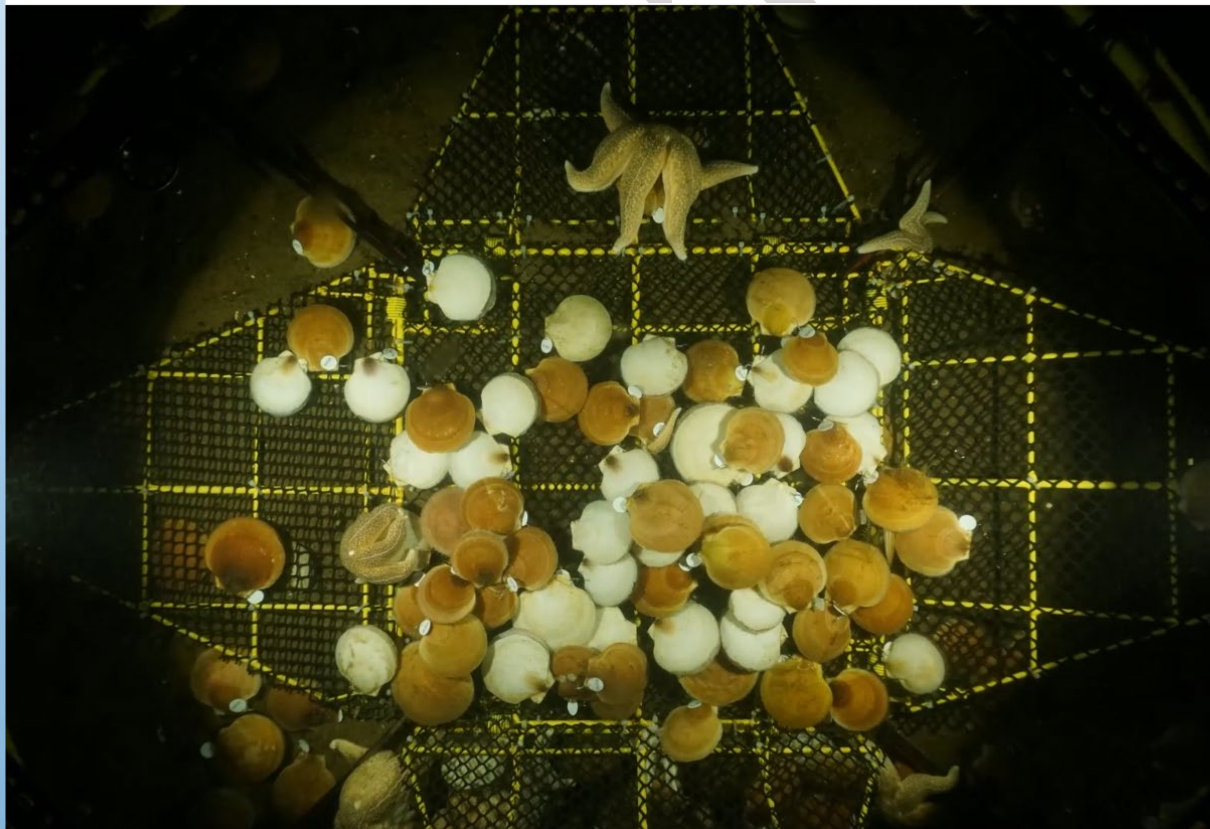
Evaluating the Key Factors that Influence the Efficacy of Transplanting to Supplement Recruitment

Final Report

Prepared for the 2022

Sea Scallop Research Set-Aside

(NA22NMF4540058)



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Executive Summary

This report summarizes transplanting efforts funded by the 2022 Sea Scallop Research Set-Aside (RSA) Program (NA22NMF4540058) as well as the results from an industry-funded project conducted under an Exempted Fishing Permit (EFP #19109) in 2020 and 2021 to fulfill the proposed objectives. The specific research objectives for the 2022 RSA project:

1. Evaluate growth, dispersal, and mortality of transplanted sea scallops addressing ***2022 RSA General Research Priority #4: Scallop recruitment supplementation***.

2. Compare a transplanted sea scallop bed to a natural bed to understand the factors influencing the formation and persistence of scallop beds ***2022 RSA High Priority #2: Research on scallop biology***.

Atlantic sea scallop transplanting has the potential to provide considerable direct and indirect regional economic benefits throughout the Northwestern Atlantic region by helping to stabilize the scallop resource or even increase yields over that from natural production. However, for transplanting to be successful, appropriate site selection is crucial. Physical and chemical environmental factors, predator-prey dynamics, and productivity can drastically influence whether a site is conducive to scallop growth and survival to reach an optimal harvest size at commercially viable densities. To evaluate the influence of these environmental and biological factors on transplanting site performance this project carried out multiple field experiments and used the finding to parameterize a Monte-Carlo Bioeconomic simulation. This model was then used to evaluate the trade-offs and opportunity costs associated with transplanting scallops.

Modelling of scallop post-transplanting redistribution indicated that the magnitude of net losses occurs closest to individual release site and likely density-dependent dispersal as scallop move away from the initial higher release densities outward to unoccupied areas. At an effort of >500,000 transplanted scallops, net gains occurred over much a broader area (189,400 m^2) and retained densities an order of magnitude above commercially viable densities (~3 scallops per m^2). This redistribution model was then used to simulate dispersal within the Monte-Carlo Bioeconomic simulation across 500 iterations that used biological, environmental, operational, and market variables to evaluate the trade-offs and opportunity costs of transplanting over a 3-year period using the extraordinary recruitment event in the Nantucket Lightship South Deep (NLS-Deep) as a case study. The results indicate that transplanting scallops from the NLS-Deep to more favorable habitat is profitable under normal market conditions at incidental mortality rates between 38 and 77%. Overall, this research indicated transplanting within the NLS region can be a viable solution to enhance production of scallops. However, regions in Closed Area I may not be suitable for transplanting due to higher relative abundances of predators. Further research is needed to decouple predator-prey dynamics from natural mortality and dispersal in this area. In addition, to more research a management framework is needed to ensure that transplanting sites are protected, and that allocation of transplanted resources is equitable.

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1. Introduction

1.1 Background

Annual Atlantic Sea scallops (*Placopecten magellanicus*) landings in Massachusetts are valued at $486 million (NOAA, 2018), making the species one of the most economically important fisheries in the region. Despite its value, sea scallop recruitment is highly variable and characterized by episodic pulses followed by periods of low settlement, resulting in boom-and-bust cycles. The current rotational management framework relies almost exclusively on natural recruitment processes, which introduces increasing uncertainty as climate change and offshore development alter benthic habitats and oceanographic conditions influencing growth, survival and distribution (Rheuban et al. 2018; O'Keefe, 2022).

Rotational management is a form of enhancement that provides protection for newly settled scallops to grow out on highly productive fishing grounds; this framework can potentially be improved through the implementation of husbandry techniques (**Figure 1**). Currently, the United States lacks the infrastructure necessary to collect and rear spat at a scale to support supplementing offshore recruitment. While shore-based sea scallop aquaculture represents a potential long-term solution, it remains highly intensive and is not yet capable of producing cost-effective quantities of scallops at the sizes appropriate for seeding (>75 mm). In contrast, transplanting is reliant upon naturally occurring recruitment events and provides an immediately available mechanism for enhancing scallop production without the need for hatchery-based seed. Recent recruitment events have produced highly dense aggregations of sea scallops in offshore areas, where growth appears to be density limited (Kowaleski et al., 2024). In contrast, scallops inhabiting lower-density environments often exhibit higher yield productivity (Kowaleski et al., 2024). Transplanting therefore offers means to capitalize on episodic recruitment pulses by relocating scallops from high-density, growth-limited source areas to environments with more favorable growth conditions. In doing so, transplanting may simultaneously improve yield per recruit in the source bed through density reduction while establishing productive scallop beds at the destination site.

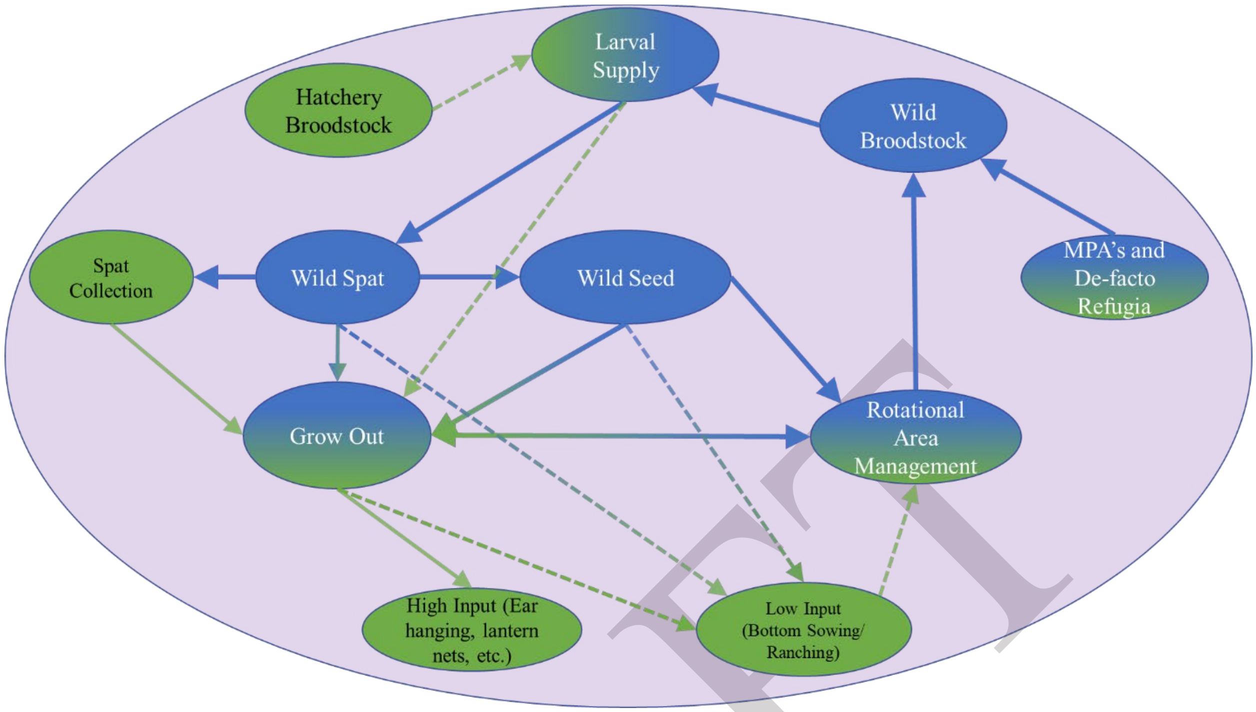

Figure 1: A conceptual framework of scallop enhancement relative to rotational area management. Blue circles represent wild processes, and green circles represent human-assisted processes. Solid arrows represent existing process paths while dashed arrows represent future enhancement paths.

The use of transplanting to enhance scallop production has historical precedent. In Greenland, researchers sought alternatives to enhance the production of Icelandic scallops (*Chlamys islandica*) on depleted fishing grounds (Engelsoft, 2000). Studies comparing two regions in Greenland showed that growth rates vary significantly across a relatively spatial scales, with some beds taking 13-15 years to reach the regulated minimum shell height of 60 mm while other "fast-growing" beds recruited to the fishery in 5-6 years. "Fast-growing" beds were typically in shoal regions with high tidal exchange. To re-establish depleted fishing grounds, Icelandic scallops were transplanted from beds with limited growth potential to areas with optimal growth parameters. While adult growth was unchanged, juvenile scallops exhibited a significant increase in growth following transplanting (Engelsoft, 2000). In the absence of large-scale spat collection and seed production, this Greenland approach demonstrates that transplanting can enhance scallop production when environmental conditions differ across small spatial scales, supporting its application to offshore scallop beds.

In U.S. federal waters, transplanting research was pioneered by Coonamessett Farm, the precursor to Coonamessett Farm Foundation (CFF), through the Seastead Project conducted between 1997 and 1998. Approximately ~120,000 scallops were transplanted to an offshore site off Martha's Vineyard in collaboration with academic scientists and industry partners.

This work resulted in the first offshore aquaculture lease in U.S. federal waters and established foundational methods for large-scale transplanting and monitoring (NA66FD0027). As scallop stocks recovered under rotational management, interest in enhancing offshore scallop resources waned. Research in this area remained limited for more than a decade, until CFF was awarded RSA funding beginning in 2013 to investigate the feasibility of large-scale transplanting on Georges Bank (CFF 2014a; CFF 2014b). Using industry dredges, approximately two million scallops were relocated from an area adjacent to the Nantucket Lightship (NLS) Access Area to Closed Area I (CAI), with a subset of individuals tagged for a post-transplant monitoring using optical survey methods. Early results demonstrated that dispersal, rather than mortality, was the primary factor controlling post-transplant scallop density (CFF 2014a; CFF 2014b).

Subsequent experimental work refined time-lapse camera deployments and quantified short-term dispersal dynamics, demonstrating that transplanted scallops disperse nondirectionally, experience limited predation, and can migrate rapidly from concentrated release areas (CFF 2018). An extraordinary recruitment event occurred in the southern portion of the NLS-South-Deep in 2012 which resulted in extreme density of scallops with markedly slower growth rates than those observed in nearby regions with more favorable environmental conditions (Clark 2021). Focus then shifted to optimizing transplanting gears, identifying two-panel box trawls as the most effective and least damaging gear configuration for large-scale transplant operations (EFP #19109).

To effectively develop transplanting as a management tool, it is essential to quantify the biological processes that govern the growth, dispersal, and mortality of transplanted scallops. Variability in these processes directly influences the formation, persistence, and economic viability of transplanted beds. By explicitly accounting for this variability, resource managers and stakeholders can identify suitable transplant locations, evaluate trade-offs relative to existing harvest strategies, and determine when transplanting provides a net benefit over a “no-action” alternative.

Ultimately, incorporating transplanting into the Sea Scallop Fishery Management Plan through adaptive framework mechanisms could provide managers with a flexible tool for responding to episodic recruitment events, climate-driven growth constraints, and emerging offshore development pressures, ensuring long-term sustainability and economic resilience of the fishery.

1.2 Project Objectives

The overall goal of this project was to evaluate the biological viability of large-scale sea scallop transplanting as a tool for enhancing offshore scallop resources under variable recruitment and environmental conditions. Specifically, the project aimed to quantify the processes governing the formation, and persistence of transplanted scallop beds.

The specific objectives of the project were:

3. Evaluate growth, dispersal, and mortality of transplanted sea scallops addressing ***2022 RSA General Research Priority #4: Scallop recruitment supplementation***.

4. Compare a transplanted sea scallop bed to a natural bed to understand the factors influencing the formation and persistence of scallop beds ***2022 RSA High Priority #2: Research on scallop biology***.

5. *Add on goal*: Evaluate the economic performance of transplanting relative to a no-action alternative by integrating biological outcomes into a stochastic bio-economic simulation that explicitly accounts for uncertainty in growth, mortality, dispersal, and market conditions ***2022 RSA General Research Priority #4: Scallop recruitment supplementation***.

2. Methods

2.1. Sampling Methods

2.1.1. Research Plan Amendment

The project was proposed to be conducted in the NLS region because it encompassed areas with contrasting high and low scallop densities as well as locations exhibiting environmental conditions considered optimal for sea scallop productivity and were closed to commercial fishing. Work under EFP #19109 prior to the RSA award had also indicated that dispersal from currents was not significant issue in this region. This heterogeneity made the NLS an ideal setting to evaluate post-transplant redistribution and persistence using repeated optical surveys. Over the course of the study, however, management actions and site-specific logistical constraints required adaptive changes to experimental locations. Portions of the original NLS transplant area were opened to fishing activity, which required the transplanting effort to be moved to CAI. Site selection was based on contrasting scallop growth potential, including sites characterized by limited growth as well as locations exhibiting environmental conditions considered optimal for sea scallop productivity and historically productive.

Tagging and transplanting research trips were conducted between 2020 and 2025 in NLS and CAI. However, the transplanting effort within CAI presented unforeseen difficulties for the research. High currents in the area caused the turbidity to be extreme, which in turn, required the towed optical vehicle to be flown closer to the seafloor to maintain image clarity. The topography of the release site was extremely variable with occasional large boulder fields. Optical survey data also indicated active sediment transport, confirming that the site was subject to strong hydrodynamic forcing. Together, these conditions represented significant risks to the towed optical vehicle.

As a result, the quantitative analyses presented in this report are based exclusively on data from the NLS-Triangle research site collected under EFP #19109, which remained undisturbed by fishing activity and was successfully observed using HabCam during two comparable surveys conducted 417 days apart (2020-2021). These paired surveys provided a robust basis for estimating scallop density and assessing spatial redistribution relative to initial release locations. Observations from subsequent transplanting efforts in CAI are therefore not included in the formal analyses but are incorporated qualitatively in the discussion to provide contextual insights.

2.1.2. Study Areas and Scallop Collection

Nantucket Lightship (2020-2022)

The proposed research plan aimed to transplant sea scallops originating from the exceptional 2012 recruitment event in the southern NLS-Deep, where individuals were exhibiting reduced growth, to a region characterized by more favorable growth conditions within a triangular area in the northwestern portion of the NLS region (**Figure 2**). The NLS-Triangle was selected as the release site based on a 2019 HabCam survey, which indicated low background densities of scallops, allowing for clear attribution of post-transplant changes in density and spatial distribution to the transplanting effort.

In May 2020, approximately 2,328 bushels, representing ~550,000 scallops, were transplanted from the NLS South-Deep to a release site within the NLS-Triangle (**Figure 2**) across four research trips. This phase focused on evaluating the use of trawl nets to efficiently transport and release scallops while minimizing handling. Three trawl net designs were tested, with the two-panel box net outperforming the yellowtail flounder and monkfish nets by transporting more scallops with less damage. The timing of these trips allowed for HabCam surveys to go over the transplant site approximately one month and one year after the final transplanting event. To evaluate further growth estimates, a second phase incorporating tagged scallops was initiated in November of 2021 and January of 2022, during which approximately 5,000 tagged individuals and ~219,333 additional scallops were transplanted over two trips. The tagged scallops used to were later recaptured in August of 2022 since the area would be opened to fishing in the forthcoming year.

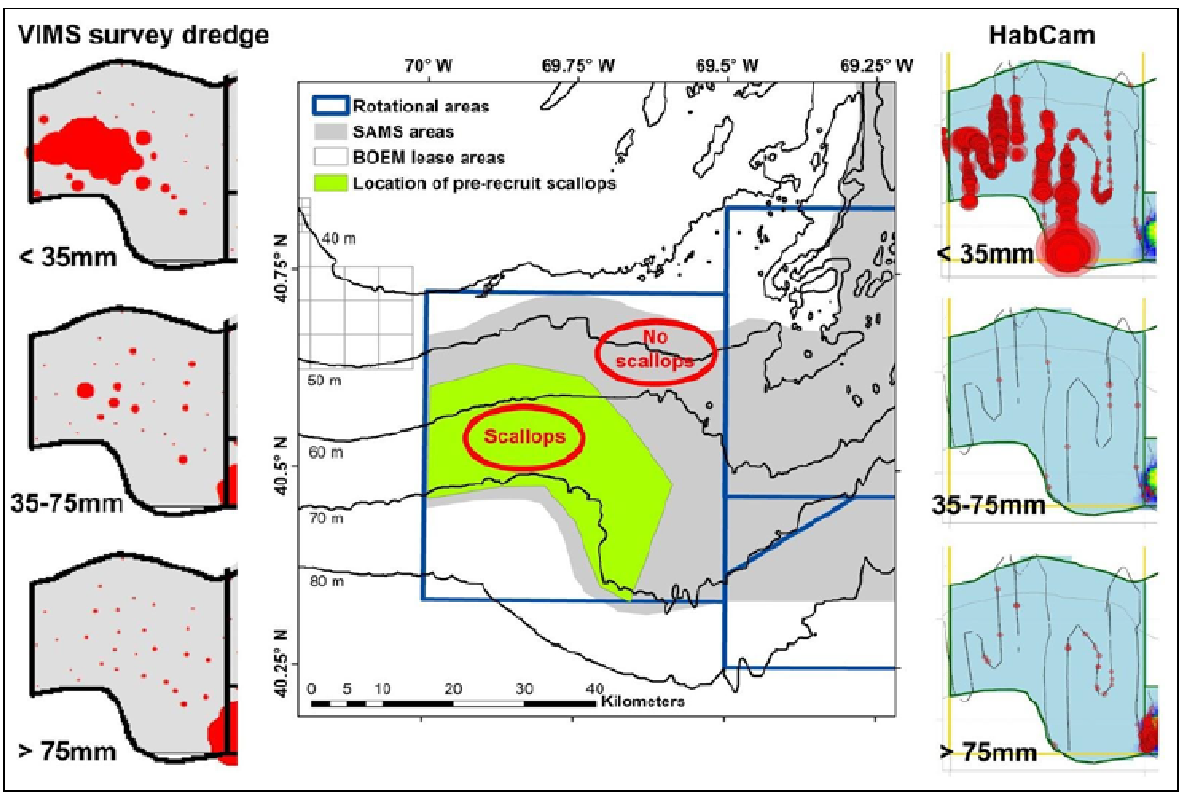

Figure 2: Comparison of sea scallop size-class distributions derived from VIMS survey dredge data (left panels) and HabCam optical imagery (right panels) within the NLS study area. The central map shows the location of pre-recruit scallop concentrations (green shading). Red annotations highlight areas with high scallop presence and adjacent areas with little to no scallop occurrence.

Closed Area I (2022-2025)

The amended research plan was implemented in CAI (**Figure 3**), with transplanting operations conducted aboard the commercial fishing vessel *F/V Small Stuff* using an industry-standard dredge. During the first ear-hanging tagging trip in May 2023, approximately 10,080 scallops were released, of which 1,637 were tagged. A second large-scale drilling and tagging effort was conducted in June 2024, during which approximately 13,440 scallops were released at the transplant site, including 2,065 tagged individuals. In addition, 1,065 scallops were tagged and released back onto the source site during the June 2024 trip to support comparative observations.

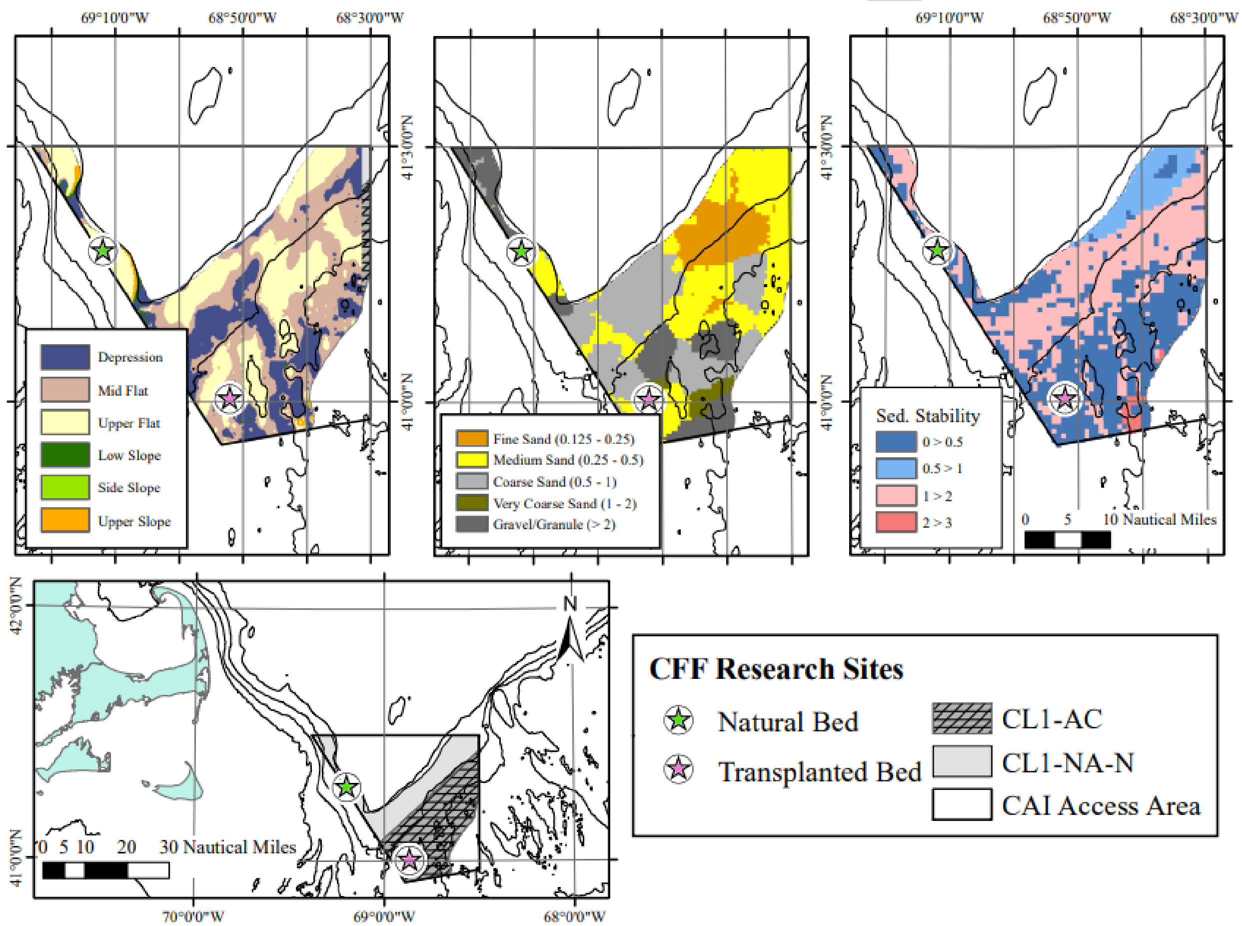

Figure 3: Location of the natural and seeded beds within CAI including the relevant substrate features used to determine site selection.

2.1.3. Tagging and Handling Procedures

Tagging of individual scallops was conducted on dedicated trips to support assessments of growth, fine-scale dispersal, and mortality following transplanting using Floy disc tags with unique numerical identifiers. Two tagging approaches were taken, one that favored tag legibility by optical platforms and another that favored long-term retention. Tagging efforts at the beginning of the study used externally affixed identification tags attached to the upper valve. Prior to tag attachment, epibiont growth was gently removed using the abrasive backing of a sponge and/or a braided stainless-steel scrubber to lightly roughen the shell surface, improving adhesive bonding. Tags were secured with cyanoacrylate adhesive (**Figure 4**), with the process of keeping the animal out of water for an average of five minutes per scallop. While scallops tagged in this way at the NLS-Triangle site in November 2021 and recaptured in January of 2022 had retained their tags in the catch, numerous detached tags were found in the catches of the recapture tows made in August of 2022 at the first research site of this project, raising concerns regarding tag retention.

In response to these observations, the tagging methodology was revised to improve tag retention by attaching tags at the hinge region using an ear-hanging drill (**Figure 4**). This method has been proven to withstand offshore conditions and allow for accurate identification of tagged scallops during post-transplant optical surveys and despite a decrease in legibility.

Throughout all tagging activities, scallops were handled following established best practices to minimize physical damage and stress. Scallops were retained onboard in fish totes covered with damp burlap and periodically watered during transit to minimize thermal and desiccation stress prior to release during the first trip. On later research trips, scallops were kept in live wells with constant circulating sea-water to reduce handling stress and mortality. Tagged individuals were held separately from untagged scallops during transport and were released at designated transplant locations concurrent with untagged individuals.

Figure 4: Tagging methods used during the study. Left: Externally glued floy disc tag on the upper valve. Right: Floy disc tag attached through the hinge region.

2.1.4. Release Design

During the initial transplanting efforts, scallops were released directly from baskets at the surface. Observations from these early deployments indicated dispersion during descent through the water column. In subsequent efforts, scallops were deployed using a controlled release system designed to minimize redistribution during descent and ensure delivery to the seafloor at targeted locations. Groups of up to 100 tagged scallops were placed into brown paper bags tied approximately four meters apart between two cinder blocks. The blocks served as the lead component of the system and were the first element released into the water, ensuring that the attached bags descended rapidly and vertically through the water column (**Figure 5**). The idea with this method was that the paper bags rapidly degraded and opened, allowing scallops to exit naturally while limiting initial redistribution caused by currents or vessel motion. Each deployment event was georeferenced and treated as a discrete release for subsequent spatial analyses of scallop redistribution and bed persistence.

Figure 5: Deployment system used to release tagged sea scallops at the study site. Paper bags containing scallops were attached to a concrete block to reduce dispersion during descent and ensure delivery to the seafloor.

2.1.5 Post-Transplant Monitoring

Post-transplant monitoring was conducted using drop camaras, stationary camara stands, benthic sled and towed optical vehicles to assess scallop density, spatial redistribution, predator-prey interactions and scallop bed persistence following release. HabCam surveys were conducted one month and one year after transplanting to document scallop distribution at the release site. Other optical deployments were used to evaluate post-transplant scallop and other organisms interactions.

2.2. Two-Part Hurdle Model Development

Optical imagery collected during the 2020 and 2021 HabCam surveys of the NLS-Triangle (EFP #19109) was used to estimate scallop density and characterize redistribution relative to initial release locations (**Figure 6**). The research site had not been disturbed in the 417 days between the two optical surveys.

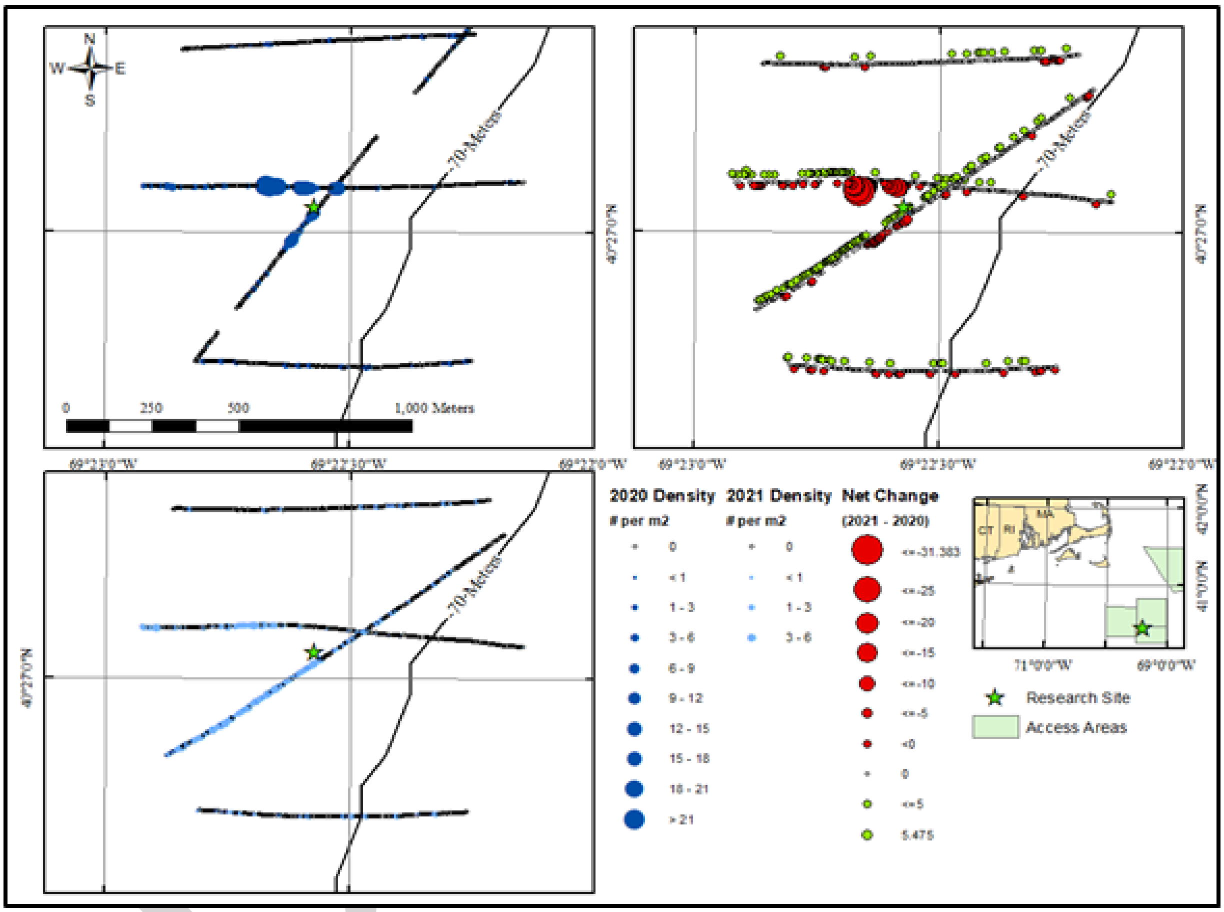

Figure 6: The observed 2020 and 2021 sea scallop density at the NLS-Triangle site and the observed net change in density.

The post-transplant dispersal dynamics of sea scallops were characterized using a two-part Hurdle modeling framework that decomposes net density flux into (*1*) the probability that a detectable change in scallop density occurs and (*2*) the conditional magnitude of that change when it occurs. This approach allows spatial regions with no detectable change to be modeled separately from regions exhibiting redistribution.

Net density change (individuals m^2) was calculated for each survey location as the difference between post-transplant (2021) and pre-transplant (2020) scallop densities.

2.2.1 Part I: Occurrence (Logistic Component)

A binomial generalized linear model (GLM) was used to predict the probability that a net change in scallop density occurred at a given distance from the release center. For each survey location, net change in scallop density (individuals m^{-2}) was calculated as the difference between post-transplant (2021) and pre-transplant (2020) densities. A binary indicator of change was defined as:

$$I(\Delta\rho \neq 0) = \begin{cases} 1, & \text{if net change } \neq 0 \\ 0, & \text{otherwise} \end{cases}$$

Because gain and loss processes may differ mechanistically, separate models were fit for both processes. For each process, the probability of observing a change was modeled as:

$$\text{Logit}[P(\Delta\rho \neq 0)] = \beta_0 + \beta_1 d + \beta_2 \rho$$

Where ρ represents normalized local stocking intensity. Candidate models differing in distance (*d*) metrics (centroid distance (m) or distance to nearest release site (m)) and covariate structure were evaluated using Akaike's Information Criterion (AIC), and the best-supported model for each process was retained.

2.2.2 Part II: Magnitude (NLS Component)

Conditional on a detectable change occurring, the magnitude of net scallop density change was modeled using a negative exponential decay function, reflecting diffusion-like attenuation with distance from the release site. A Nonlinear Least Squares (NLS) regression was used to model the density of scallops. Four candidate decay functions (Exponential, Exponential with Stocking Intensity, Gaussian, and Power-Law) were compared using AIC.

2.2.3 Parameterizing Local Stocking Intensity (ρ)

A key feature of the model was the inclusion of local stocking intensity (ρ). Unlike global density metrics, ρ was calculated by identifying the specific "compactness" of each individual scallop release, or drop.

1. The local mean density of the 2020 release was calculated for each unique Drop ID ($Drop_{UID}$).
2. The initial area (m^2) for each drop was derived from the number of scallops released ($N_{released}$) divided by this local density.
3. ρ was then calculated as the ratio of $N_{released}$ to that initial footprint, allowing the model to test if highly concentrated drops dispersed differently than diffuse ones.

2.2.4 Expected Net change as a Spatial Redistribution Kernel

For each distance *d*, expected net change was computed by combining occurrence and magnitude components:

$$E[\Delta(d)] = P_g(d)\, E[\Delta^{+}(d)] - P_l(d)\, E[|\ \Delta^{-}(d)\ |]$$

This formulation defines a radial redistribution kernel, representing the expected net gain or loss of scallop density as a function of distance from the release site.

2.3. Post-hoc Anisotropy Analysis of Residuals

To assess whether directional structure remained after accounting for distance- and density-dependent processes, we conducted a post-hoc anisotropy analysis on residuals from the final two-part hurdle models. This analysis was intended as a diagnostic test for unmodeled directional effects (e.g., tidal advection), rather than as a mechanism included directly in the fitted models.

For each observation, angular position relative to the transplant center was calculated using the bearing from the site centroid to the observation location. Directional predictors were represented using sine and cosine transformations of this angle, which together provide a continuous and rotation-invariant representation of directional dependence. This formulation avoids discontinuities associated with circular predictors and allows detection of any preferred axis of redistribution.

Residuals from the hurdle models were then regressed on the sine and cosine terms using Gaussian linear models. Analyses were conducted separately within distance bins to evaluate whether potential anisotropy varied with spatial scale. Model coefficients were examined for significance and consistency across bins, and model fit was compared to intercept-only models using Akaike's Information Criterion (AIC).

To summarize directional tendency, a preferred direction was estimated post-hoc as

$$\theta = \mathrm{atan2}(\beta_{\sin}, \beta_{\cos}),$$

Where $\beta_{\sin}$ and $\beta_{\cos}$ are the fitted coefficients on the sine and cosine terms, respectively. Because this quantity is only meaningful when directional effects are present, interpretation was restricted to cases where both coefficients were statistically distinguishable from zero and model support exceeded that of the null model.

This post-hoc approach allowed evaluation of residual anisotropy without altering the structure or inference of the primary hurdle models, providing an independent check on whether redistribution patterns exhibited persistent directional bias after accounting for the dominant radial processes.

2.4. Integrating Statistics into the Spatial Kernel

The results of the Two-Part model provided mathematical architecture for the Anisotropic Redistribution Kernel. Rather than using an arbitrary diffusion rate, the kernel's shape and behavior were directly derived from the Hurdle model's coefficients:

- **Geometric Anisotropy:** Post-hoc analyses of residuals from the gain component revealed weak and spatially limited directional structure after accounting for distance-dependent loss processes. Evidence for anisotropy was strongest at intermediate distances (250–446 m) from the transplant center, while residuals at the smallest and largest spatial scales showed little or no directional signal. The resulting coefficients (β_{sin}, β_{cos}) were used to calculate a Stretch Factor (λ):

$$\lambda = 1 + \sqrt{\beta_{sin}^2 + \beta_{cos}^2}$$

- **Initial Dispersion (σ):** The Gaussian NLS candidate, which performed competitively in AIC testing, provided the baseline standard deviation (σ_{base}) for the kernels. This ensured that the starting "spread" of each simulated drop matched the dispersion observed in the field.

2.5. Spatiotemporal Redistribution Simulation

The simulation was executed on a *10m X 10m* grid. For each release event, an anisotropic Gaussian kernel was projected, incorporating the rotation angle (53º NE) and the stretch factor derived above.

2.5.1. Expansion and Elasticity

To account for the "Elastic" redistribution over the 417-day period, we implemented a time-dependent expansion of the kernel's standard deviation. This allowed the footprint to grow from its initial state (*T=0*) to a wider, more diffused state (*T=417*):

$$\sigma(t) = \sigma_i \cdot \left(1 + \left(\frac{t}{417}\right)^{0.7}\right)$$

2.5.2. Satiation and Mass Conservation

To maintain biological realism, we applied a satiation function to areas where multiple kernels overlapped. An upper density limit (*K*), derived from the 2021 survey variance, capped the maximum density. Finally, a mass-balance normalization was applied to ensure that the total number of scallops (*N* = 550,388) remained constant throughout the simulation, regardless of the degree of spread.

2.6. Bio-Economic Monte-Carlo Simulation

To evaluate the long-term economic viability of stock enhancement, we integrated the validated spatiotemporal redistribution model into a Bio-Economic Monte-Carlo Simulation. This approach has been used to evaluate the environmental influences on the success of Manila clam farming (Melia and Gatto 2004). This approach was used to simulate the financial outcomes of the transplanting efforts in the NLS over a three-year horizon, accounting for biological growth, environmental variability, and market dynamics using stochastic parameters derived from empirical approaches. The workflow of the simulation is illustrated in **Figure 7.**

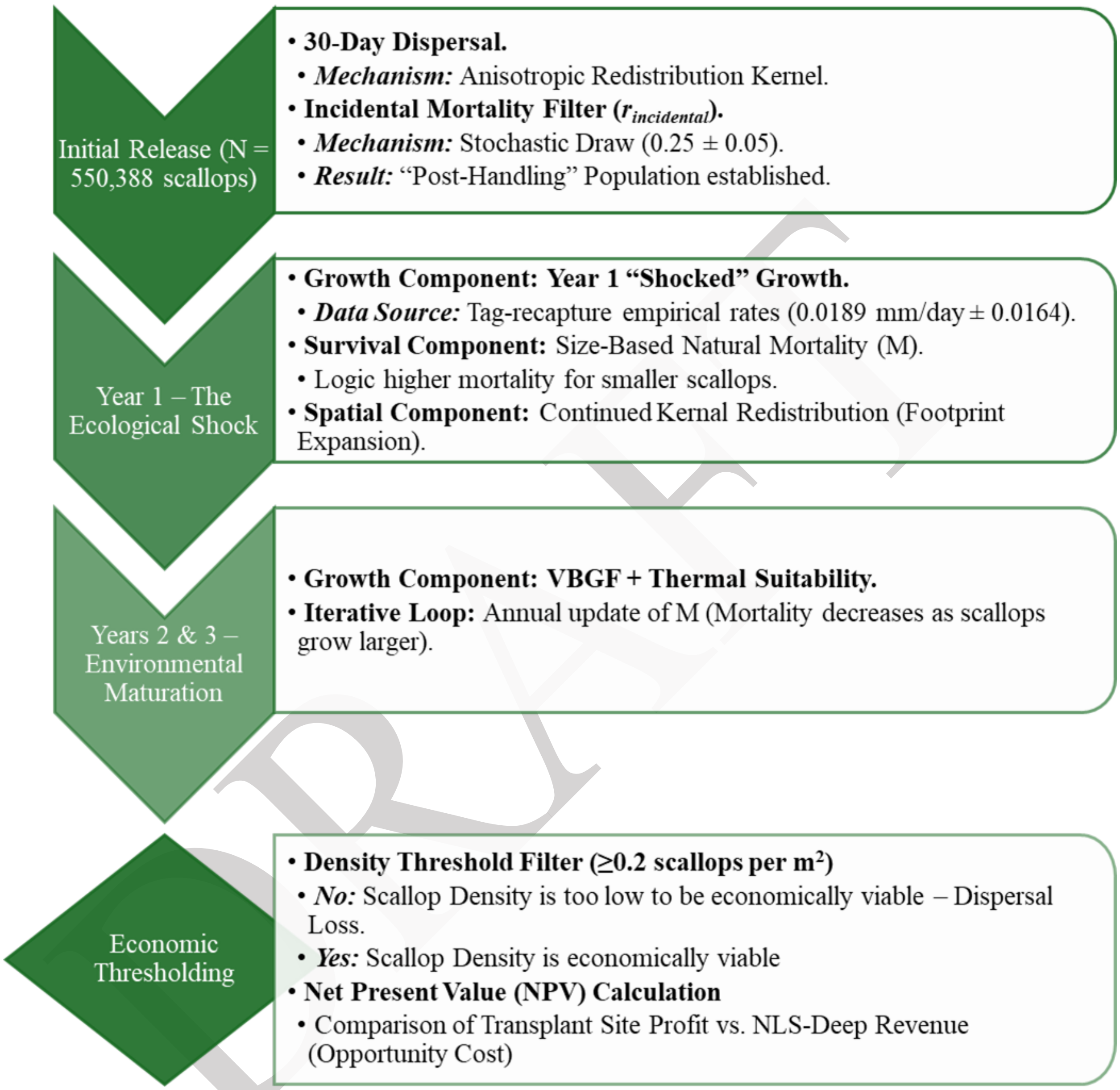

Figure 7: A diagram of the logic of the Monte-Carlo simulation.

2.6.1. Stochastic Parameterization

The simulation was parameterized using a combination of fixed constants and stochastic variables representing environmental and economic uncertainty derived from scientific publications, CFF's research, and stakeholder input. ***Table A1 of the Appendix*** summarizes the input distributions used in the bio-economic simulation. By allowing these variables to fluctuate, the model captures the 'envelope of risk' associated with the 3-year growth period.

2.6.2. Integrated Dispersal, Mortality, and Growth

The simulation utilizes the Anisotropic Redistribution Kernel to project the population's spatial extent at Year 1 and Year 3 after incidental mortality ($r_{incidental}$), natural mortality (*M*), and growth are applied incrementally to the simulation grid:

- **30-Day Dispersal and Incidental Mortality**: During the first 30-days scallops were allowed to disperse before $r_{incidental}$ was applied to the grid. This was done to allow density-dependent dispersal processes to dominate the spatial expansion of the site footprint.
- **Year 1 'Shocked" Growth:** The "surviving" scallops after *rincidental* was applied continue to disperse for the remainder of Year 1. A Year 1 "Shocked" Growth Rate (GR_{Y1}) was then applied to the "surviving" scallops within the grid (**Table 1**). The GR_{Y1} was estimated from growth data from six tagged scallops recaptured from the transplant site. A size-based M was then applied.

Table 1: Mark-recapture data used to parameterize the Year 1 "Shocked" Growth Rate.

Tag #	*Release Date*	*Recapture Date*	*Days at Large*	*Shell Height (mm) at Release*	*Shell Height (mm) at Recapture*
6299	11/17/2021	8/17/2022	272	105	107
5455	11/18/2021	8/17/2022	272	102	107
5328	11/18/2021	8/17/2022	272	99	99
9832	1/27/2022	8/17/2022	202	100	106
9582	1/27/2022	8/17/2022	202	107	112
9387	1/27/2022	8/17/2022	202	91	104
			Mean	100.667	105.833
			Std. Deviation	5.610	4.262

- **Years 2 & 3**: Growth for years 2 and 3 were modeled using a von Bertalanffy Growth Function (VBGF) adjusted by optimal temperature days (8º to 12º C), derived from local depth-strata temperature curves. For each year of the simulation, the size-based *M* was applied to the grid.

Since the total number of scallops is conserved within the kernel, an economically "Harvestable Area" is defined by a density threshold of 0.2 scallops/m^2. Areas falling below this density are considered unviable for commercial harvest and individuals in these areas are considered lost to dispersal.

2.6.3. Financial Analysis and Opportunity Cost

For each iteration, the model calculates Net Profit and Opportunity Cost:

- **Revenue Generation:** Meat weights are calculated via allometric scaling (Shell Height (mm) and Depth (m)) and converted to market "count-per-pound" categories to determine stochastic market prices.
- **Opportunity Cost Framework:** This metric evaluates if transplanting is favorable to "no action" by subtracting the potential revenue of the NLS-Deep population from the transplanted site's net profit.
- **Sensitivity Analysis:** Spearman Rank Correlation is applied to identify the primary drivers of financial success, correlating inputs to final net profit.

3. Results

3.1. Two-part Hurdle Model Selection and Covariate Influence

The two-part Hurdle model successfully isolated post-transplant redistribution into distinct drivers of scallop presence (occurrence) and density change (magnitude). Model selection using AIC revealed that spatial dispersal is highly dependent on both distance from the release locations and initial stocking intensity (ρ), confirming that post-release movement was neither random nor purely diffusive. **Figure 8** shows the best fitting model relative to the observed net density change.

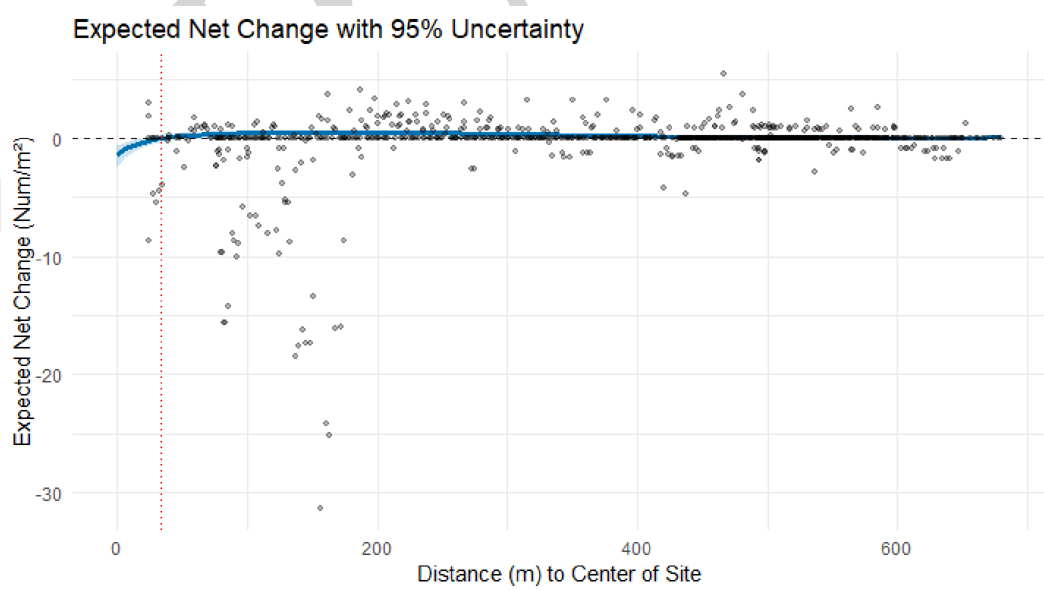

Figure 8: The distance-based expected net change as predicted by the two-part hurdle model relative to the observed net change showing net emigration within 30 m of the transplant location and net immigration to approximately 400m.

3.1.1 Scallop Gain - *Movement Into Unoccupied Areas*

Table 2: Logistic model coefficient estimates from the best-performing gain model.

	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-1.368	0.5673	-2.412	1.59E-02	*
Center_Dist	0.0132	0.006522	2.024	0.043	*
I(Center_Dist	-4.94E-05	2.15E-05	-2.298	2.16E-02	*
I(Center_Dist	4.11E-08	2.12E-08	1.942	5.22E-02	.

The best-performing logistic model for scallop gain was the cubic center distance model (**Table 2**). The significance of the cubic term suggests a non-linear "ring" of recruitment, where the probability of finding new scallops peaks at intermediate distances from the release center before tapering off.

Table 3: The estimated model coefficients for the best-performing loss magnitude model.

Net Change ~ A * exp(-Center_Dist*sigma^2)					
	Estimate	*Std. Error*	*t value*	*Pr(>|t|)*	
A	1.429	0.1057	13.52	<2e-16	***
sigma	993.3471	459.4436	2.162	3.21E-02	*

For the best-performing magnitude model the estimated amplitude (A = 1.429) indicates a peak density increase of approximately 1.43 individuals per m^2 at the center of the release coordinates (**Table 3**). The scale parameter (σ = 993.37) reflects the significant spatial footprint of the transplant effort. This relatively high sigma value suggests that density-dependent dispersal and handling-induced movement resulted in a broad redistribution of biomass across the site. See Appendix **Tables A2** and **A3** for gain model selection details.

3.1.2 Scallop Loss - *Movement Away from a Drop Site*

Table 4: Logistic model coefficient estimates from the best-performing loss model.

	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-3.059765	0.359526	-8.511	2.00E-16	***
Drop_Dist	0.008635	0.002493	3.464	0.000533	***
ρ	1.66927	0.235122	7.1	1.25E-12	***
Drop_Dist: ρ	-0.015428	0.003427	-4.502	6.73E-06	***

Loss dynamics exhibited stronger spatial structure and greater intensity than gains. The probability of scallop loss was best explained by an interaction between distance from release sites and local stocking intensity (ρ) (**Table 4**). Higher initial stocking densities significantly increased the likelihood of loss near release locations, indicating density-dependent emigration immediately following transplanting.

Table 5: The estimated model coefficients for the best-performing loss magnitude model.

abs(Net Change) ~ A * exp(-(b + c * ρ) * Drop_Dist)					
	Estimate	*Std. Erro*	*t value*	*Pr(>|t|)*	
A	8.41016	1.79819	4.677	7.81E-06	***
b	0.04878	0.01532	3.185	0.00185	**
c	-0.009	0.00157	-5.767	6.59E-08	***

The magnitude of loss was best described by an exponential decay function with an interaction between distance and stocking intensity (**Table 5**). Predicted losses were highly concentrated at release locations, with flux reaching 8.4 scallops/m^2/m at the center of a drop site and decaying rapidly with distance. The negative interaction term ($c<0$) suggests that in areas of higher initial scallop density (ρ), the rate of decay is slightly moderated by stocking intensity. Essentially, the flux footprint was wider for release sites with higher stocking intensities than those with sparser ones. See Appendix **Tables A4** and A**5** for loss model selection details.

3.2. Kernel Calibration and Initial State (*T = 0*)

The optimization of the dispersion parameter (α) and the integration of the hurdle model coefficients provided a highly accurate initialization of the release site.

- **Dispersion Exponent (α):** The optimized value of 0.581 indicates a moderate scaling effect; larger bushel drops created wider initial footprints, but the expansion was slightly less than linear, suggesting a degree of "clumping" in larger release volumes.
- **Anisotropy:** While the primary model selection favored a simpler geometric approach, post-hoc analysis identified a significant anisotropic signal. The population exhibited a directional bias along the NE-SW axis (53º), with the most pronounced spreading occurring at intermediate distances from the release points.
- **Satiation Limit (*K*):** The carrying capacity was capped at 1.801 scallops/m^2, preventing the simulation from predicting biologically unrealistic densities in high-overlap areas.

3.3. Spatiotemporal Footprint Expansion

The redistribution simulation captured the expansion of the site over the 417-day study period (**Figure 9**). The footprint followed a power-law growth curve increasing from an initial area of 67,300 m^2 (4.4% of the total area surveyed of 1,539,380 m^2) to an estimated 189,400 m^2 by day 417. This represents a total area expansion of approximately 181% from the time of release, as individual kernels merged and diffused, ultimately occupying 12.3% of the total site area.

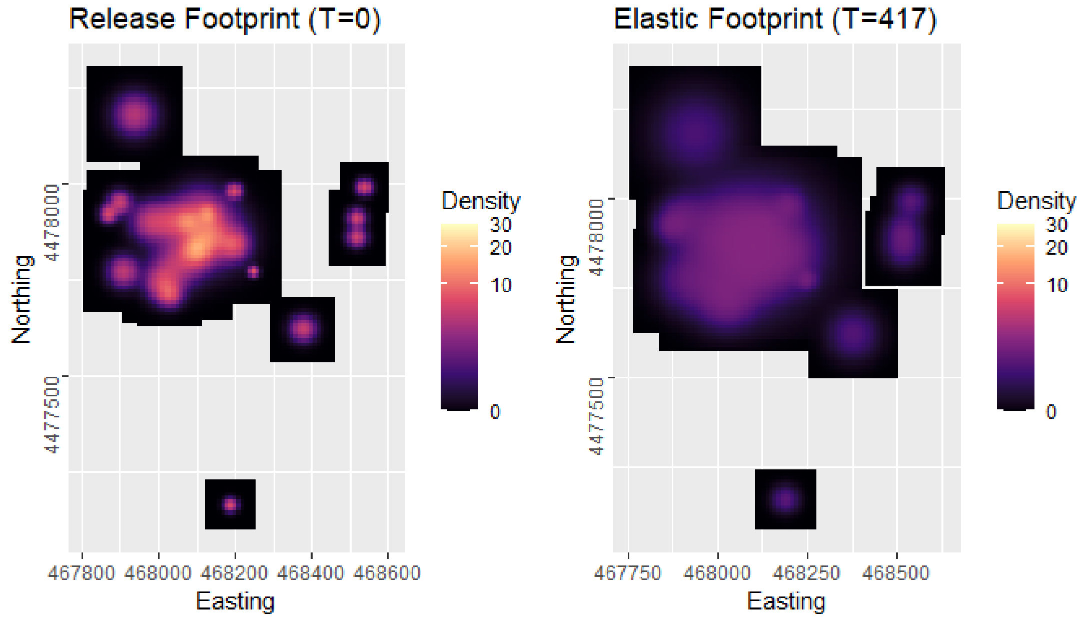

Figure 9: A comparison of the simulated release footprint (T=0) and the final footprint 417 days post release (T=417).

3.4. Model Validation and Predictive Accuracy

The redistribution model was validated against field survey data from 2020 and 2021. Immediately following release (T=0), the calibrated model achieved a Pearson correlation of $r = 0.313$ when compared with the 2020 post-release survey, representing an improvement over the baseline model ($r = 0.265$). this increase indicates that incorporation of optimized α parameters and local density metrics improved the model's ability to reproduce observed initial scallop distributions.

Model performance remained stable over longer timescales. After 417 days of simulated dispersal, the correlation between predicted and observed scallop distributions was $r = 0.282$. The relatively small reduction in correlation over time suggests that the model adequately captured long-term redistribution dynamics without excessive numerical diffusion.

3.5. Bio-Economic Simulation Results

3.5.1. Biological Performance and Opportunity Cost

The bio-economic simulation decoupled the growth trajectories of the transplanted scallops from those remaining in the NLS-Deep. The NLS-Deep source population was modeled with a static shell height distribution centered at 94.25 mm (± 3.7 mm), reflecting the "stunted" growth in the high-density source area. In contrast, the transplanted population exhibited significant biological gains despite the application of a "shocked" growth rate (0.0189 mm/day) in Year 1 and the improved suitability of the transplanted site further increased gains after the application of the von Bertallanffy growth in Years 2 and 3.

This divergence in biological performance drove the opportunity cost calculation. By Year 3, the biomass of the transplanted scallops significantly exceeded that of an equivalent amount of the "No Action" scenario, creating a positive net benefit in the majority of iterations despite the deduction of potential revenue from an equivalent biomass in the NLS-Deep.

3.5.2. Economic Viability and Break-Even Analysis

The Monte-Carlo analysis indicated that transplanting is a highly resilient investment, particularly at moderate-to-high market prices (**Figure 10**). The interaction between Incidental Mortality (scallop loss during harvest) and Market Price was analyzed to determine the "Break-Even Frontier," the specific mortality rate at which the Net Present Value (NPV) of transplanting equals the NPV of harvesting an equivalent number of scallops in the NLS-Deep in 2020/21.

The project demonstrates two distinct stability zones:

- **High Resilience Zone ($12.00 – $19.00/lb):** In this price range, the biological gains from transplanting are so substantial that they outweigh the costs of "No Action" even at high mortality rates. The break-even analysis indicates allowable mortality rates exceeding 60% (e.g., 77.5% at $12/lb). This suggests that within standard market conditions, the effort remains economically viable even with significant gear-induced loss (**Figure 10**).
- **High Opportunity Cost Zone (>$20.00/lb):** At premium price points ($21–$22/lb), the break-even mortality threshold tightens to approximately 38–45%. This counter-intuitive trend occurs because the NLS-Deep scallops, while smaller, become highly valuable at these prices (**Figure 10**). Under these conditions, transplanting remains viable but requires greater operational efficiency to offset the value of harvesting the source bed directly. Despite this effect, transplanting remained the more profitable option relative to wild harvest based on the expected mortality of 25%.

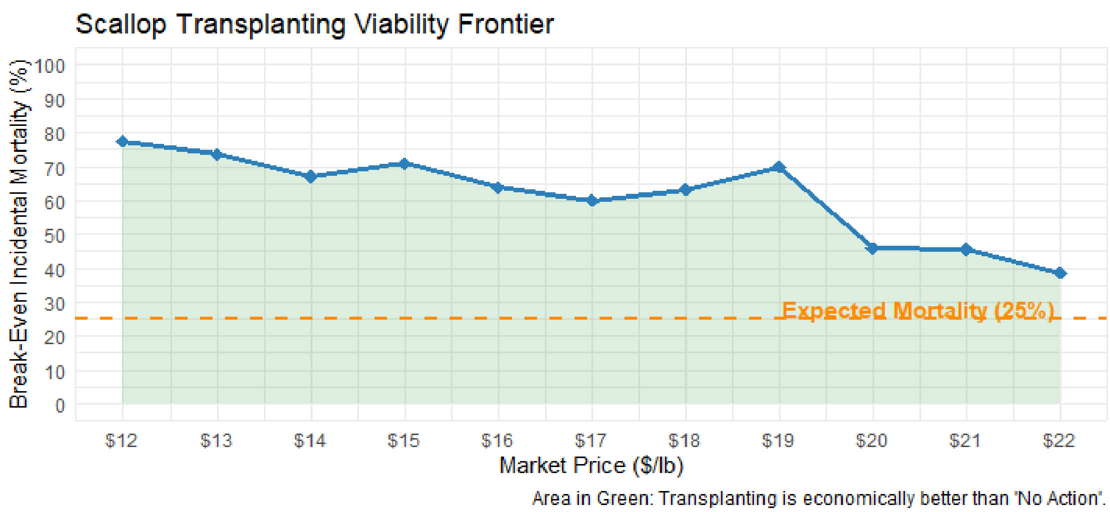

Figure 10: Influence of market price and incidental mortality on the opportunity cost of transplanting. The green shaded area shows the percentage of scenarios where transplanting is economically better than no action.

3.5.3. Sensitivity to Input Variables

A Spearman Rank Correlation analysis confirmed that market price and Year-1 growth rate were the primary positive drivers of net profit, while incidental mortality was the strongest negative driver (**Figure 11**). However, the break-even analysis demonstrates that unless incidental mortality exceeds the calculated thresholds (typically >40% for most price scenarios), the transplanting effort is projected to yield a higher net present value than the status quo alternative.

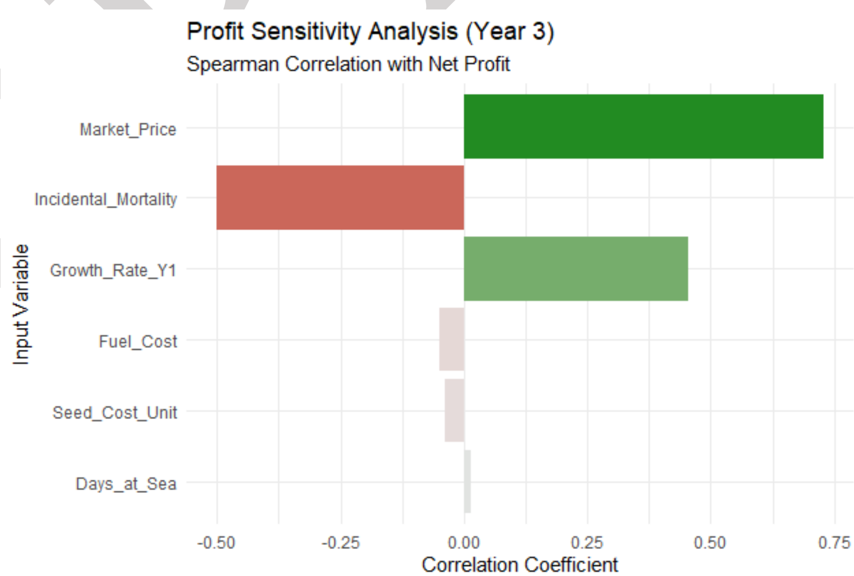

Figure 11: Impacts of input variables on profitability identified by sensitivity analysis. Green and red indicates positive and negative impact.

4. Discussion

4.1. Biological Release and Market Prices

The core finding of this study is the successful "biological release" of sea scallops transplanted from high-density, deep-water "sink" areas to shallower, more thermally optimal environments. Upon transplantation to the shallower site, the scallops exhibited a compensatory "shock" growth response during the first year following transplanting, after which the applied growth was consistent with site-specific von Bertalanffy parameters. Despite the transplanting “shock”, the divergence in growth trajectories is the primary driver of predicted economic success. By transplanting the stock from a resource-limited source environment, the effort converted high-volume, low-value biomass (higher meat counts) into lower-volume, high-value biomass (lower meat counts), effectively capitalizing on the higher market prices paid for higher meat yields.

4.2. Spatial Dynamics: Redistribution vs. Aggregation

The application of the Two-Part Hurdle Model provided a high-fidelity characterization of how the transplanted population settled within the site. A critical concern in transplanting efforts is "dilution," the risk that scallops will disperse so widely that they fall below commercially harvestable densities. The modelling of the magnitude of change indicates that this concern is unwarranted for sites in the NLS region. This is further confirmed by the successful effort to relocate transplanted scallops with an optical survey vehicle (**Figure 12**). While the loss model showed a sharp, concentrated deficit at the release center (reflecting the immediate removal intensity), the gain model revealed a Gaussian dispersal pattern ($\sigma \sim 993$ m). This indicates that while the population did spread, it did so into a coherent, wide-area "mound" rather than diffusing into background noise. Crucially, the resulting densities across this expanded footprint remained largely above the 0.2 scallops/m^2 economic threshold after mortality was iteratively applied. At this economic threshold catch rates are ~300 lbs. per hour and it is likely that lower density thresholds could sustain transplanting operations (**Table 6**).

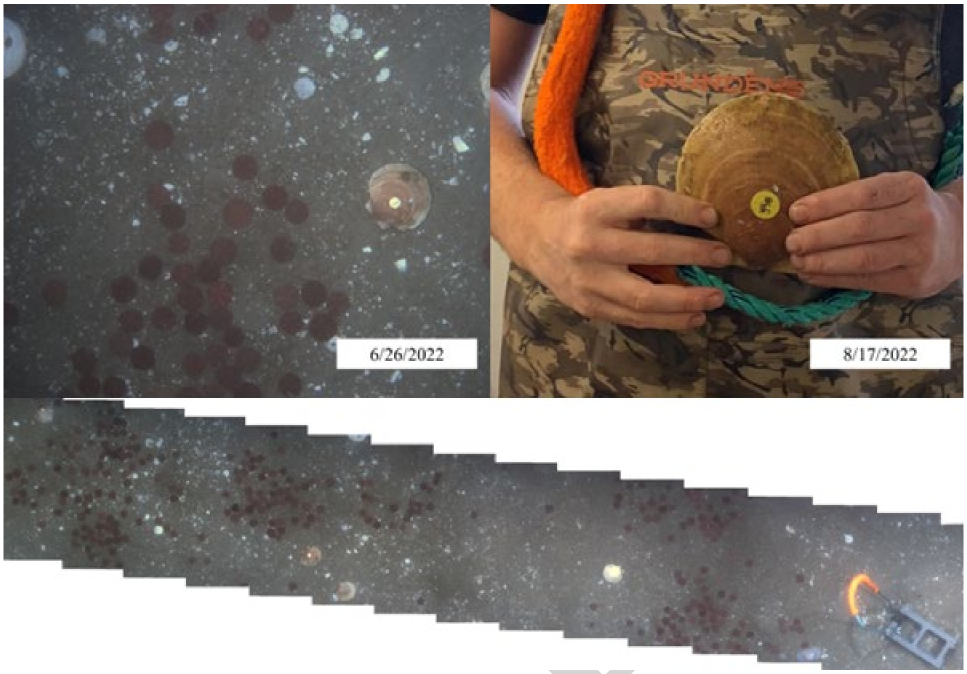

Figure 12: The top left image is of a tagged transplanted scallop, and the top right is the same scallop recaptured 3-months later. Below these images is a mosaic of a HabCam transect with a site marker and tagged transplanted scallops.

Table 6: A comparison of the predicted hourly catch rates relative to different density thresholds.

Two 15' Dredges	Swept Area per Hour (m^2)	Density Threshold (# per m^2)	Number per Hour	Number Caught (q = 0.4)	lbs. of per hour (U20s)
		0.25	19052	7621	381.0
		0.2	15241	6096	304.8
		0.15	11431	4572	228.6
9.144 m	76206	0.1	7621	3048	152.4
		0.05	3810	1524	76.2
		0.01	762	305	15.2
		0.005	381	152	7.6

4.3. Economic Resilience and Opportunity Cost

The bio-economic simulation revealed a nuanced relationship between market price and project risk. Typically, higher market prices are assumed to buffer against operational inefficiencies. However, our Break-Even Analysis uncovered a counter-intuitive "High Opportunity Cost" zone at premium prices (>$20/lb).

- **At Moderate Prices ($12–$19/lb):** Transplanting efforts are highly resilient because the biological value added by transplanting (growth from U30 to U10/U12 sizes) is so significant that it outweighs the "No Action" alternative even if incidental mortality rates rise as high as 60–70%.
- **At Premium Prices (>$20/lb):** The break-even mortality threshold tightens (dropping to ~38%). This occurs because the source population (NLS-Deep), despite being small, becomes highly valuable at these price points.

This finding implies that the economic justification for transplanting shifts depending on the market. In a low-to-medium price environment, transplanting is a mechanism to *create* value where little exists. In a high-price environment, transplanting becomes an optimization problem where operational efficiency (minimizing incidental mortality) is paramount to justify moving an asset that is already valuable in situ.

4.4. Contextual Comparison - *Insights from CAI*

Although data from CAI were not directly incorporated in the Monte-Carlo bioeconomic simulation, observations from this site provide important context for evaluating the conditions under which transplanted scallop beds persist. Differences in physical forcing, predator assemblages, and stocking intensity between CAI and the NLS region likely contributed to contrasting transplant outcomes. Observed persistence of transplanted scallops in the NLS region may be attributable to a combination of lower tidal range, a low predator abundance, and substantially higher stocking intensity. In contrast, camera-based observations in CAI indicated elevated turbidity and strong currents, suggesting that tidal currents may have exceeded the capacity of the transplanted population to maintain a cohesive bed under these conditions (Hatcher et al. 1996). Over 500,000 scallops were transplanted during the NLS-Deep effort while 14,500 scallops were released at the CAI research site in May 2023. The reduced stocking intensity in CAI was intentionally selected to minimize handling stress and crowding-related mortality during tagging operations, based on observations from a June 2022 research trip in the NLS-North during which higher holding densities were associated with increased stress.

To further reduce the potential for current-driven dispersion during descent, tagged scallops released in both NLS-North (6,970 individuals) and CAI (4,958 individuals) were deployed using a weighted paper-bag release system. Optical observations from HabCam surveys in 2022 (NLS-North) and from a rudimentary drop camera system i.e. a metal frame with GitUp Duo 3 actions cameras used in 2023 (CAI) indicate that this approach effectively limited dispersion during descent and produced a detectable transplant signature immediately following release (**Figure 13**). Despite this, transplanted scallops in CAI were not subsequently recaptured, suggesting that factors operating after initial settlement, rather than release mechanics, governed bed persistence.

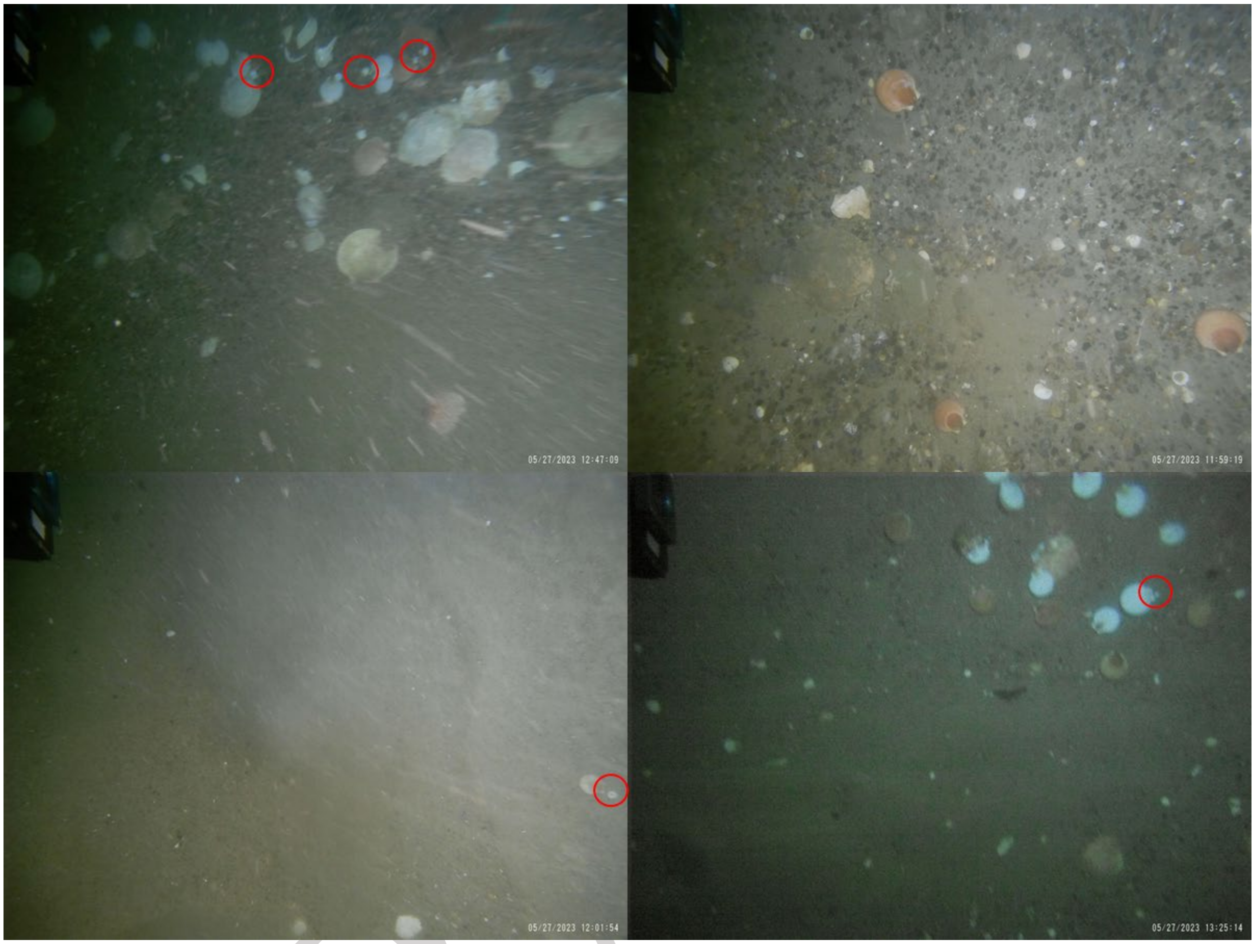

Figure 13: Images of tagged scallops (red circles) in the CAI-Access Area research site taken by the drop camera system used in May 2023.

Scale effects are further highlighted by earlier transplanting efforts in CAI, during which approximately 1.64 million scallops were released (CFF 2014a and 2014b), roughly twice the effort of the NLS-Deep project. At this higher stocking intensity, researchers also reported difficulty detecting a persistent transplant footprint by the end of the study period, underscoring the complexity of site-specific responses even at large release scales.

In addition to lower stocking intensities, transplanted scallops in CAI were substantially smaller, with a mean shell height of 65.18 mm compared to 87 mm in the 2014 effort and 94.1 mm in the NLS-Deep transplanting project. Smaller shell size likely increased susceptibility to predation, despite efforts to minimize incidental mortality (Barbeau and Scheibling 1994). During the 2023 research trip, predation by sea stars (*Asterias* sp.), rock crabs (*Cancer irrotatus*), and moon snails (*Euspira heros*) was documented using drop camera video (**Figure 14**). The same predator assemblage was observed in time-lapse camera imagery collected in May 2025, although mean shell height at that time had increased to 92.8 mm.

While scallops transplanted in the NLS-Deep were only modestly larger than those deployed beneath the CAI camera stand, differences in predator density and diversity between regions likely contributed to contrasting persistence outcomes. Together, these observations suggest that transplant success is governed by interacting effects of stocking intensity, size structure, physical forcing, and predator pressure, and that failure to meet threshold conditions for any of these factors may limit the long-term persistence of transplanted beds.

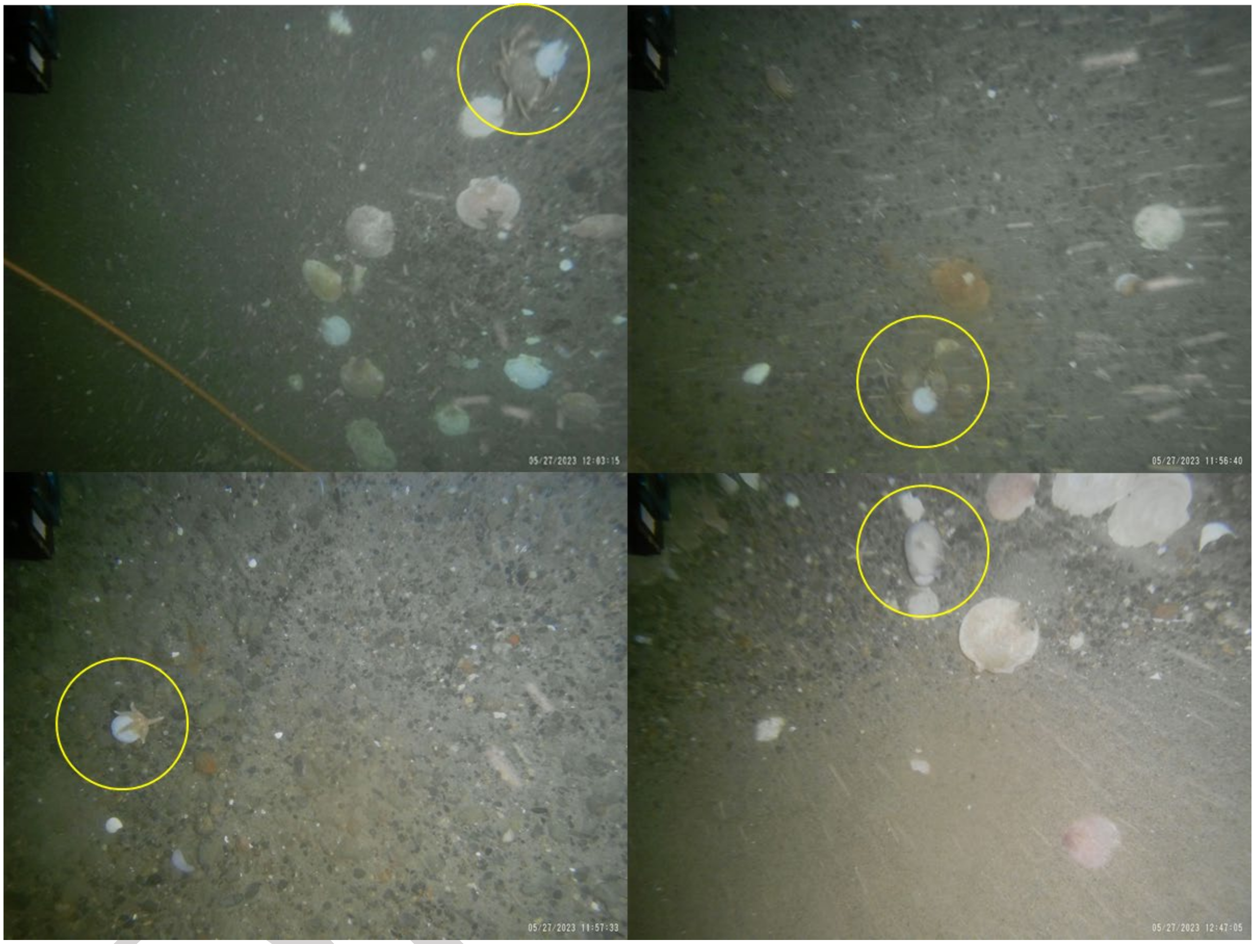

Figure 14: Images predation events observed by the drop camera system used in May 2023. The top two images are of crabs, the bottom left image is of a starfish, and the bottom right image is of a moonsnail.

4.5. Management Implications

Collectively, this research indicates that transplanting sea scallops from high-density, growth limited areas to more favorable environments can yield substantial biological and economic benefits. Transplanted scallops exhibited accelerated growth and redistributed into a broad but coherent footprint but remained above commercially viable density thresholds, mitigating concerns about excessive dilution. The coupled spatial and bio-economic simulations demonstrate that transplanting can convert low-value, slow-growing biomass into higher-value product across a wide range of market and mortality scenarios. Together, these findings support transplanting as a viable, though context-dependent, tool for enhancing scallop productivity under conditions of unpredictable recruitment.

Successful implementation depends on several key criteria:

- **Site Selection:** The destination must offer a thermal regime distinct enough to trigger the compensatory growth response observed in Year 1.
- **Stocking Intensity and Size Structure:** Adequate biomass and shell height are required to offset dispersal and predation.
- **Mortality Control:** Incidental mortality is the strongest negative driver of economic performance. Investments in gear modification or handling protocols to keep mortality below the 25–30% range yield high returns on investment.
- **Economic context:** Managers must explicitly consider the opportunity cost of the source bed, particularly under high market prices.

4.5.1 Site Selection across the Range of the Resource

Several regions across Northwest Atlantic exhibit coastal and oceanographic characteristics that may support sea scallop enhancement while minimizing conflicts with other ocean users. The Gulf of Maine has numerous sheltered nearshore areas landward of barrier islands where scallops occur naturally and where rocky substrates limit the use of bottom-tending fishing gears. The cooler bottom-water temperatures in this coastal region also tend to remain within suitable ranges for scallop growth throughout the year. These characteristics have led to the greatest development of hatcheries and advancements in Atlantic sea scallop aquaculture techniques in the United States. However, despite its suitability for suspended and contained aquaculture, the Gulf of Maine's steep bathymetry and extensive rocky substrate reduce its applicability for large-scale bottom-sowing approaches.

In contrast, several physical and oceanographic features of Cape Cod Bay make this region well suited for both aquaculture and bottom-sowing enhancement strategies. Cape Cod Bay is a semi-enclosed embayment, relatively free of user conflict with existing aquaculture facilities, and cooler waters originating from the Gulf of Maine. Similar to Funka Bay in Japan, Cape Cod Bay may serve as an effective spat collection and grow-out site, with the additional advantage of proximity to heavily fished offshore grounds on Georges Bank and surrounding waters.

Another region with potential for sea scallop enhancement is the Mid-Atlantic coastal zone between Delaware and New York. Seasonal stratification within this region maintains relatively cooler bottom water temperatures in nearshore waters (Chen et al. 2018), an area that has experienced poor natural recruitment for several years (Hart et al. 2020). Transplanting scallops from offshore waters into this cold pool may enhance survival and growth by alleviating thermal stress during the summer months, a stressor expected to intensify as climate change continues to reduce habitat suitability across the Mid-Atlantic shelf (Rheuban et al. 2018).

4.6. Considerations for Allocating Transplanting Resource

Instead of exclusive ownership rights to transplanted scallop resources, if scallop enhancement activities are funded through an enhancement set-aside then transplanting the resulting scallop resource should be considered a publicly owned good. Under this framework, enhanced scallops would be harvested under the same regulatory structure as wild scallops, with no distinction made between naturally recruited and enhancement-derived individuals. Permitted vessels would therefore be allowed to harvest both components of the population in accordance with existing fishery regulations, eliminating the need to define or enforce individual property rights associated with enhanced stocks.

Management oversite could incorporate temporary enhancement area closures to allow sufficient periods of growth prior to harvest, following similar process to the current rotational area management program. Analogous to Research Set-Aside programs, enhancement set-aside quota could be allocated based on vessel participation or effort contributed toward enhancement activities within an access area. Overall, treating enhancement set-asides as a form of public investment provides a more efficient and equitable mechanism for scaling scallop enhancement while maintaining alignment with existing management frameworks.

4.7. Bioeconomic Model Limitations and Future Work

The simulation presented in this report assumes constant environmental parameters for the projection period. Future model iterations would benefit from incorporating stochastic environmental variability (e.g., temperature anomalies), which may influence growth trajectory and the calculation of Optimal Temperature Days. Furthermore, the inclusion of the redistribution kernel allows for the integration of density-dependent predation via a 2D Holling Type II functional response (Barbeau and Caswell 1999). Incorporating this mechanic would enable managers to quantitatively assess the potential economic benefits of predator control strategies and better assess how predator–prey interactions influence the long-term efficacy of transplanting-based enhancement.

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6. Appendix

Table A1: Stochastic parameters for the Bioeconomic Monte-Carlo simulation.

Category	Parameter	Variable	Value / Distribution	Description	Source
Biological	Mean Shell Height	μSH	94.12±9.3 mm	Initial size at release (Normal)	Field Data
	Year 1 "Shocked" Growth Rate	GR_{Y1}	0.0189±0.0164	Linear daily growth increment (Truncated Normal)	Tag-Recapture Data see Table
	Natural Mortality	M	0.15−0.45	Dynamic; size-based decay function	Hart & Chang 2022
	Incidental Mortality	$r_{incidental}$	25%±5%	Loss from handling (Normal)	Field Data
Environmental	Site Depth	D_{site}	49.7±0.46 m	Determines Temp Strata & Meat Weight	Field Data
	NLS-Deep Depth	D_{deep}	75.0±1.04 m	Baseline for Opportunity Cost	Kowaleski et al., 2024
	Thermal Window		8 C−12 C	Range for Optimal Temperature Days	Zang et al., 2022
Operational	Initial Release	$N_{released}$	550,388	Total quantity of scallops transplanted	Field Data
	Seed Cost	C_{seed}	\$0.06−\$0.12	Handling price per seed (Uniform)	Industry Input
	Vessel Rate	R_{vessel}	\$4,000−\$6,000	Daily charter cost (Uniform)	Industry Input
	Fuel Cost	C_{fuel}	\$1,500−\$2,500	Daily fuel expenditure (Uniform)	Industry Input
	Days at Sea	T_{DAS}	6±1 days	Initial duration of transplant effort	Field Testing
Market	Harvest Threshold	τ	0.2/m²	Minimum density for viable harvest	-
	Market Price	P_{mkt}	\$8.50−\$21.50	Stochastic price based on Meat Count	BASE Auction Data

Table A2: Model selection table for the gain logistic model.

Model Candidate	Intercept	Slope	AIC	ΔAIC
Center_Dist^3	-1.37	0.01	758.85	0
Center_Dist^2	-0.58	0	760.46	1.61
Center_Dist^2 + anisotropy	-0.52	0	761.35	2.5
Center_Dist^2 + ρ	-0.82	0	761.47	2.62
Center_Dist^2 + anisotropy + ρ	-0.76	0	762.28	3.43
Center_Dist * anisotropy	0.13	0	763.04	4.19
Center_Dist + anisotropy	0.09	0	763.43	4.58
Center_Dist	0.11	0	763.97	5.12
Center_Dist * ρ	0.25	0	764.39	5.54
Center_Dist + anisotropy + ρ	-0.12	0	764.56	5.71
Center_Dist + ρ	-0.08	0	765.19	6.34
Drop_Dist^2 + anisotropy + ρ	-0.48	-0.02	773.88	15.03
Drop_Dist^2 + ρ	-0.47	-0.02	775.76	16.91
Drop_Dist^2 + anisotropy	-0.04	-0.02	778.72	19.87
Drop_Dist^2	-0.02	-0.02	780.54	21.69
Drop_Dist^3	0.2	-0.02	781.08	22.23
Drop_Dist + anisotropy + ρ	-1.34	0	791.98	33.13
Drop_Dist + ρ	-1.32	0	793.88	35.03
Drop_Dist * ρ	-1.43	0	795.44	36.59
Drop_Dist * anisotropy	-0.83	0	801.81	42.96
Drop_Dist + anisotropy	-0.85	0	801.9	43.05
Drop_Dist	-0.83	0	803.95	45.1

n = 806

Table A3: Model selection for the exponential gain model.

Model	k	AIC	ΔAIC
Gaussian	2	411.81	0.00
Exponential	2	412.63	0.82
Power	2	413.09	1.28
Exp. with ρ	3	414.60	2.80

Table A4: Model selection table for the loss logistic model.

Model Candidate	Intercept	Slope	AIC	ΔAIC
Drop_Dist * ρ	-3.06	0.01	525.61	0
Center_Dist * ρ	-2.66	0	541.28	15.67
Center_Dist^2 + ρ	-0.49	-0.01	545.16	19.55
Center_Dist^2 + anisotropy + ρ	-0.37	-0.01	545.25	19.64
Drop_Dist^2 + ρ	-1.19	-0.02	547.88	22.27
Drop_Dist^2 + anisotropy + ρ	-1.16	-0.02	549.43	23.82
Center_Dist + ρ	-1.68	0	560.53	34.92
Drop_Dist + ρ	-2.07	0	561.49	35.88
Center_Dist + anisotropy + ρ	-1.65	0	562.59	36.98
Drop_Dist + anisotropy + ρ	-2.05	0	563.57	37.96
Drop_Dist^3	0.94	-0.05	583.6	57.99
Center_Dist^2 + anisotropy	1.2	-0.02	588.04	62.43
Center_Dist^3	0.23	0	588.57	62.96
Center_Dist^2	1.12	-0.02	591.13	65.52
Drop_Dist^2 + anisotropy	0.22	-0.03	594.19	68.58
Drop_Dist^2	0.23	-0.03	595.33	69.72
Center_Dist * anisotropy	-0.03	0	605.61	80
Center_Dist + anisotropy	-0.06	0	607.31	81.7
Center_Dist	-0.05	0	608.02	82.41
Drop_Dist + anisotropy	-0.7	-0.01	628.54	102.93
Drop_Dist	-0.69	-0.01	629.93	104.32
Drop_Dist * anisotropy	-0.72	-0.01	630.91	105.3

n = 763

Table A5: Model selection for the exponential loss model.

Model	k	AIC	ΔAIC
Exp. with ρ	3	667.52	0.00
Gaussian	2	750.00	82.48
Exponential	2	753.12	85.60
Power	2	767.32	99.80