Final Report

Scallop Mark-Recapture to Estimate Density Dependent Natural Mortality and Growth

AGENCY AWARD NUMBER: NA16NMF4540040
VIMS Marine Resource Report No. 2018-04

Submitted to:

National Marine Fisheries Service
Northeast Fisheries Science Center
Cooperative Research Program
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August 24, 2018

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Project Summary

Natural mortality, growth and movement are fundamental processes critical to understanding and describing population dynamics. These population characteristics not only inform and influence stock assessment models, but are also highly relevant with respect to the design and implementation of management strategies to meet fishery objectives. For many species, including sea scallops, these population parameters are difficult to measure due to the nature of the habitats inhabited and as a result, minimal information is often available. In many cases, what estimates do exist are highly uncertain as a result of both observation and process error. The uncertainty of these parameters is exacerbated for a species such as the sea scallop whose life history strategy is predicated on large, episodic recruitment events where natural mortality and growth may vary as a function of animal density.

In 2015, resource surveys by the Virginia Institute of Marine Science (VIMS) and others observed what appeared to be an exceptionally large incoming year class of sea scallops throughout the Mid Atlantic Bight (MAB), with the locus of the event located in the Elephant Trunk Closed Area (ETCA). At the time of first encounter, these animals were roughly two years old and the scale of the event in terms of the spatial extent and magnitude was extensive. Multiple surveys delineated the distribution of the event and confirmed the enormous magnitude of scallops in the area, but critical questions remained. What is the survival rate of the unfished cohort (i.e. natural mortality rate)? What is their growth rate? Would the scallops survive? Would they grow at rates similar to what was expected? Would the animals move either inshore or offshore to a different habitat? To address these questions, we conducted a sea scallop mark-recapture study in the area of newly recruited scallops in the ETCA.

In order to address some of these critical questions, a proof-of-concept tagging study was conducted by VIMS in the ETCA. As part of the tagging study, VIMS conducted two tagging events and one recapture event. A total of 56,928 scallops were tagged and every tenth scallop was double tagged during the first tagging event. Nine of the double tagged scallops were recaptured, of which 7 had both tags and 2 had just one tag. From this, it can be estimated that 87.5% of the tags remained in place 11 months after tagging (95% CI: 70 – 100%). The study design was intended to provide several estimates of survival rate. First, three cohorts would be tagged one year apart (at times 0, 1 and 2) and then, in a fourth cruise shortly after the third cruise, the ratio of recaptures from the first and second cohorts, and from the second and third cohorts, would provide estimates of the survival rate in years one and two.

Second, by noting the presence of dead, tagged scallops, the survival rate could be estimated from the proportion of tagged animals recovered that were alive.

Unfortunately, a decision was made to open the study area to fishing after one year. Consequently, the above design was modified to tag at time 0 and at time 1 (with 11 months separating the two tagging events) and then continuing the second cruise to recover tagged animals from the two cohorts. Another complication arose when the study area was opened sooner than had been anticipated. This meant that the scallops were affected by natural mortality and an unknown amount of fishing mortality.

From the 9 cohorts of tagged scallops in each of the two tagging cruises, it is possible to estimate 9 survival rates for the first year of the study. Eight of the estimates range from 0.06 to 0.40 and one estimate was much higher at 100% survival. There was no trend in survival estimates with initial density. Combining all of the data to boost sample size gives an overall estimate of annual survival of 0.20 (corresponding to an instantaneous rate of mortality of 1.62. This is much lower survival rate than has been estimated for adult scallops.

Project Background

The sea scallop, *Placopecten magellanicus,* supports a fishery that in the 2015 fishing year (FY) landed 11,702 mt of meats with an ex-vessel value of over US $440 million (Lowther and Liddel, 2016). These landings resulted in the sea scallop fishery being one of the most valuable single species fishery along the East Coast of the United States. While historically subject to extreme cycles of productivity, the fishery has benefited from recent management measures intended to bring stability and sustainability. These measures included: limiting the number of participants and total effort (days-at-sea), gear and crew restrictions, and a strategy to improve yield by protecting young scallops through rotational area closures. Sea scallops represent a well-studied species that has responded well to management measures founded on a stock assessment that benefits from numerous fishery independent surveys, a comprehensive understanding of scallop biology as well as a broad array of fishery dependent information. Despite this data rich situation, gaps in knowledge still exist.

Natural mortality and growth and its relationship to stock density and to a lesser extent movement are fundamental parameters where a greater understanding of the underlying processes would benefit both managers and assessment scientists. According to the latest scallop stock assessment, until 2010, natural mortality was based on very old studies examining the ratio of clappers to live shells on Georges Bank (Merrill and Posgay, 1964; Dickie, 1955). These estimates were subsequently refined using output from the size-structured forward projecting stock assessment model (CASA), ratio estimators from growth parameter estimates, an observational study in Atlantic Canada and the monitoring of a large recruiting year class in an Essential Fish Habitat closure area (NEFSC, 2014). While the estimates range from 0.1 (initial Merril and Posgay (1964) estimate) to 0.3 (for the latest CASA generated estimate for the oldest animals in the MAB), there has been little focused, experimental work done on this important topic. The natural mortality rate is a key parameter that permeates all aspects of the stock assessment. Its value directly and strongly affects the determination of stock status and total allowable catch (Mangel et al., 2013). The wide variability in the estimates argues that there is a need for further examination of natural mortality.

Scallop growth is a much better understood process. With a long history of study in the literature, there has been much interest in understanding growth across time and space. With this process representing such an important aspect of assessment and projection models, the nuances surrounding growth should be a constant topic of refinement. Dynamic environmental factors such as warming waters due to climate change and ecological processes like competition for food and space are sources that may change the characteristics of how scallops grow both spatially and temporally (Gwyther and McShane, 1988). Recent work by Hart and Chute (2009) has documented spatial and temporal differences in growth across the range of the scallop. They also examined the underlying factors driving these differences and postulated the causative factors include the effects of fishing and spatial management. Even as this process is well described, an opportunity to investigate the extreme of observed historical scallop densities in the closed portion of the ETCA represents a unique opportunity to study density dependence.

Scallop movement for the offshore component of the species is a very difficult phenomenon to measure. Scallops are generally thought of as sedentary, with movements primarily as a predatory escape response and not as a part of a direct effort to change location (Stokesbury and Himmleman, 1996; Posgay, 1981). This is especially the case as the scallop ages and the hydrodynamics of swimming become more difficult. Fishermen, however, tend to disagree and believe that scallops travel great distances, typically offshore to inshore. Whether this is a directed movement or simply passive transport is unknown. Mark-recapture studies offer a singular approach to estimate movement of sea scallop on the offshore beds. Depending on commercial recaptures is often uninformative due to tow lengths exceeding 4 nautical miles (nm), rendering fine scale estimates of movement unreliable. Given this level of observational error, Posgay (1981) observed high levels of site fidelity, with some evidence for travel at greater scales.

Greater understanding of natural mortality, growth and movement are essential for accurately assessing sea scallops. These population parameters have additional implications with respect to the approaches used to manage the fishery. Amendment #10 to the Sea Scallop Fishery Management Plan (SSFMP) officially introduced the concept of area rotation to the fishery. This strategy seeks to increase the yield and reproductive potential of the sea scallop resource by identifying and protecting discrete areas of high densities of juvenile scallops from fishing mortality. By delaying capture, the rapid growth rate of scallops is exploited to realize substantial gains in yield over short time periods. In addition to the formal attempts established by Amendment #10 to manage discrete areas of scallops for improved yield, specific areas on Georges Bank (GB) are also subject to area closures as a result of efforts to facilitate the recovery of various groundfish species. Since 1999, limited access to three closed areas on GB has been allowed for the harvest of scallops. While not spatially adaptive with respect to area boundaries, similar biological principles that guide rotational scallop areas apply to the GB areas.

The spatial management strategy for the MAB and GB regions as well as open areas not currently included in the rotational area management program is predicated on identifying and protecting large incoming recruiting year classes of scallops. Understanding natural mortality, growth and movement of animals especially in extreme cases of high density becomes critical to the success of this strategy. If density has a significant impact on growth and/or natural mortality and their impact is different than assumed, spatial management strategies may not perform to expectations. For example, if growth is slower or natural mortality higher than assumed, then modifications to the timing of the strategy to harvest animals later or earlier than planned may be justified. Given the importance of spatial management to the sea scallop fishery, it is incumbent on assessment biologists to the provide managers with the highest level of information to maximize yield to the fishery.

For this study, we conducted a one-year mark recapture in the closed portion of the ETCA. The project objectives were:

1. Conduct a proof-of-concept mark-recapture study;
2. Estimate growth and natural mortality;
3. Examine the effect of scallop density on growth and natural mortality; and
4. Examine fine-scale spatial movement of scallops.

Methods

Study Area

The closed portion of the ETCA or Flex area was chosen as the study site because the area has been closed since the 2011 FY, a large recruitment event had been observed by several survey groups in 2014 and 2015 and the area would satisfy assumptions needed for a mark-recapture study (Figure 1). The area also provided a gradient of scallop densities. Having the area closed for the majority of the research

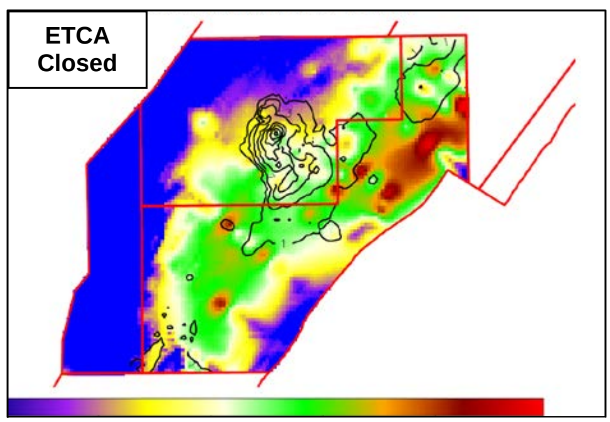

Figure 1. Interpolated distribution of scallops observed in 2015. Contours are recruits (<75mm). Heat map colors represent adult scallop (>75mm). Figure from draft Framework 27.

project minimized removals as a result of fishing. Research trips were taken onboard two commercial fishing vessels, the F/V Horizon and the F/V/ Polaris out of New Bedford, MA.

Experimental Design

The sequence of cruises was specified to satisfy mark-recapture assumptions, as well as, define study sites with the ETCA and assess fine-scale movement of scallops. Two cruises were completed over the course of 11 months. The first cruise was a site identification and tagging cruise where nine study sites, described below, were identified and the first cohort of scallops was tagged and released. After the study sites were selected, tows were completed within each site to capture scallops for tagging. The second cruise, conducted a 11 months later, was partitioned into two components and occupied the same nine study sites. The objective of the first portion of the second cruise was to tag the second cohort of scallops and recapture tagged scallops from the first cohort opportunistically, referred to as the tagging event for the remainder of the report. All scallops captured were examined for the presence of a tag(s). The second objective of the cruise was to look for migration of scallops out of the study sites. Tows were completed around and between the nine sites to look for tagged scallops, within approximately 1 nautical mile (nm) of a site boundary and referred to as the sentinel event for the remainder of the report. All scallops captured were examined for the presence of a tag(s). This also allowed for the second cohort of tagged scallops to recover from the tagging process. The third portion of the cruise was designed to function as the final recapture event and is referred to as the recapture event for the remainder of the report. Tows were completed in all nine study sites and all scallops were examined for tags. All recaptured scallops had identifying information (i.e., shell height, tag identifier and study site) and disposition (i.e., alive, dead-clapper or dead-disarticulated hinge) recorded.

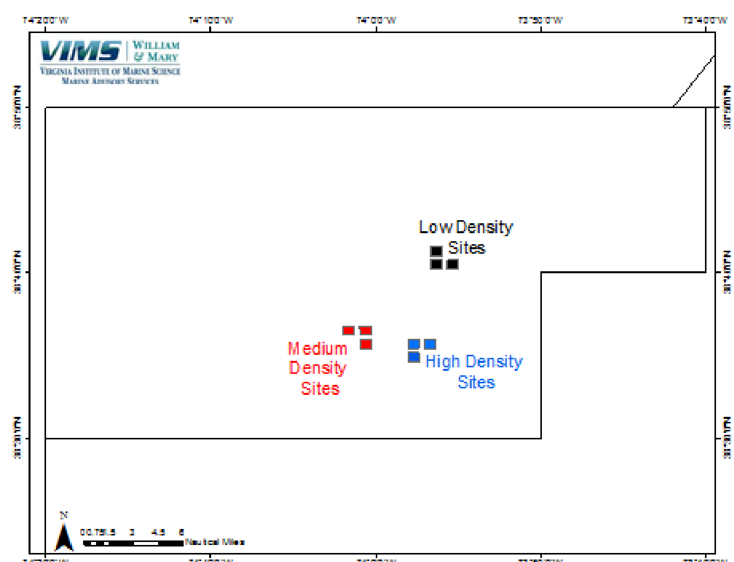

Figure 2. Map of density level sites, designated by color, in the ETCA.

Study Sites

Within the study area, three density level sites were selected. Each site had an aerial coverage of 1nm^2, with the selected sites based upon observed scallop densities at three density categories. The low density sites were defined as having a scallop density of ~1 scallop/m^2. The medium density sites were defined as having of ~10 scallops/m^2 and the high density sites were defined as having >50 scallops/m^2. Exploratory tows on the first cruise were used to determine the actual densities for site selection prior to initiating tagging. Each density level had 3 replicates and was delineated by GPS coordinates (Figure 2).

Sampling Protocols

Scallops were captured with a lined NMFS sea scallop survey dredge. This dredge is 8 feet in width and equipped with 2-inch rings, 4-inch diamond twine top and a 1.5-inch diamond mesh liner. Captains were instructed to tow at a towing speed of approximately 3.8-4.0 kts. Tow durations varied from approximately 1 to 15 minutes, depending on density level. A tilt sensor (records angle of inclination, temperature, depth) was placed on the dredge to determine dredge bottom contact time and bottom water temperature.

Figure 3. Picture of the on-board holding tank.

Tagging Protocols

The tagging protocol attempted to minimize the cumulative stress placed on individual scallops. This stress could be a contributor to mortality and influence experimental results. Based on the volume of catch, either a subsample of scallops or the entire scallop catch was placed in an on-board refrigerated, flow through deck tank system (Figure 3). This system was developed to provide a thermal environment that approximates the seafloor (Knotek et al., 2015). After a short recovery time period in the holding tank system, scallops were measured (umbo to margin, millimetres), excess water was removed from the shell and a Hallprint shellfish glue-on tag or tags were affixed to the bottom of the shell using super glue (Figure 4). The Hallprint tags were 8 mm by 4 mm and each tag had a unique identifier. On the first trip, every 10^{th} scallop was double tagged to estimate tag loss. Tag identification on the first trip was a combination of tag color (orange, green or yellow) and four-digit number. For the second cruise, tag identification was a combination of tag color (orange, green or yellow) and a

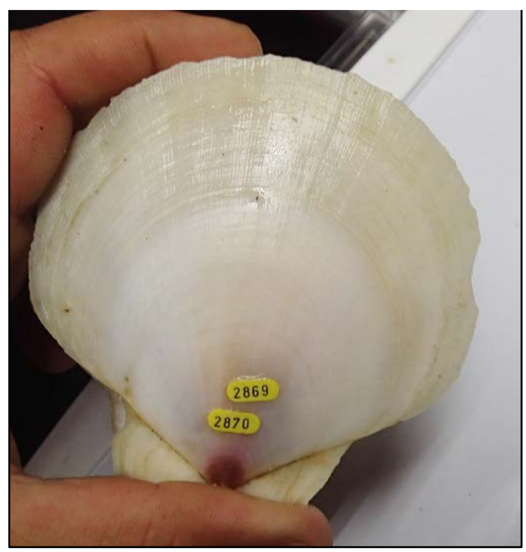

Figure 4. Example of tag placement and picture of a double tagged scallop from the first trip.

letter followed by three numbers. All doubled tagged scallops had both values photographed for potential future growth analysis using the annual ring identification and measurement technique described in Hart and Chute (2009). Shell height, corresponding tag identification information (tag color and code) and associated density level information for every scallop tagged was recorded using an electronic Ichthystick measuring board integrated with the data acquisition program Fisheries Environment for Electronic Data (FEED).

Results

Issues

The study was designed to be conducted in an area closed to commercial fishing effort for a minimum of one year to allow the first cohort of tagged scallops to have a year of growth and experience processes that contribute to natural morality. Framework Adjustment 28 to the Sea Scallop Fishery Management Plan was adopted by the New England Fishery Management Council in November of 2016 and the Final Rule was published by the National Marine Fisheries Service on March 27, 2017 (50 CFR § 648). This framework allowed access to the ETCA by the fleet after the Final Rule was published. To deal with the opening of the area and potential fishing effort that would occur, the timing of the second trip was moved up by approximately one month. This was an attempt to minimize any potential impacts of commercial fishing in the study sites and as a result the first cohort of scallops was not at liberty for an entire year. Outreach was conducted to provide information about the study and study sites to the fleet (Appendix A). We did observe two vessels fishing in several of the study sites. We also had to shorten the trip duration for the second trip because of bad weather. This reduced the amount of time available for recapturing scallops.

Field Work Characteristics

The first cruise was completed on the F/V Polaris in April of 2016 from the 21st – 27th. A total of 75 tows were completed; thirty tows were conducted to identify the nine study sites and 45 tows were completed in the different study sites to tag scallops (Table 1). The second cruise took place from March 21 – 31, 2017 onboard the F/V Horizon. The number of tows completed by study site for tagging/recapturing and for dedicated recapture tows are provided in Table 1. The number of sentinel tows to look for movement of scallops out of and between sites varied by density level and time constraints. Six tows were completed around the low density sites, four tows around the medium density sites and three tows around the high density sites.

Table 1. Number of tows completed by cruise and type. No recapture tows were completed on the first cruise.

Tow Type	Cruise 1	Cruise 2
SITE IDENTIFICATION TOWS	30	-
LOW SITE 1	5	12
LOW SITE 2	18	7
LOW SITE 3	7	4
MEDIUM SITE 1	2	2
MEDIUM SITE 2	2	2
MEDIUM SITE 3	3	4
HIGH SITE 1	2	2
HIGH SITE 2	3	5
HIGH SITE 3	3	4
RECAPTURE LOW SITE 1	-	13
RECAPTURE LOW SITE 2	-	14
RECAPTURE LOW SITE 3	-	15
RECAPTURE MEDIUM SITE 1	-	8
RECAPTURE MEDIUM SITE 2	-	7
RECAPTURE MEDIUM SITE 3	-	7
RECAPTURE HIGH SITE 1	-	10
RECAPTURE HIGH SITE 2	-	9
RECAPTURE HIGH SITE 3	-	8

Tagging and Recaptures

For the first cohort of scallops, a total of 26,622 scallops were tagged on the first trip (Table 2). Of those, 2,914 scallops were doubled tagged and photographed. On the second trip, 30,306 scallops were tagged in the second cohort, for a total of 56,928 scallops across the two tagging events. We recovered 399 tagged scallops during the second trip, with a total 84 recaptures from the first cohort and 353 recaptures from the second cohort (Table 2). There were 66 scallops from the first cohort recaptured during the recapture event. The remainder of the recaptured first cohort (n=14) were found during the tagging event on the second cruise. We received 38 recaptures from the fishery, although this type of information was not in the original experimental design. Location information was not provided for all fishery recaptures and if provided was at a much courser resolution than the recapture information from the second cruise. Fishery recaptures were assumed to be recaptured from the same study site as released. For the fishery recaptures, 4 scallops were from the first cohort and 34 from the second cohort. Fishery recaptures through August 17, 2018 are included in this analysis. No recaptured scallops were found on sentinel tows conducted outside and between study areas. All recaptured scallops from the first cohort were recaptured alive. Thirteen scallops recaptured from the second cohort were dead. These scallops had either a disarticulated hinge and damaged shell or were reported as clappers.

Table 2. Number of scallops tagged and recaptured by cohort and event (tagging or recapture event) by site and replicate (density level and replicate).

Cohort	Site & Replicate	Number Tagged	Number Recaptured during Tagging Event	Number Recaptured during Recapture Event	Number of Fishery Recaptures
FIRST	LOW SITE 1	2,147	2	2	
FIRST	LOW SITE 2	2,762	4	3	2
FIRST	LOW SITE 3	2,734		6	
FIRST	MEDIUM SITE 1	2,461		7	
FIRST	MEDIUM SITE 2	2,459		7	
FIRST	MEDIUM SITE 3	2,327	3	10	
FIRST	HIGH SITE 1	3,691	2	9	2
FIRST	HIGH SITE 2	4,032	3	14	
FIRST	HIGH SITE 3	4,009		8	
SECOND	LOW SITE 1	2,640		10	21
SECOND	LOW SITE 2	2,523		12	9
SECOND	LOW SITE 3	2,628		30	4
SECOND	MEDIUM SITE 1	4,031		11	
SECOND	MEDIUM SITE 2	4,844		38	
SECOND	MEDIUM SITE 3	3,025		40	
SECOND	HIGH SITE 1	4,242		29	
SECOND	HIGH SITE 2	4,748		113	
SECOND	HIGH SITE 3	1,625		36	
	Total	56,928	14	385	38

Tag Loss and Recaptures

Of the 84 recaptures from the first cohort, 9 scallops had been doubled tagged. There did seem to be some tag loss for the first cohort of scallops. Seven of the 9 double-tagged scallops recaptured from the first cohort had two tags on the shell when recovered and two scallops had only one tag. An unknown number of scallops lost both tags and were indistinguishable from untagged scallops. If we let *n* be the number of double tagged scallops recovered (with 1 or 2 tags present on the shell) and *x* be the number of scallops recovered with 2 tags, then the probability, *p*, of a scallop retaining a tag for 11 months (the time between surveys) can be estimated as

$$\hat{p} = \frac{2x}{n + x}$$

where the caret (^) symbol denotes an estimate. This can be shown to be a maximum likelihood estimator. With *n* = 9 and *x* = 7, the estimated tag retention rate is 87.5%. The variance of the estimated retention rate can be found using the delta method (see Seber, 1982). Letting $\hat{\pi}$ be the sample proportion *x/n*, the variance of $\hat{p}$ is

$$V(\hat{p}) = \frac{4}{(1 + \hat{\pi})^4} V(\hat{\pi})$$

This estimator is the same as one would obtain from the Fisher Information matrix. Substituting 7/9 for $\hat{\pi}$ gives an estimated variance of 0.00769. An approximate 95% confidence interval is obtained as the estimate plus and minus two standard errors, i.e., (0.70 – 1.00).

Survival rate was estimated by the usual maximum likelihood estimator (see Brownie et al., 1985). The estimator has the form:

$$\hat{S} = \left(\frac{p_1}{p_2}\right)^{12/11}$$

where the *p*'s are the proportions recovered from the cohorts, e.g., p_1 = number of recaptures from the first tagging event obtained from the recapture event on the second cruise (and from the subsequent fishery returns) divided by the number tagged in the first cruise. The exponent 12/11 converts the estimate from an 11-month basis to an annual basis.

Tagging was undertaken at 9 sites, such that there were 3 sites at each of 3 levels of scallop density. This gave rise to the following individual estimates of survival.

Site & Replicate	Survival Estimate
LOW SITE 1	0.06
LOW SITE 2	0.19
LOW SITE 3	0.14
MEDIUM SITE 1	1.05
MEDIUM SITE 2	0.33
MEDIUM SITE 3	0.29
HIGH SITE 1	0.40
HIGH SITE 2	0.12
HIGH SITE 3	0.07

The estimates range from 0.06 to 0.40 except for one estimate of 1.05 (i.e., one estimate of 100% survival).

If we look at the estimates by density (pooling the 3 replicates within each density level) we get:

Site	Survival Estimate
LOW	0.13
MEDIUM	0.41
HIGH	0.14

Finally, if we pool all of the data we get 0.20. This implies an M of 1.62.

Growth

Growth analysis was limited to comparing length at release to length at recapture due to the limited number of tag returns. Data from all recaptures for the first cohort, second cohort and fishery recaptures were included. Length frequency distributions by density level were plotted for length at release and length at recapture (Figure 5). Growth increment was also plotted (difference between length at release and length at capture, mm) versus size at recapture to examine how growth varied by size and density level (Figure 6).

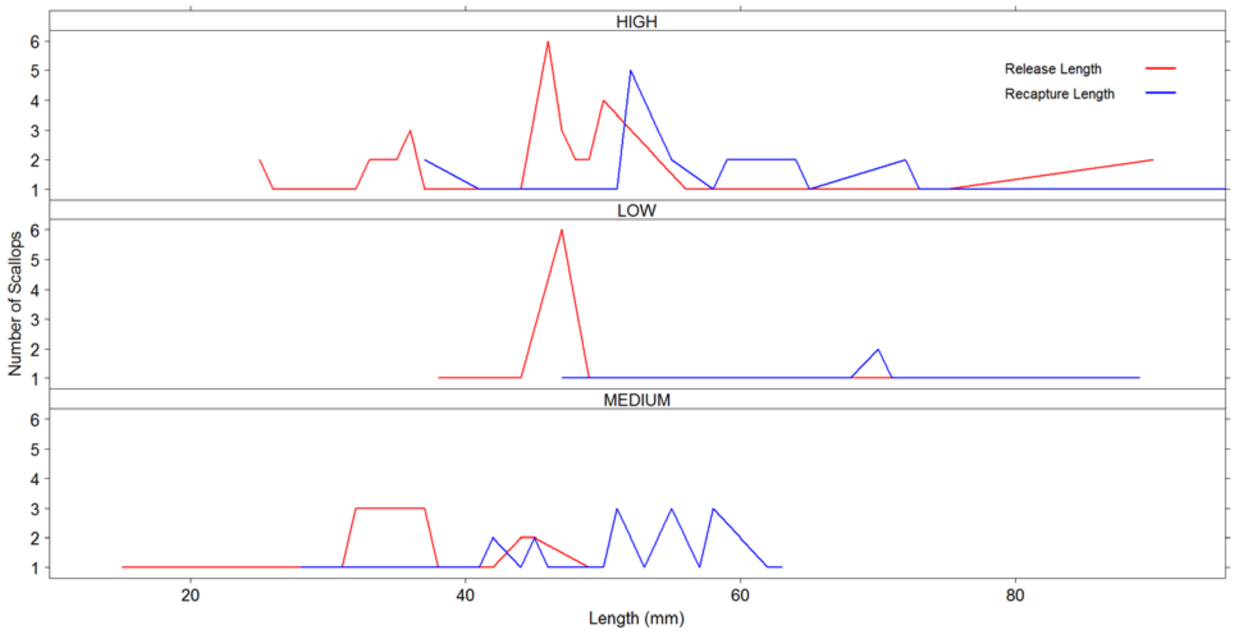

Figure 5. Length distribution of scallops tagged on the first cruise (first cohort) and recaptured on the second cruise. Red line is the release length and the blue line is the recapture length.

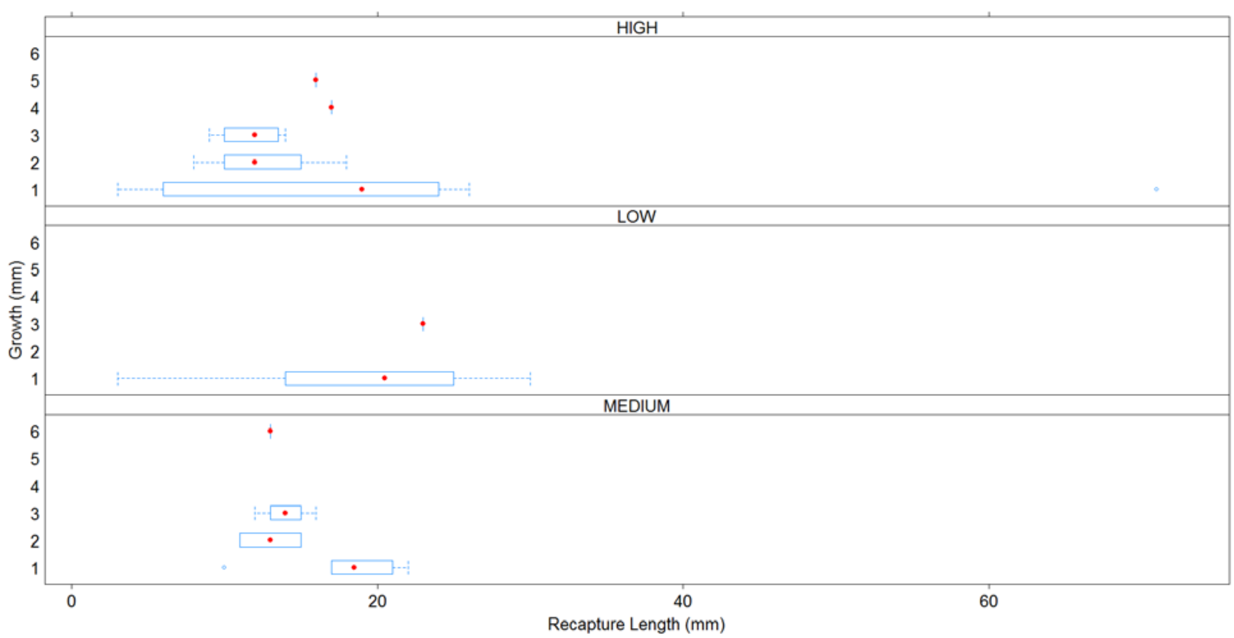

Figure 6. Growth increment plotted against recapture size by density level.

Discussion

Overall, the proof-of-concept study design was able to be conducted in a similar manner in which the project was intended. Several management decisions did alter the timing of the second trip as well as the general design of the project. The project was able to recover scallops at large for 11 months (first cohort of tagged scallops), as well as, recover recaptures from the second cohort. This recapture data was able to provide estimates of tag retention and survival, as well as, document fine scale movement of scallops within and around the study area.

While we were able to recover scallops, the recapture rate was lower than we had hoped for, especially for the first cohort. Growth analysis was limited due to the small number of recaptures. Also, survival estimates by density replicate were variable with no clear signal for the effect of density on survival. Survival estimates provided for each density level also did not provide evidence for a density effect on natural mortality. The medium density level survival estimate was greater than both the low and high density levels estimates, with an estimated survival of 0.41. Survival estimates for the low and high density levels were similar (0.13 and 0.14, respectively). The estimated survival rates are much lower than what has been estimated for large scallops. If true, this has important implications for our understanding of the population dynamics of sea scallops. A repeat of this study is advisable to see if the results are replicable.

Tag retention estimates indicated the Hallprint tags can be appropriate for long term tagging studies, although the confidence intervals around the estimate are large. This may be a result of the small number of double tagged scallops recaptured or an indication we should have increased the number of double tagged scallops on the first cruise.

Small scale movement of scallops was not observed during sentinel tows completed around the study sites during the second cruise or during the second tagging trip (i.e., scallops moving from one study site to another site). This may be a result of a limited number of tows we were able to complete surrounding the study sites, as well as, evidence for a lack of fine-scale scallop movement. Previous tagging studies have shown that tagged scallops are largely recaptured within close proximity to their release points. Posgay (1981) had 74 percent of recaptures within 5 miles and 85 percent within 10 miles of the original release points. Allison and Brand (1995) also noted no large-scale movement of queen scallops, *Aequipecten opercularis*, using a tag and recapture study, as no tagged scallops were reported as being caught further than 5 km (3.1 miles) from the release area. Both of these studies also observed the recapture of consecutively numbered tags in the same tow or from the same fishing trip in batches, further indicating that active movement and dispersal is limited across multiple scallop species.

Some modifications to the study design may assist in improving results if the study is conducted again in the future. One suggestion would be to use two density levels with three replicates each instead of three density levels. This would provide more time for a recapture event to potentially increase the number of scallops recaptured. In high density areas, we were unable to complete a large number of recapture tows and this reduced the area within the high density replicates we were able to sample for recaptures. The sheer number of scallops in these high density areas requires more recapture tows to be completed. Another suggestion would be to conduct more sentinel tows around the study sites at increasing distances from the sites. This would allow for a more robust understanding of fine scale movement of scallops out of the study sites.

The project budget and compensation is provided in Appendix B.

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