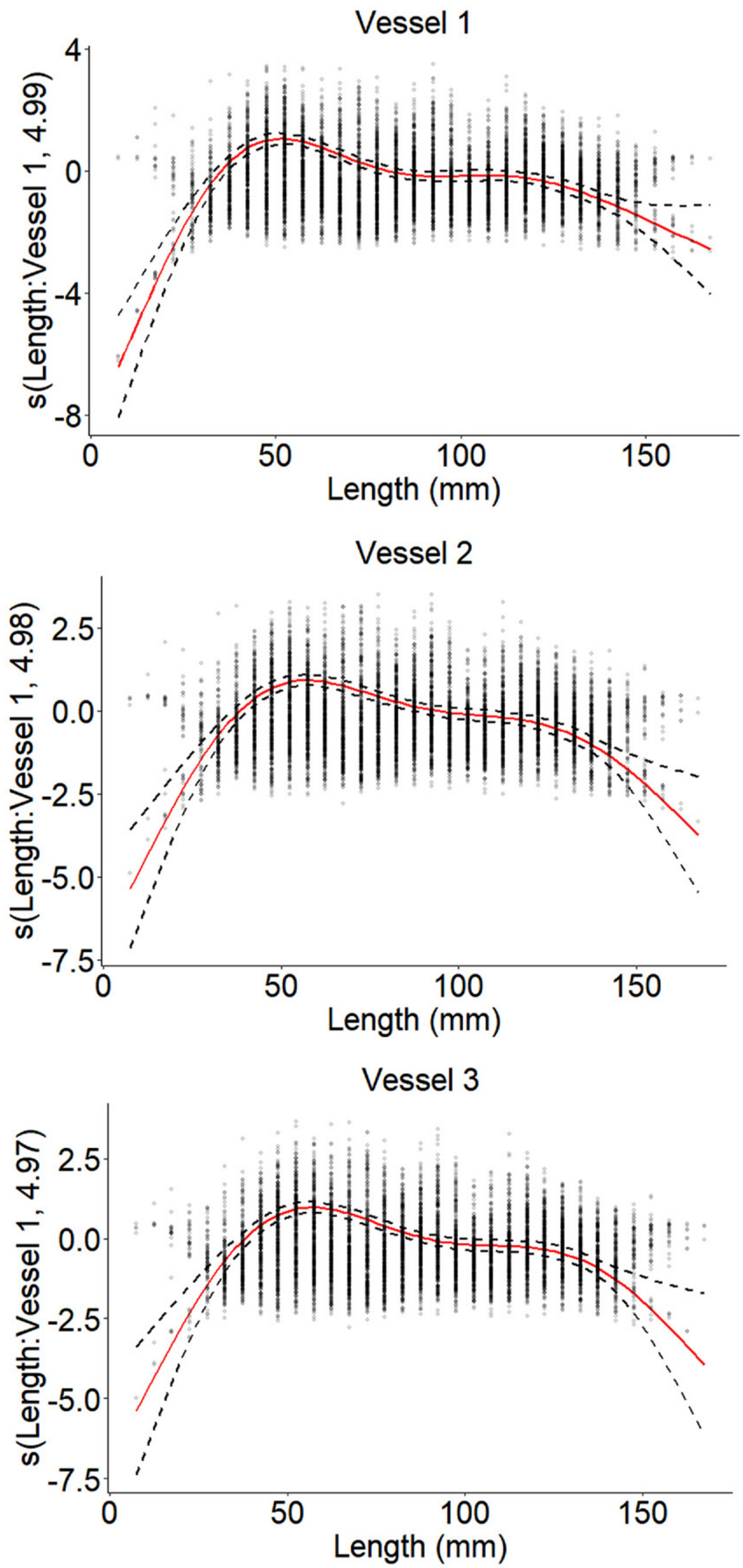

Figure 5. Partial effect plots from the preferred scallop catch-at-length GAMM (gam7) for the smoother interaction terms of length by vessel. Residuals (black circles) are also plotted. Red lines are mean smoothers and dashed lines are 95% confidence intervals. The *y*-axis is on the link scale. The effective degrees of freedom for each vessel specific smooth are provided in the parentheses on the *y*-axis label.

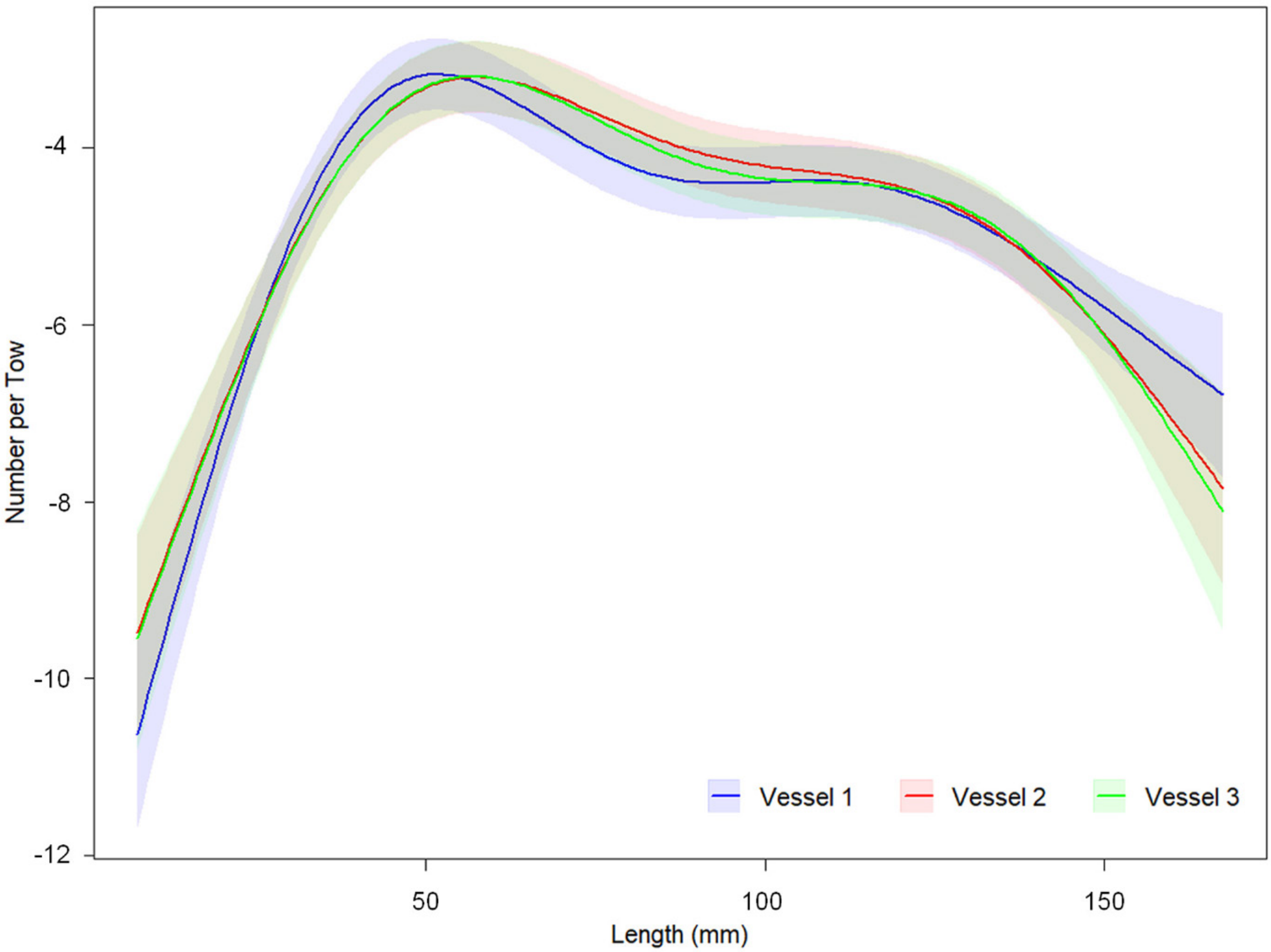

Figure 6. Summed effect plots with 95% confidence intervals by vessel predicted from the preferred scallop catch-at-length GAMM (gam7) for the smoother interaction term of length by vessel. The *y*-axis is on the link scale.

In practice, scallops <40 mm are not included in biomass estimates, so the resulting differences have an attenuated impact on survey output (NEFSC 2018). Data collected on scallops <40 mm are used primarily as an indicator of the presence of potential recruitment events that may need to be tracked by subsequent resource surveys and fishery managers over the upcoming years. Minor differences among vessels, however, would not inhibit the identification and subsequent monitoring of incoming recruitment events. The difference in observed catch for scallops in the midrange of the distribution could be attributed to growth. Growth is a dynamic process in the MAB resource area, with both depth and latitude gradients observed across the resource (Hart & Chute 2009, NEFSC 2018). There is also differential growth among scallops provided protection through rotational areas and scallops in open areas, as well as rapid growth for smaller size classes during the time period when the VIMS survey was conducted in the MAB (Hart & Chute 2009, NEFSC 2018). We believe that the minor differences were a result of these external, biological factors and not driven by intrinsic factors that were a function of vessel characteristics or operations related to vessel. The survey was conducted over the course 43 days to allow for all three vessels to have sufficient time to complete the survey. Rudders and DuPaul (2010) found differences in catch-at-length during a 2009 project designed to test for differences between a retiring research vessel and commercial vessels, and the project was conducted over several months. Vessel 1 completed the first survey leg starting in mid-May over 9 days and then there was 11 days between the first and second legs. The survey legs conducted by Vessels 2 and 3 were completed in the month of June with just 7 days between the two legs. Our typical survey plan is to limit the temporal spread between survey legs and this should minimize any potential effects of scallop growth on survey results.

The findings are consistent with several past calibration studies conducted for sea scallop dredge surveys in the Northeast United States (DuPaul & Rudders 2008, Lai & Kimura 2002, Rudders & DuPaul 2010, Serchuk & Wigley 1986). These studies concluded that sea scallop dredge surveys are generally robust to the effect of vessel. One calibration study conducted by VIMS and the NEFSC in 2007 onboard a retiring research vessel and two commercial vessels found fishing power correction factors were minor and no systematic bias existed for the pooled catch of scallop (DuPaul & Rudders 2008). Another calibration study, completed in 2009 by the same organizations, found no significant difference in scallop catch between an industry vessel and a research vessel (Rudders & DuPaul 2010).

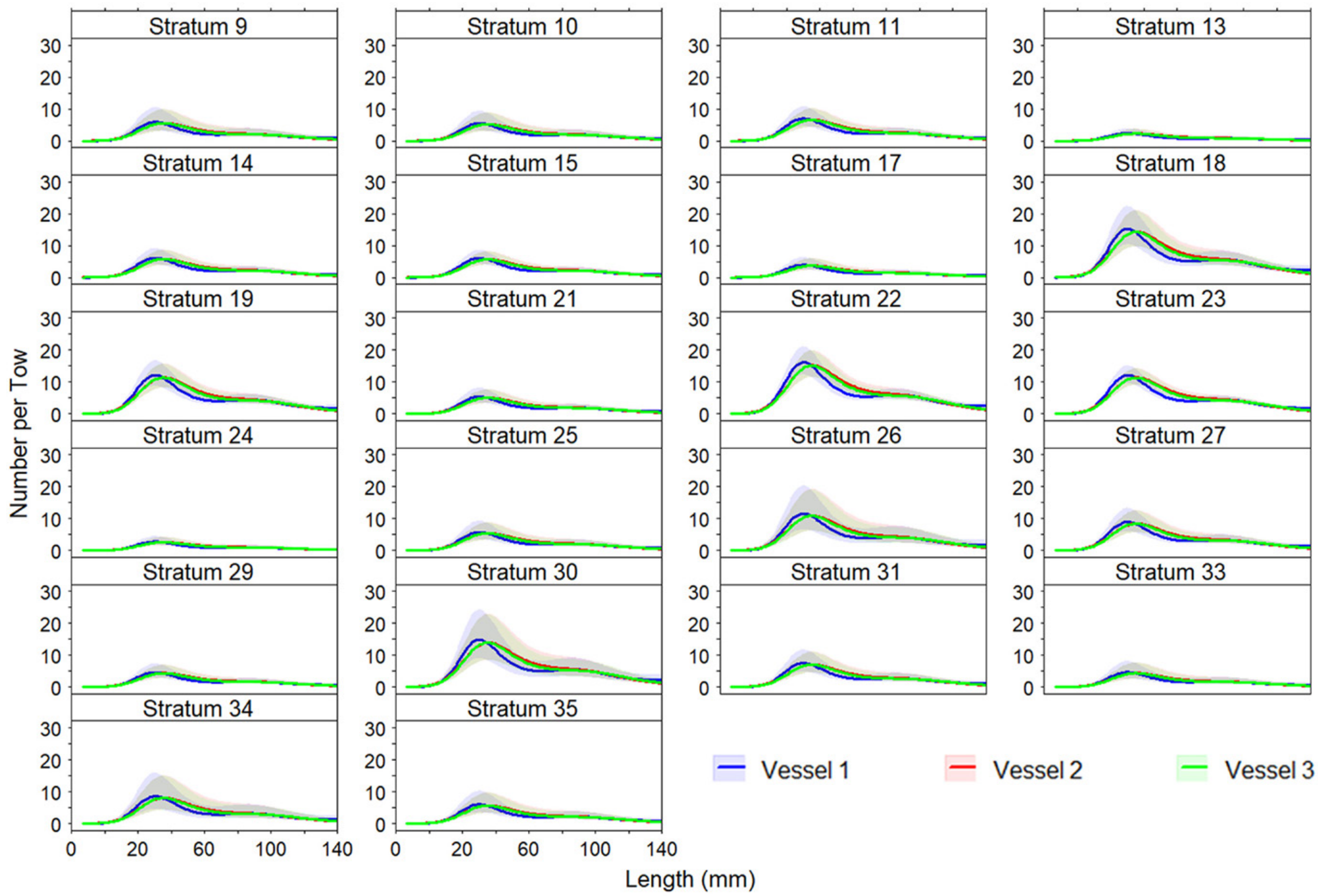

Figure 7. Predicted number of scallops caught at-length by vessel and strata for the preferred GAMM (gam7) with 95% confidence intervals.

Two early studies also reached the same conclusions, although these studies focused on comparisons between research vessels and not commercial vessels used as research platforms (Lai & Kimura 2002, Serchuk & Wigley 1986). One difference between past results from Rudders and DuPaul (2010) and findings are that Rudders and DuPaul (2010) found significant catch-at-length differences between the commercial vessel and research vessel participating in the 2009 study. This difference may be a result of varying types of analysis, as well as a slight modification to the survey dredge, and the amount of time among sampling events for the project (i.e., several months). Rudders and DuPaul (2010) applied a GLMM with a single length term in their modeling efforts and used a binomial logistic regression. The modified survey dredge included the addition of a wheel on the dredge frame and minor modifications to the mesh count on the twine top and liner.

Overall, results for sea scallop dredge gear used on the U.S. East Coast differ from findings for another primary gear type used for resource surveys concerning differences in fishing power among vessels. Calibration studies conducted for trawl gear surveys have found species-specific significant effects of vessel on catch and catch-at-length (Miller 2013, von Szalay & Brown 2001). In Alaska, United States, von Szalay and Brown (2001) found that a new NMFS research vessel had higher catch rates of pelagic species and lower catches of flatfish compared with a retiring NMFS research vessel but found no difference in catch-at-length. This resulted in species-specific fishing power correction factors being applied to the new research vessel catch rates. In the Northeast United States, a new NMFS research vessel had higher catch rates for the majority of the 16 species examined for both pooled catch and catch-at-length (Miller 2013). The divergence in results for these two gear types may be related to the design and performance of the survey gears. Trawl gear can be more variable compared with a scallop dredge. A scallop dredge has a rigid metal frame with set dimensions that are not generally altered by fishing conditions. In contrast, trawl gear dimensions and performance can be affected by many variables including depth and bottom type (von Szalay & Somerton 2005).

Results from the study, in conjunction with conclusions from the previous studies, provide a basis for the continued use of multiple commercial vessels to conduct the sea scallop dredge surveys. Thereby allowing ongoing surveys to continue under the current sampling framework and providing practitioners a means to expand stakeholder involvement in future survey efforts. Diversifying the stakeholder group involved in the surveys may lead to expanded buy-in from industry as more industry members observe and participate in the data collection process. These results will also allow research groups to charter different vessels in the Northeast United States to conduct surveys of the various portions of the sea scallop resource and support the vessel criteria currently used for vessel selection. There is also no support for modifying biomass estimation methods to account for a vessel effect or for a systematic bias in biomass estimates that may have impacted management measures or recent assessments. Biological data (i.e., maturity stage and sex), which is related to the length data collected during the survey, should also be viewed as unbiased because there was no impact of vessel on catch-at-length.

Although the analyses included herein did not provide evidence of a vessel effect, other studies have highlighted future areas to consider in the cooperative research survey framework. These topics are crosscutting and may provide guidance for other organizations to consider when developing or maintaining cooperative research surveys. Cooper et al. (2004) found that the frequency at which vessels were exchanged could affect biomass calculations and recommended that a regular group of vessels with similar characteristics be used to reduce a potential vessel effect on biomass estimates. Although Cooper et al. (2004) focused on a trawl survey, results may not be universal and gear/survey specific considerations are likely to be impactful on these logistic decisions. It is important to have an established protocol for selecting vessels with certain vessel characteristics but consideration of how many additional vessels to include in future surveys is another decision point. Helser et al. (2004) suggested using more vessels in a multivessel survey to improve precision in biomass estimates and reduce variability. Both studies focused on understanding the optimal number of vessels needed for robust biomass estimates and this subject is applicable to all cooperative survey programs. A future area of research could be determining the appropriate number of vessels needed to provide robust biomass estimates. Another area of future research could be to assess varying modeling approaches for biomass estimation to determine whether there are effects of year and vessel on catch and biomass in a similar manner to Helser et al. (2004). Helser et al. (2004) found variability existed among years for individual vessels and by including both year and vessel as random effects, biomass estimates for several groundfish species on the U.S. West Coast were improved.

Peer reviewed literature on vessel effects in multivessel cooperative surveys has been primarily focused on trawl surveys conducted on the U.S. West Coast (Cooper et al. 2004, Helser et al. 2004, Thorson & Ward 2014, Thorson et al. 2015). As the use of cooperative surveys expands, additional analyses for different gear types, species, survey designs, and regions will aid in better understanding the benefits and disadvantages of cooperative multivessel surveys. Also, assessing alternative experimental designs for understanding the impact of vessel may be beneficial to resource surveys as a whole. As resources (i.e., budgets, equipment, vessels, and staff) may become limited in the future, assessing the use of different experimental designs to maintain survey time series may be critical.

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LITERATURE CITED

Barton, K. 2009. Mu-MIn: multi-model inference. R Package Version 0.12.2/r18. Available at: http://R-Forge.R-project.org/projects/mumin/.

Benoít, H. P. & D. P. Swain. 2003. Accounting for length and depth diel variation in catchability of fish and invertebrates in an annual bottom-trawl survey. *ICES J. Mar. Sci.* 60:1298–1317.

Bolker, B. M. 2008. Ecological models and data in R. Princeton, NJ: Princeton University Press.

Burnham, K. P. & D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach second edition. New York, NY: Springer.

Cadigan, N. G., D. L. Boulos & W. M. Hickey. 1996. Analysis of subsampled catches from trouser trawl size selectivity studies. *J. Northw. Atl. Fish. Sci.* 19:41–49.

Cadigan, N. G. & J. J. Dowden. 2010. Statistical inference about the relative efficiency of a new protocol, based on paired-tow survey calibration data. *Fish Bull.* 108:15–29.

Cadigan, N. G., S. J. Walsh & W. Brodie. 2006. Relative efficiency of the Wilfred Templeman and Alfred Needler research vessels using a Campelen 1800 shrimp trawl in NAFO Subdivision 3Ps and Divisions 3LN. Research Document 2006/085. Canadian Science Advisory Secretariat. Fisheries and Oceans Canada.

Cochran, W. 1977. Sampling techniques, 3rd edition. New York, NY: John Wiley & Sons, Inc.

Cooper, A. B., A. A. Rosenberg, G. Stefansson & M. Mangel. 2004. Examining the importance of consistency in multi-vessel trawl survey design based on the U.S. West Coast groundfish bottom trawl survey. *Fish. Res.* 70:239–250.

DuPaul, W. D. & J. E. Kirkley. 1995. Evaluation of sea scallop dredge ring size. Contract report submitted to NOAA, National Marine Fisheries Service. Grant # NA36FD0131.

DuPaul, W. & D. Rudders. 2008. Final report: calibrating industry scallop surveys with NOAA vessel platforms. Marine Resource Report No. 2008-6. Virginia Institute of Marine Science, William & Mary.

DuPaul, W., D. B. Rudders & P. Rago. 2000. Results of commercial sea scallop survey in the Hudson Canyon south closed area June 2000. VIMS Marine Resource Report No. 2000-8. Submitted to the Sea Scallop Plan Development Team New England Fishery Management Council New Bedford, MA, August 2000.

Ehrich, S. 1991. Comparative fishing experiments by research trawlers for cod and haddock in the North Sea. *ICES J. Mar. Sci.* 47:275–283.

Fox, J. & S. Weisberg. 2019. An R companion to applied regression, 3rd edition. Thousand Oaks, CA: Sage.

Fowler, G. M. & M. A. Showell. 2009. Calibration of bottom trawl survey vessels: comparative fishing between the Alfred Needler and Teleost on the Scotian Shelf during the summer of 2005. Canadian Technical Report of Fisheries and Aquatic Sciences 2824: iv + 25 pp.

Hanna, S. S. 1995. User participation and fishery management performance within the Pacific Fishery Management Council. *Ocean Coast. Manage.* 28:23–44.

Hart, D. R. & A. S. Chute. 2009. Estimating von Bertalanffy growth parameters from growth increment data using a linear mixed-effects model, with an application to the sea scallop *Placopecten magellanicus. ICES J. Mar. Sci.* 66:2165–2175.

Hartley, T. W. & R. A. Robertson. 2006. Stakeholder collaboration in fisheries research: integrating knowledge among fishing leaders and science partners in northern New England. *Soc. Nat. Resour.* 22:42–55.

Hastie, T. J. & R. J. Tibshirani. 1990. Generalized additive models. New York, NY: Chapman and Hall.

Helser, T. E., A. E. Punt & R. D. Methot. 2004. A generalized linear mixed-model analysis of a multi-vessel fishery resource survey. *Fish. Res.* 70:251–264.

Holst, R. & A. Revill. 2009. A simple statistical method for catch comparison studies. *Fish. Res.* 95:245–259.

Hothorn, T., F. Bretz & P. Westfall. 2008. Simultaneous inference in general parametric models. *Biom. J.* 50:346–363.

Johnson, T. R. & W. L. T. van Densen. 2007. The benefits and organization of cooperative research for fisheries management. *ICES J. Mar. Sci.* 64:834–840.

Lai, H. & D. K. Kimura. 2002. Analyzing survey experiments having spatial variability with an application to a sea scallop fishing experiment. *Fish. Res.* 56:239–259.

Major, R. N., D. I. Taylor, S. Connor, G. Connor & A. G. Jeffs. 2017. Factors affecting bycatch in a developing New Zealand scampi potting fishery. *Fish. Res.* 186:55–64.

Maunder, M. N. & A. Punt. 2004. Standardizing catch and effort data: a review of recent approaches. *Fish. Res.* 70:141–159.

Millar, R. B. 1992. Estimating the size-selectivity of fishing gear by conditioning on the total catch. *J. Am. Stat. Assoc.* 87:420, 962–968.

Miller, R. G. 1981. Simultaneous statistical inference, 2nd edition. New York, NY: Springer-Verlag.

Miller, T. 2013. A comparison of hierarchical models for relative catch efficiency based on paired-gear data for U.S. Northwest Atlantic fish stocks. *Can. J. Fish. Aquat. Sci.* 70:1306–1316.

Moriarty, M., S. A. Sethi, D. Pedreschi, T. S. Smeltz, C. McGonigle, B. P. Harris, N. Wolf & S. P. R. Greenstreet. 2020. Combing fisheries surveys to inform marine species distribution modeling. *ICES J. Mar. Sci.* 77:539–552.

Nanda, A., B. B. Mohapatra, A. P. K. Mahapatra, B. B. Mohapatra & A. P. K. Mahapatra. 2021. Multiple comparison test by Tukey's honestly significant differences (HSD): do the confident level control type I error. *Int. J. Stat. Appl. Math.* 6:59–65.

NEFMC (New England Fisheries Management Council). 2003. Amendment #10 to the Atlantic sea scallop fishery management plan with a supplemental environmental impact statement, regulatory review, and regulatory flexibility analysis. New England Fisheries Management Council.

NEFSC (Northeast Fisheries Science Center). 2018. 65th Northeast Regional Stock Assessment Workshop (65th SAW) Assessment Report. U.S. Dept Commer, Northeast Fish Sci Cent Ref Doc. 18–11; 659 pp. Available at: http://www.nefsc.noaa.gov/publications/.

NOAA (National Oceanic and Atmospheric Administration). 2020. Accessed September 23, 2020. Available at: https://www.fisheries.noaa.gov/national/sustainablefisheries/commercial-fisheries-landings.

Pedersen, E. J., D. L. Miller, G. L. Simpson & N. Ross. 2019. Hierarchical generalized additive models in ecology: an introduction with mgcv. *PeerJ.* 7:e6876.

Pinheiro, J. C. & D. M. Bates. 2000. Mixed-effects models in S and S-PLUS. New York, NY: Springer.

Politis, P. J., J. K. Galbraith, P. Kostovick & R. W. Brown. 2014. Northeast Fisheries Science Center bottom trawl survey protocols for the NOAA ship Henry B. Bigelow. U.S. Dept Commer, Northeast Fish Sci Cent Ref Doc. 14-06; 138 pp. Available at: http://www.nefsc.noaa.gov/publications/.

R Core Team. 2020. R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Available at: https://www.R-project.org/.

Raftery, A. E. 1995. Bayesian model selection in social research. *Sociol. Methodol.* 25:111–163.

"Research Set-Aside Programs." NOAA. N.p., n.d. Web. 27 Oct. 2016.

Roop, H. J., N. C. Poudyal & C. A. Jennings. 2018. Assessing angler effort, catch, and harvest on a spatially complex, multi-lake fishery in middle Georgia. *N. Am. J. Fish. Manage.* 38:833–841.

Rudders, D. R. & W. D. DuPaul. 2010. Final report: continuing the time series: calibrating the NMFS sea scallop survey to the R/V Hugh R. Sharp. Submitted to the National Marine Fisheries Service Northeast Fisheries Science Center Cooperative Research Program. Woods Hole, Massachusetts, May 29, 2010.

Runnebaum, J., L. Guan, J. Cao, L. O'Brien & Y. Chen. 2018. Habitat suitability modeling based on a spatiotemporal model: an example for cusk in the Gulf of Maine. *Can. J. Fish. Aquat. Sci.* 75:1784–1797.

Serchuk, F. M. & S. E. Wigley. 1986. Evaluation of USA and Canadian research vessel survey for sea scallops (*Placopecten magellanicus*) on Georges Bank. *J. Northwest Atl. Fish. Sci.* 7:1–13.

Stokesbury, K. D. E., B. P. Harris, M. C. Marino & J. I. Nogueira. 2004. Estimation of sea scallop abundance using a video survey in off-shore U.S. waters. *J. Shellfish Res.* 23:33–44.

Smith, S. J. & P. Rago. 2004. Biological reference points for sea scallops (*Placopecten magellanicus*): the benefits and costs of being nearly sessile. *Can. J. Fish. Aquat. Sci.* 6:1338–1354.

Thorson, J. T., A. O. Shelton, E. J. Ward & H. J. Skaug. 2015. Geostatistical delta-generalized liner mixed models improve precision for estimated abundance indices for West Coast groundfishes. *ICES J. Mar. Sci.* 72:1297–1310.

Thorson, J. & E. Ward. 2014. Accounting for vessel effects when standardizing catch rates from cooperative surveys. *Fish. Res.* 155:168–176.

Venables, W. N. & B. D. Ripley. 2002. Modern applied statistics with S, 4th edition. New York, NY: Springer.

von Szalay, P. G. & E. Brown. 2001. Trawl comparisons of fishing power differences and their applicability to National Marine Fisheries Service and Alaska Department of Fish and Game trawl survey gear. *Alsk. Fish. Res. Bull.* 8:85–95.

von Szalay, P. G. & D. A. Somerton. 2005. The effect of net spread on the capture efficiency of a demersal survey trawl used in the eastern Bering Sea. *Fish. Res.* 74:86–95.

Wood, S. N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *J. R. Stat. Soc. Ser. A Stat. Soc.* 73:3–36.

Wood, S. N. 2017. Generalized additive models: an introduction with R. Boca Raton, FL: Chapman & Hall.

Wurtzell, K. V., A. Baukus, C. J. Brown, J. M. Jech, A. J. Pershing & G. D. Sherwood. 2016. Industry-based acoustic survey of Atlantic herring distribution and spawning dynamics in coastal Maine waters. *Fish. Res.* 178:71–81.

Zhang, C. & Y. Chen. 2015. Development of abundance indices for Atlantic cod and cusk in the coastal Gulf of Maine from their bycatch in the lobster fishery. *N. Am. J. Fish. Manage.* 35:708–719.

Zuur, A. F., E. N. Leno, N. J. Walker, A. A. Saveliev & G. M. Smith. 2009. Mixed effect models and extensions in ecology with R. New York, NY: Springer. 50 CFR § 648.53, 2017.