



How often do small scallop aggregations grow into fishable beds and what are the drivers?

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1.0 EXECUTIVE SUMMARY

Project Title: How often do small scallop aggregations grow into fishable beds and what are the drivers?

Year Awarded: 2023

RSA Priorities Addressed By This Research: Scallop Biology

Industry Partners: Desk based study and awarded pounds were distributed through a lottery.

This study used the long-term SMAST drop camera fishery-independent survey dataset (2003–2023) to identify high-density aggregations of pre-recruit (<35 mm shell height) and recruiting (35–75 mm shell height) Atlantic sea scallops and quantify how often these aggregations successfully contribute to the harvestable adult population. Understanding the fate of juvenile scallop aggregations is critical to the area rotation management system that underpins the U.S. Atlantic sea scallop fishery.

A total of 116 pre-recruit and 230 recruit aggregations were identified across the 21-year survey time series. Each aggregation was tracked over subsequent years to determine whether adult scallop density increased within and around the aggregation footprint. Success was defined as an identified juvenile aggregation leading to a detectable increase in adult density, and success rates ranged from 43.9% for the recruit size group to 48.3% for the pre-recruit size group. These rates establish a quantitative baseline expectation that slightly fewer than half of detected juvenile aggregations will materialize into fishable adult beds.

Drivers of success were examined using Bayesian hierarchical models incorporating environmental variables (bottom water temperature, salinity, chlorophyll *a*, water speed), biotic variables (sea star and crab predator densities, substrate type), aggregation characteristics (juvenile density, patch size), and commercial fishing effort (VMS data, 2010–2023). Key findings include that higher juvenile scallop density within aggregations consistently led to significantly greater adult density increases across all models, consistent with stock-recruitment theory. More days of warm bottom temperature (>18°C) increased the probability of success for pre-recruits but decreased the probability for recruits, suggesting size-dependent thermal vulnerability or differential predator dynamics. Greater commercial fishing effort significantly reduced both the probability and magnitude of adult density increase for the recruit size group (35–75 mm) but had no significant effect on the smaller pre-recruit group. This result is consistent with the size selectivity of 102.5 mm dredge rings, which interact more with larger juveniles.

These findings have direct management implications. Protecting recruit-sized scallop aggregations from fishing pressure through spatial closures could significantly improve recruitment into the harvestable population. The existing rotational management framework is well positioned to implement such protections when recruit aggregations are identified by surveys. Additionally, the modeling framework developed here offers a pathway for generating probabilistic forecasts of recruitment success using environmental and biotic data, which could support more informed and timely spatial management decisions for the fishery.



2.0 PRELIMINARY RESULTS AND DISCUSSION

Identification of Juvenile Aggregations

The SMAST drop camera survey dataset spanning 2003 to 2023 was used to identify 116 pre-recruit (scallops less than 35 mm shell height) and 230 recruit (scallops 35 to 75 mm shell height) scallop aggregations across Georges Bank, Gulf of Maine, and the Mid-Atlantic Bight. Aggregations were defined as three or more contiguous stations that each had a density of 0.4 scallops per m² for the respective size class, and this density threshold was chosen to be inclusive of meaningful juvenile concentrations of scallops while maximizing sample size for statistical analysis. The identified aggregations were primarily on sandy substrate (74 of 116 pre-recruit and 132 of 230 recruit), with the remainder on gravel. Mean juvenile scallop density within the aggregations ranged from 0.42 to 90 scallops per m² for pre-recruits and 0.42 to 50 scallops per m² for recruits, reflecting substantial variability.

Success Rates

Identified juvenile aggregations were tracked over subsequent survey years to determine whether they resulted in a detectable increase in adult scallop (greater than 75 mm shell height) density within a 10 km buffer of the original aggregation footprint. For the pre-recruit group 48.3% of aggregations experienced a detectable increase in adult scallop density two or three years after identification. For the recruit size group, 43.9% of identified aggregations resulted in such an increase one to two years after detection. The dataset was then restricted to 2010-2023 to accommodate the inclusion of fishing effort data in statistical modeling and similar success rates were detected for each size group (48.6% of 105 aggregations for pre-recruits and 46.2% of 130 for recruits). These results indicate that more than half of identified juvenile aggregations by fishery-independent surveys do not contribute to the harvestable adult population, and that greater understanding of the drivers of success of juvenile aggregations is needed.

Statistical modeling framework

To identify the drivers of success, a Bayesian hierarchical modeling framework consisting of six linked sub-models was implemented. This structure was selected to account for the interdependence of environmental and biotic covariates that were suspected to influence juvenile aggregation success rates. For example, salinity influences chlorophyll a concentration (proxy for food availability), water speed influences substrate type, and bottom temperature influences food availability and predator densities. By modeling these processes using linked sub-models, the direct and indirect effects of covariates on juvenile aggregation success rates and magnitude could be quantified while reducing covariate confounding. A total of four models were examined that included two models for each size group, one which excluding fishing effort and used data from 2003 to 2023 and one where the data were truncated to 2010-2023 to accommodate the inclusion of fishing effort. All models passed standard Bayesian convergence diagnostics, had well-mixed chains, and normally distributed posterior distributions.



Juvenile Density and Adult Density Increase

All four models found that higher juvenile density in the identified aggregation led to a significantly higher increase in adult scallop density in subsequent years. This finding is consistent with stock-recruit theory, where larger juvenile cohorts are more likely to produce detectable increases in the adult population. This significant finding was robust to outlier observations in three of the four models, with the exception being the recruit model including fishing effort. In this case, the relationship between juvenile and adult density increase was sensitive to a small number of very high-density juvenile aggregation observations. However, the robust significant findings from the other three models suggest a detectable pattern existed between juvenile density and future adult density increase in the datasets.

Temperature effects

Bottom water temperature emerged as a consistent significant driver of the probability of success of juvenile aggregations across all four models, but with contrasting effects for each size group. For the pre-recruit size group, a greater number of warm temperature days (bottom temperature greater than 18°C) led to an increased probability of adult density increase. Oppositely, for the recruit size group, more warm temperature days led to a decreased probability of success.

The divergence between the size groups may reflect differences in size-dependent thermal vulnerability. Larger recruit-sized scallops may experience greater physiological stress relative to their energy requirements during prolonged warm periods. Pre-recruits may be proportionally less affected by thermal stress due to already higher baseline natural mortality rates. Alternatively, warmer temperatures increase predator foraging, and predators may disproportionately target the larger recruit size examined here. This explanation was supported by a secondary finding that crab density and the probability of observing crabs was significantly higher with more warm temperature days in the recruit model that did not include fishing effort.

Fishing Effort

Including the fishing effort data derived from vessel monitoring system (VMS) data from 2010 to 2023 revealed a significant negative effect of fishing pressure on both the probability and magnitude of adult scallop density increase in the recruit model. The commercial scallop dredges operating in this fishery have 102.5 mm rings that largely restrict the catch to adult scallops. However, recruit sized scallops (35-75 mm shell height) still interact negatively with the dredges through incidental contact, capture and discard mortality, and habitat disturbance. Importantly, the inclusion of fishing effort did not significantly affect the recruitment of pre-recruits into the adult population. These combined findings, significant negative effect on the larger group and no significant effect on the smaller group, are consistent with the size selectivity of the commercial scallop dredges, which would negatively impact the smaller size group to a lesser extent compared to the larger size group examined here.

Secondary Significant Findings

Several significant secondary relationships were consistently identified across models and provided some ecological context for the primary findings. Higher chlorophyll a concentration was



significantly detected with lower salinity across all models, reflecting the known interaction between nutrient-rich, lower salinity slope water and primary production across the northwest Atlantic continental shelf. Sea star density was significantly higher on gravel substrates, while crab density was significantly higher on sand. These predator and substrate significant findings are consistent with known predator habitat preferences. Crabs were more likely to be present in juvenile aggregations covering a larger area, which may reflect predator preferences to congregate on large juvenile aggregations or may be a sampling effect given the relatively low densities of crabs observed in this study compared to scallops and sea stars. Crab presence and density were also significantly affected by the number of warm temperature days and salinity in the recruit models, which helps support that warm temperatures had a negative effect on the probability of success of recruit aggregations through the influence of temperature on predators.

Internal Consistency

The suite of four models (including two for each size group, including and excluding fishing effort, and spanning different periods) provided a valuable internal consistency check for this statistical analysis. The two pre-recruit models produced almost identical results, indicating that significant findings were robust to length of the time series and unaffected by fishing effort. The two recruit models shared key findings of juvenile density and temperature on adult density increase, and the significant finding of fishing effort highlighted the importance of fitting a second model to include this variable. Some of the differences in the secondary significant findings from the two recruit models (such as relationships between water speed and chlorophyll a concentration, or crab density and substrate) may reflect genuine changes in ecological dynamics between the different periods used in each recruit model or may be an artefact of the truncated time series in the model including fishing effort.

Sensitivity and Robustness

Leave-one-out sensitivity analyses were conducted to examine the influence of outlier observations on all significant relationships detected. Most relationships were robust to the removal of outlier observations. The few exceptions were the relationships between crab density and juvenile aggregation size for pre-recruits, sea star density and juvenile density, and juvenile density and adult density increase from the recruit model including fishing effort. These significant, but sensitive, findings would benefit from more sampling across the upper quartiles of their distributions to allow better understanding of the expected relationships and strengthen confidence in these findings.

3.0 SPECIAL COMMENTS

The most management-relevant finding from this work is that commercial fishing effort both reduces the likelihood and magnitude of recruit-sized scallop recruitment success but did not significantly affect either of these for the pre-recruit size group. This aligns directly with known size selectivity and provides quantitative evidence to support targeted protection of recruit aggregations when identified by surveys. The existing management framework is well positioned to protect scallops 35 to 75 mm shell height from fishing pressure, and this study has highlighted that there is a measurable benefit of doing so.



Managers should also calibrate their expectations when juvenile aggregations are detected by fishery-independent surveys, and it is important to acknowledge that sometimes there is overoptimism about the contribution of identified juvenile aggregations to the future of the fishery. This study has provided a realistic baseline that slightly less than half of the aggregations observed will successfully contribute to the harvestable population in the future. Therefore, precaution is recommended when planning harvesting strategies around juvenile aggregations and reinforces the importance of continued and consistent monitoring through space and time to track juvenile aggregations.

The contrasting effects of temperature on the two size groups warrants attention in an environment where bottom water temperatures are expected to continue to increase. If these results are genuine ecological patterns, then the impacts of rising sea temperatures may benefit one size group but simultaneously disadvantage another. Temperature is likely to become a highly important variable for managers that should be more explicitly considered in management decisions.

This work also raised, but did not resolve, the scale of juvenile aggregations, with juvenile aggregations being detected that ranged 2.3 km² to 3,500 km². Spatial protection measures should ideally closely follow the size of juvenile aggregations, and this is a practical consideration that warrants further discussion among scientists, managers, and stakeholders. The 10 km buffer used in this study was derived from literature based on scallop tagging studies and serves as a reasonable starting point, but optimal closed area sizes need further research.

The fishing effort data were summed over three-minute cells and three-year windows to capture broad scale fishing patterns but smoothed out potentially highly important acute high-intensity fishing events that may have had a disproportionate impact on juvenile recruitment success. This level of detail was not in keeping with the scale of the study and managers should keep in mind that the negative impacts of fishing pressure on the recruit size group may be underestimated in this work.

This research was successful thanks to the long-term and spatially consistent coverage of the drop camera survey, which spanned 21 years. The resultant spatially explicit, fishery-independent observations formed the backbone of the study. Without continued annual sampling in areas it would not have been possible to track many of the identified aggregations and this reinforces the importance of funding to support consistent scientific monitoring for both annual stock assessments and the ability to conduct long-term ecological studies to advance knowledge.

Further strengths of the work include the translation of raw survey estimates into a statistical dataset that was analyzed to provide useful findings, the use of a sophisticated statistical method designed to handle covariate confounding and analyze binary success and magnitude of success individually from the same model, the integration of multiple sources of data for covariates, and the use of multiple models to strengthen the evidence base and provide internal consistency checks.

Lastly, the next step for this work should be to test the operational potential of the models developed by applying them to the real-time survey data examined each year for the annual projection cycle. When a juvenile aggregation is detected by fishery-independent surveys, a suite



of environmental and biotic covariates could be assembled and used in the model to generate a probabilistic forecast of recruitment success for specific aggregations. This type of tool would represent an advancement in the scientific evidence available for spatial management decisions in the Atlantic sea scallop fishery.