Fisheries Research 280 (2024) 107163

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Integrating *in situ* environmental covariates in an American lobster catch model to improve impact assessment

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A R T I C L E I N F O

Handled by: Richard Andreas Wahle

Keywords:
Generalized additive models
Fishery characterization
Offshore wind
BACI

A B S T R A C T

The installation and operation of floating offshore wind power is an integral component of societal transition to renewable energy generation where fixed bottom offshore wind is not possible. However, it will cause unique ecosystem changes. To disentangle the effects of offshore wind installations from the concurrent effects of climate change and the fishing practices on commercially significant resources, we must develop detailed characterizations of the resources before development occurs. In the Gulf of Maine, American lobster is the most commercially and culturally important fishery. At the time of writing, this is the largest fishery by value in North America. Our understanding of baseline localized parameters (such as catch per trap at the spatial scale of individual turbines) should be informed by relationships to environmental, biological, and survey-specific functional drivers of catch. A more mechanistic understanding of catch will allow for strategic adjustments to Post-Deployment fishery responses and ultimately, the development of research- and commercial-scale floating offshore wind development. Here, we used survey data from the New England Aqua Ventus Pre-Construction Commercial Trapping Survey to develop Generalized Additive Models describing seasonal catch per trap for legal and sublegal lobsters. We found fall catch to be nearly twice that of spring. Bottom temperature dynamics could be used to predict catch, and the Fall survey was associated with a warmer temperature regime. By using analytical tools that incorporate environmental heterogeneity, we developed monitoring methods from pre-construction baseline data that will be applicable over the post-construction operating period of an offshore wind farm.

1. Introduction

The nascent US offshore wind (OSW) industry was recently encouraged by a Biden Administration Executive Order to double the amount of installed offshore wind power, with an updated goal of 30 GW by 2030 (E.O. 14008, 2021; The White House, 2021). The United States has over 50 GW of OSW power in the pipeline, but only 42 MW is currently installed (Musial et al., 2023). More broadly, over 59 GW of OSW power has been installed with an additional 427 GW in the global pipeline, where China and the UK lead in recent deployment capacity (Musial et al., 2023). While the development of OSW is a necessary component of the societal transition to renewable energy and, in turn, a solution for the significant changes in marine ecosystems caused by climate change, the development of these projects may also cause changes in marine ecosystems (Carey et al., 2020; Hutchinson et al., 2020a; Farr et al., 2021; Zupan et al., 2023). To determine whether measurable changes to existing resources occur will require a two-fold understanding of both the baseline resource abundance and the nature and magnitude of expected changes at higher trophic levels. The American lobster (*Homarus americanus)* fishery landed $730 million in ex-vessel value (value of landings at first purchase) in 2021 in Maine alone (ME DMR, 2022) making it the most valuable single species fishery in the US (NEFSC, 2020). Like many fisheries, the Maine industry consists of owner-operator small businesses; so quantifying changes that impact

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https://doi.org/10.1016/j.fishres.2024.107163
Received 31 March 2024; Received in revised form 23 July 2024; Accepted 21 August 2024
Available online 12 September 2024

fishery targets or operations will be important in ensuring equitable outcomes of wind development for fishery participants (Dayton and Tokunaga, 2023).

The Holderness Fishing Industry Group at Westernmost Rough Wind Farm in the UK conducted the most comprehensive fixed gear lobster fishery survey at an offshore wind installation to date (Roach et al., 2018; Roach et al., 2022). They did not find lasting significant impacts to European lobster (*Homarus gammarus)* catch rates due to the wind farm when compared to a control site, although catch increased during the construction period's fishery closure (Roach et al., 2018). Holderness Fishing Industry Group performed long term monitoring over six years (the maturation timescale for European lobsters) with one pre-construction and three post-construction surveys to determine whether potential impacts to larval life stages during pile-driving could be observed in survey catch six years later (Roach et al., 2018; Roach et al., 2022). While European and American lobster fishery operations are comparable with similar gear and vessels, European lobster catch rates are much lower than that of American lobster in the Gulf of Maine (GOM), and extrapolating expected impacts to catch from one species to another would be uncertain given the varied responses crustacean species have exhibited under offshore wind development (Carey et al., 2020; Hutchinson et al., 2020b; Perry and Heyman, 2020). Additionally, the Westernmost Rough Wind Farm consists of fixed-bottom turbines with a smaller infrastructure footprint than the floating systems that will be deployed in the Gulf of Maine. The ecological changes associated with fixed-bottom turbines radiate in decreasing gradation from structures (HDR, 2020), while impacts to fixed gear fishery operations and ecological change within a floating offshore wind (FOSW) turbine footprint with multiple infrastructure components (i.e., anchors, mooring lines, and floating substructure) remain unknown.

To develop a baseline understanding of lobster catch dynamics at a designated FOSW demonstration site, where the University of Maine and Diamond Offshore Wind plan to deploy New England Aqua Ventus I (NEAV I), we conducted a pre-construction commercial trapping survey in fall 2021 and spring 2022. We partnered with local Monhegan Island fishermen to implement the survey, which is the "before" or baseline period of a Before-After Control-Impact study examining potential impacts of NEAV I on commercial fishing. The Monhegan Island Lobster Conservation Area (MILCA) is a restricted fishing area subject to seasonal closures and as such presents a unique opportunity to study lobster dynamics in a small-scale system with less heterogeneity than the larger Gulf of Maine lobster fishery (Wilson, 2010). We used Generalized Additive Models (GAMs), a flexible spline regression modeling scheme, to consider possible environmental, ecological and survey design drivers of fishery outcomes. Offshore wind projects have an expected lifespan of 20–25 years, and resource monitoring must consider disentangling climate change and fishery responses from development impacts. To begin this process, we must first contextualize baseline fishery catch relative to current conditions using tools that can incorporate environmental heterogeneity over time. Here, we present and contextualize baseline American lobster catch dynamics in one of the most valuable and climate sensitive fisheries globally that is simultaneously the future site of multiple floating offshore wind demonstration and commercial projects.

2. Methods

2.1. Survey design

There are multiple survey design approaches used to assess resource impact from OSW projects, including Before-After Control Impact (BACI) and Before-After Gradient (BAG) (Methratta, 2021). We considered the spatial scale of a single FOSW turbine and associated infrastructure along with recent precedents involving lobster fishery surveying at OSW sites (Stokesbury, 2020; Roach et al., 2022) and determined that a BACI commercial trapping survey design was appropriate. BAG designs look to survey a potentially impacted site and additional sites with increasing distance to detect a gradient in impact. This approach may be a logical choice for detecting an effect at an array level when it is unlikely a control site of similar size and habitat diversity can be identified. In the case of a single turbine where impacts are expected to be highly localized and related to different infrastructure components (i.e. anchors, mooring lines, and substructure) we felt the BACI approach was stronger because it investigates site-scale differences before and after project deployment. Including the control region allows larger-scale interannual variations in catch, outside of the scope of turbine effects, to be included in impact models. However, identifying an appropriate control site is complicated. Ultimately, we used an expert elicitation approach by consulting with Monhegan lobsterman to identify a location with similar depth range, bottom characteristics, and catch history to the FOSW site (Hillyer et al., 2021; Roach et al., 2022).

As the baseline period of our BACI study of lobster fishery dynamics in the MILCA, we performed a pre-construction commercial trapping survey in collaboration with fishermen during the Fall (October 10 - November 21, 2021) and Spring (April 21 - May 27, 2022). The MILCA is harvested exclusively by Monhegan Island lobster boats and is the one of few GOM regions with seasonally restricted lobster fishing (open October 1- June 7) (Wilson, 2010). The restricted fishing season prevents removal of legal lobsters and reduces handling at the peak of molting in the summer, resulting in unique lobster population dynamics relative to the rest of the GOM fishery (Grabowski et al., 2010). The MILCA fishery primarily operates during fall and spring "shoulder seasons." Our sampling periods coincide with the local peaks in seasonal fishing intensity to fully characterize the potential for FOSW development to affect commercial operations in the MILCA. We used a random stratified grid sampling approach, employing paired *vented*, standard industry lobster traps (i.e., 1.2 ×0.6 ×0.4 m with 3.8 cm. mesh, 3 parlors, 3 bricks and 3 escape vents for Sublegal lobsters constructed with 17.8 cm entrance heads), and *ventless* traps (the same dimensions without the escape vents) to quantify and model seasonal legal and sublegal catch-per-unit effort in each grid space sampled (Stokesbury, 2020).

2.2. Study sites

The survey control and test sites were 1 ×1 km (1 km^2) regions within the MILCA, and the future anchor, mooring line, and turbine locations are identified in Fig. 1. The NEAV I test site is centered at

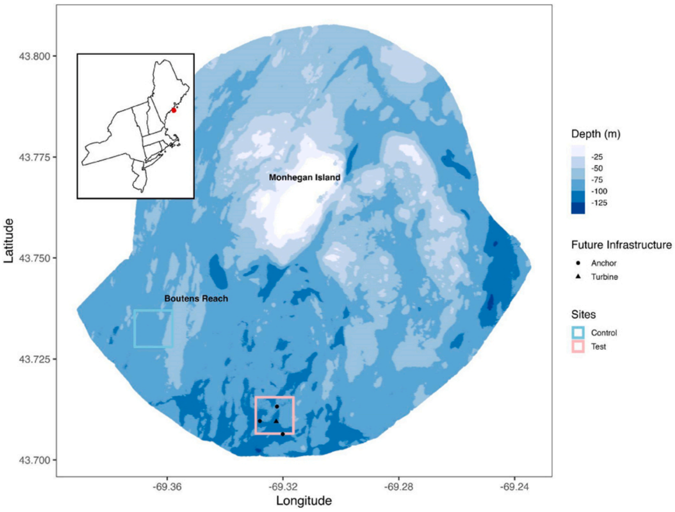

Fig. 1. Bathymetry of the Monhegan Island Lobster Conservation Area (MILCA) with the control and test study sites highlighted. Note that we include the likely location of the floating turbine platform and mooring infrastructure in the test site.

43.7095° N 69.3229° W, located in 90–100 m of water, with bottom type varying between complex hard-bottom and soft-bottom sediments (Fugro, 2021). The test site was identified by the State of Maine through engagement with both stakeholders and relevant state agencies in accordance with legislation implemented to encourage OSW energy development in Maine (Title 12 M.R.S.A. Section 1868). The control site, centered at 43.7325° N 69.3560° W, southwest of Monhegan and west of Boutens Reach was selected through expert elicitation from Monhegan fishermen.

We divided the test and control regions into 6 ×6 grids of 36 0.16 km x 0.16 km (0.0256 km^2) aliquots. Of these aliquots, 18 were randomly selected for sampling in each sampling session to cover 50 % of each site's grid (Fig. 2). As opposed to fixed monopile OSW turbines, FOSW structures will include more complex subsurface infrastructure, including three anchors embedded beneath the benthos that are connected to the floating platform by hybrid catenary chain synthetic-rope mooring lines (West et al., 2023). Randomized site stratification protects against biasing results through targeted sampling (HDR, 2020), while allowing for sampling of multiple potential impact sites introduced by the presence of a FOSW turbine. Targeted sampling with a distance gradient can detect radiating effects of a turbine but is less suitable for discerning local fishery impacts when fishing patterns are not structured in this way.

2.3. Stakeholder engaged commercial trap survey

Survey traps were baited with three Atlantic menhaden (*Brevoortia tyrannus*) and deployed as pairs consisting of a vented and a ventless trap. By using these two trap types, we were able to sample a large range of commercially relevant size classes. Industry standard lobster traps target legal-sized (83–127 mm Carapace Length (CL)) lobsters and have escape vents that allow sublegal (< 83 mm CL) lobsters to exit traps, while ventless traps can effectively sample the smaller size classes that consist of future recruit populations (Jury et al., 2019). Thus, previous research has found sampling with both vented and ventless trap types to capture a wider size-range of commercially-relevant lobsters (Courchene and Stokesbury, 2011).

Our fishing protocol and gear matched the local fleet wherever possible. We fished each pair of co-located traps on ~ 120 m of warp line with traps separated by ~ 40 m of groundline. Lines were rigged with a standard weak link configuration per Maine Department of Marine Resources regulations chapter 75.02, Section 3. Additionally, the lines featured ~ 0.9 m of pink marking within 4 m of the buoy and 30.5 cm pink marking at the top and bottom of the line, at the request of the NOAA Atlantic Large Whale Take Reduction Team (NOAA ALWTRT). The additional pink marking allowed survey gear to be identified as non-commercial in case of whale entanglement.

Each trap pair was also equipped with a HOBO temperature logger (HOBO Pendant UA-MX2203) on the tailing trap (the trap attached to the groundline rather than the buoy endline) to record bottom temperature every 10 minutes during deployment. GPS locations were recorded (Garmin GPSMAP 76sc) at the surface for each trap pair to match each trap to depth and bottom characteristics from previous multibeam surveys at each site (Wilson, 2010). The Fall and Spring sampling sessions lasted roughly six weeks and traps were hauled on a biweekly basis with a target four night soak. Occasionally, soak times varied due to inclement weather and we incorporated soak time into model development to standardize effort. We sampled the randomly-stratified locations at each site 7–9 times. For each pair of traps hauled, the trap ID number and location (in decimal degrees) were recorded and the catch was emptied into buckets. Size (carapace length (CL) in mm), sex, shell condition, cull, v-notch (a man-made mark on the tail preventing harvest and denoting reproductive status of females), and egg status or mortality were recorded by voice for transcription (Reardon et al., 2018; Carey et al., 2020; Stokesbury, 2020). We tagged live lobsters in the musculature beneath the carapace with red Floy

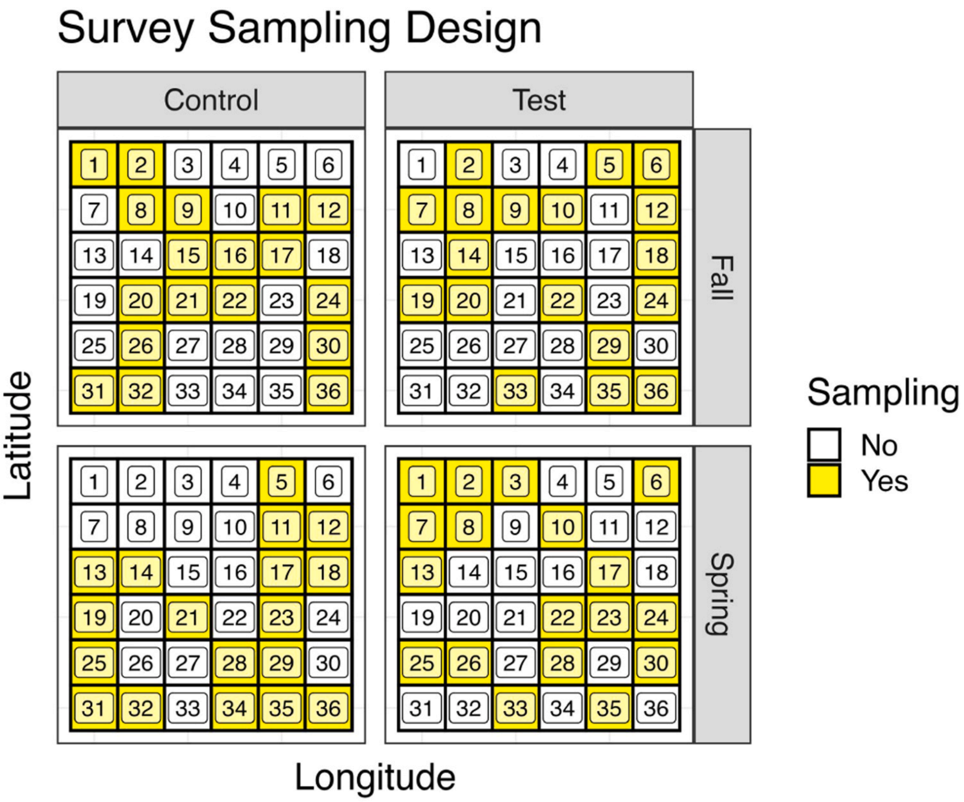

Fig. 2. An example randomized grid sampling selection used throughout the 2021–2022 Fall and Spring commercial trapping survey sessions at the control and test sites.

T-bar FD-94 tags, and the unique tag numbers were recorded to perform mark-recapture analyses. Tags were inserted at the base of the carapace above the abdomen and were offset from the center to avoid the lobster's nervous system (Skerritt, D., pers. comm., 2021). Previously tagged lobsters had their tag number recorded and were considered a 'recapture.' While by-catch was identified, enumerated, measured, and released for each trap (including the carapace length of the first five Jonah crabs in each trap (i.e., the most frequent other species captured in the survey) and fork length of all finfish; tagging and by-catch results were beyond the scope of this study.

2.4. Data analysis

We examined the legal catch per trap and sublegal catch per trap grouped by trap type (i.e., vented and ventless), site (i.e., test and control), and season (i.e., fall and spring). We used F-tests of equal variance to compare catch rate between groups. For groups with unequal variances (all groups tested), Kruskal-Wallis tests were used to determine significant differences in group medians. By examining time-series and size distributions of grouped data, we characterized season and site-specific catch dynamics and lobster population structure during each survey.

Before modeling catch response variables, observations of catch per trap at locations with benthic slopes $> 20^\circ$ were removed. While random stratified sampling results in a more robust survey design, it can also result in gear deployed in areas that fishermen would generally avoid including high relief habitat that may cause gear to not fish properly. Excluding this data resulted in the loss fewer than 10 samples per group from the dataset and when practicable should be avoided during site selection. We excluded survey days 32 and 35 from the spring survey (5/23/22 and 5/26/2022) due to suspected tampering with survey traps at the future wind site. The test region is located on the edge of the MILCA bordering the fishing territory of another harbor. While territoriality has decreased relative to past conditions (Acheson and Gardner, 2004), offshore wind projects are currently controversial among fishermen, and it is possible that this survey and future surveys could be subject to difficulties with gear or reporting.

To link environmental and fishery conditions to lobster fishery dynamics, we described functional drivers of catch per trap (Table 1) using Generalized Additive Models (GAMs) developed for each season (Fall, Spring) and size-class (Sublegal, Legal) combination. Due to interannual variability in the changing GOM, understanding functional relationships between covariate terms in the model and catch response variables will provide necessary context to post-deployment data that will improve our ability to detect a change in catch due to the project's operation.

2.5. Generalized additive model development

Full GAMs describing response variables were first run with all candidate covariates (Table 1): depth, benthic slope, local temperature anomaly (i.e., site averaged temperature minus trap specific temperature used to account for small spatial variability within sites), trap temperature, tidal height, soak time, trap type and, when feasible, biological terms influenced by the composition of lobsters in a trap (trap-specific sex ratio, and molt ratio). Categorical covariates such as trap type were included in the model as linear intercepts, while continuous covariates were modeled as smooth 1D splines and thin plate splines of multiple covariates combined as surfaces (i.e., the combined sex ratio/molt ratio function and latitude/ longitude function) (Wood et al., 2016). Spline functions were developed with five knots, or turning points within the function, to prevent fitting unrealistically complicated relationships. Thin plate splines describing latitude and longitude were an exception in that we allowed ten knots to describe complex spatial relationships not captured by other covariates. Soak time was defined with three knots as there were not enough unique soak time values over the survey to define a four or five knot function. We gave the function fewer potential degrees of freedom than allowed in previously published models of American lobster catch dynamics because the spatial scale of the survey was relatively small (< 10 km) compared with previous GOM-scale analyses (Tanaka et al., 2019b). The full GAMs most likely overfit the data. That is, they resulted in low bias but relatively high variance.

Table 1
Candidate covariate table.

Covariate	Covariate type	Effect type	Description
Percent Female, Percent Soft	Biotic - continuous	Thin plate spline with k = 5 basis functions	Coordinate pair describing trap specific ratio of male (0) to female (1) lobsters and ratio of hard (0) to soft (1) shell lobsters expressed as means
Depth	Abiotic - continuous	Smooth with k = 5 spline basis functions	10-m multibeam bathymetry with GPS referenced pair specific locations
Slope	Abiotic - continuous	Smooth with k = 5 spline basis functions	Calculated with queen case method (8 neighbors) from 10-m multibeam bathymetry using R raster::terrain
Temperature Anomaly	Abiotic - continuous	Smooth with k = 5 spline basis functions	Site averaged temperature minus trap specific temperature
Temperature	Abiotic - continuous	Smooth with k = 5 spline basis functions	Trap specific mean temperature during sampling from HOBO temperature logger
Tidal Height	Abiotic - continuous	Smooth with k = 5 spline basis functions	Mean tidal height over the soak duration calculated from predicted tidal height at NOAA Portland tide station
Latitude / Longitude	Abiotic - continuous	Thin plate spline with k = 10 basis functions	Handheld GPS measured coordinates during trap haul
Soak Time	Survey design - discrete	Smooth with k = 5 spline basis functions	Number of nights between hauls, or soak time
Trap Type	Survey design - categorical	Linear effect	Specifies ventless or vented trap
Site	Survey design - categorical	Linear effect	Specifies test or control site

For each response group (season and size combination), we developed models using two approaches: (1) a two-stage GAM and (2) a Tweedie GAM. The approaches used are commonly employed to deal with zero-inflated or overdispersion in an ecological response variable and were informed by the right-skewed and zero-inflated distribution we identified for all of our catch response variables (Figure S1). To use the two-stage GAM approach, two separate models were developed for each response group. The first describes presence and absence as a probability of presence using a binomial distribution; the second describes catch at sample observations for catch > 0 using a Gaussian distribution. The predictive results from these two models were multiplied to predict catch adjusted for probability of lobster presence. The Tweedie GAM was developed using all catch data, including catch $= 0$, preventing the inclusion of covariates which only have value for traps that have catch > 0. Models developed using the Tweedie distribution had a power parameter between 1 and 2, which assumes a compound Poisson-Gamma distribution and gamma set to 1.4 to prevent overfitting (Tanaka et al., 2019b; Coleman et al., 2022). The Tweedie distribution, similar to a 2 Stage, approach is increasingly being used to describe model error and has shown increased stability in errors and thus improved predictive power over Gaussian assumptions in previous studies (Shono, 2008). Finally, for each response group, a final model was selected for use from the fully-developed approaches based on cross-validation.

To mitigate the low bias but high variance tradeoff, we simplified the full initial GAMs. First, we checked full models for concurvity between covariates and eliminated covariate pairs hierarchically with scores of > 0.8 (Dormann et al., 2013). Then, models were refined by iteratively removing insignificant terms using a p-value threshold of 0.05. For each initialization, the term with the highest p-value was removed until the Akaike's Information Criterion (AIC) did not improve or all remaining terms were significant. The developed models were then tested with the inclusion of spatial covariates to determine whether site differences were present for the response group. If this further improved the model, a thin plate spline function of longitude and latitude was fit with ten knots to describe spatial dynamics not captured by other covariates. The developed model was selected based on AIC score and used in cross-validations for comparison between methods.

2.6. Cross-validation

We cross-validated each model by randomly sampling 80 % and 20 % of the survey data to create a training and test dataset, respectively. The training dataset was used to initialize the appropriate fully-developed model selection for the given refinement, or model simplification, approach and response group (i.e., season and size combination). Then the test dataset and model training results were used to predict modeled catch values. A linear model was then developed for each test validation describing how well modeled values matched observations. In theory, a perfect model would provide an intercept of 0, slope of 1, and R^2 of 1. This process was iterated 100 times and the mean of these values was used to assess model performance (Tanaka et al., 2017). Finally, for each response group, a final model was selected for use from the three fully-developed approaches based on cross-validation performance.

3. Results

3.1. Descriptive catch statistics

Legal lobster catch was significantly greater in the fall than spring surveys (Fig. 3). The median fall legal catch per trap was three times that of the spring survey indicating surveys sampled from different population structures (3.34 ± 0.09 and 1.82 ± 0.06 Kruskal-Wallis, $p < 0.001$; F-test of variance, $p < 0.001$). We detected no significant differences in legal catch per trap between sites during the spring, but catch in the test site was 22 % higher than the control site during the fall (3.66 ± 0.13 and 2.99 ± 0.11 with a range of 0–12 and 0–9 respectively lobsters trap^{-1}, Kruskal- Wallis, $p < 0.001$). The primary cause of the test site's relatively higher legal catch was a 78 % increase in mean catch in vented traps between during survey day 23 and 29 (Nov. 2 and Nov. 8) sample sessions (Fig. 3).

In contrast to legal catch per trap, sublegal catch per trap dynamics varied less between fall and spring surveys (Fig. 4). Sublegal catch per trap was over five times higher in ventless than vented traps during both seasons at both sites (15.1 ± 0.3 and 3.27 ± 0.12 lobsters trap^{-1} respectively, Kruskal- Wallis, $p < 0.001$). However, trap type specific catch rates were generally similar across sites. While fall sublegal catch per trap was higher than legal catch per trap (9.85 ± 0.36 and 3.34 ± 0.08 lobsters trap^{-1} respectively), the change in catch per trap following break up of water column stratification (29 % increase) was not at the same level as the legal catch response, indicating the legal catch dynamics were more sensitive to bottom water temperature increases than sublegal catch.

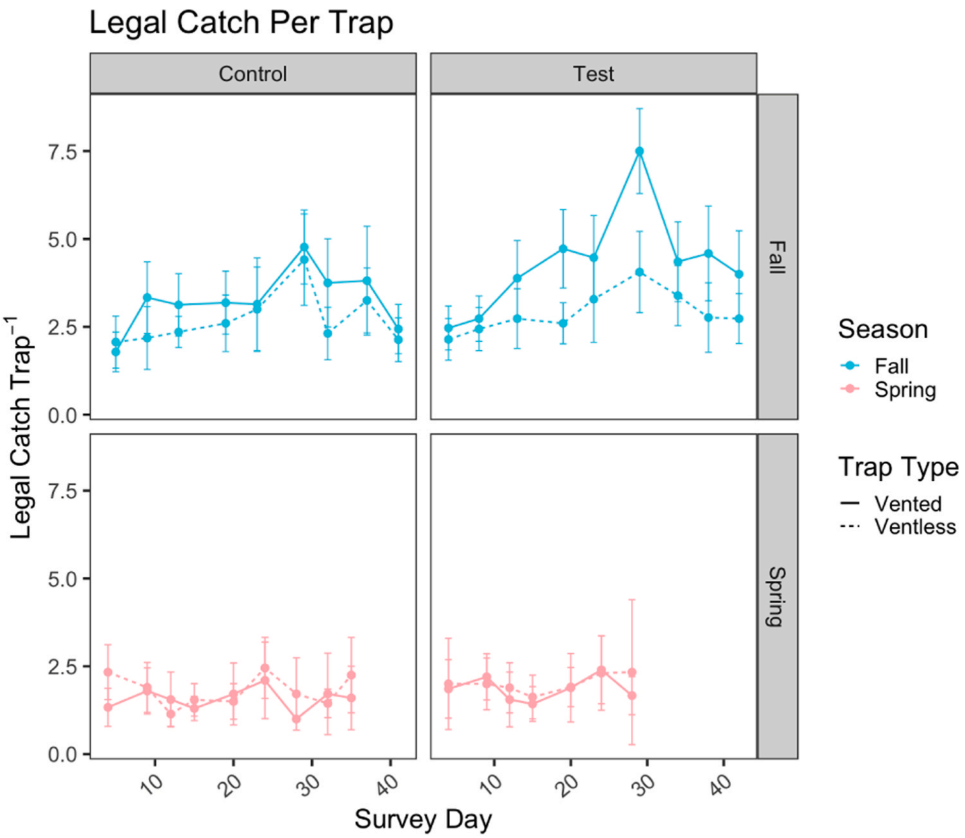

Fig. 3. Time series of mean legal catch per trap +/- standard deviation at control and test sites during the Fall and Spring surveys, survey day: 4–42 (Oct. 14 - Nov. 21, 2021) and 4–35 (April 25 - May 27, 2022). (Test site data from survey days 32 and 35 (5/23/22 and 5/26/22) is excluded due to suspected tampering.).

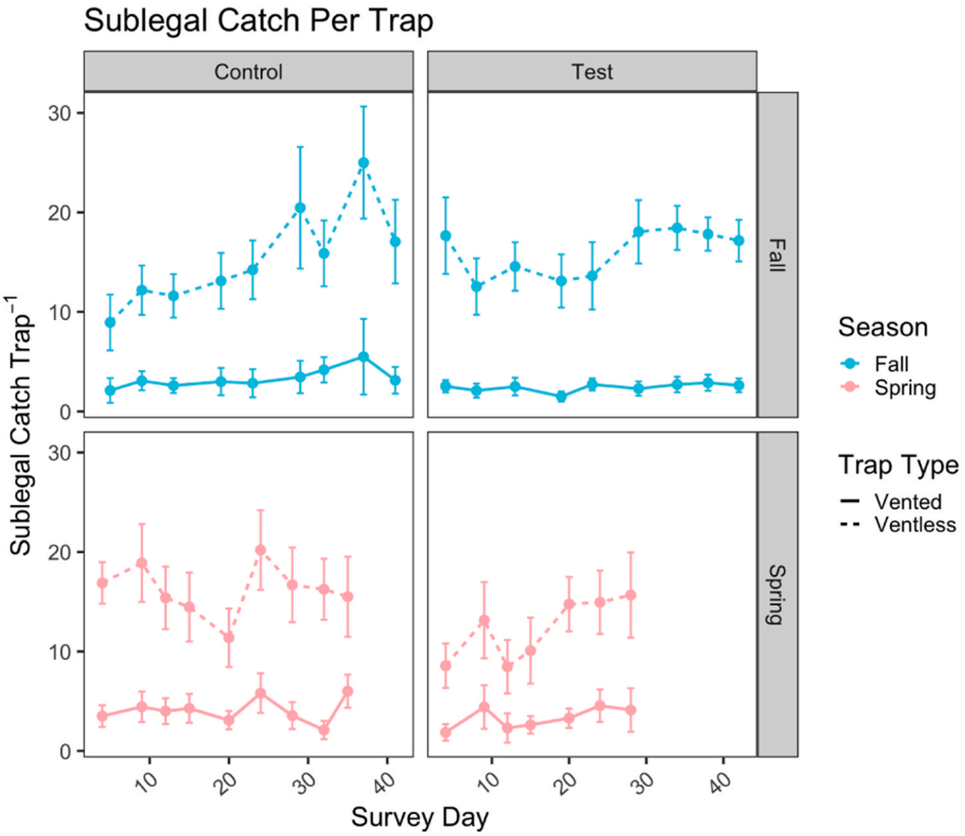

Fig. 4. Time series of mean sublegal catch per trap +/- standard deviation (Vented and Ventless) at the control and test sites during the Fall and Spring surveys, survey day: 4–42 (Oct. 14 - Nov. 21, 2021) and 4–35 (April 25 - May 27, 2022), respectively.

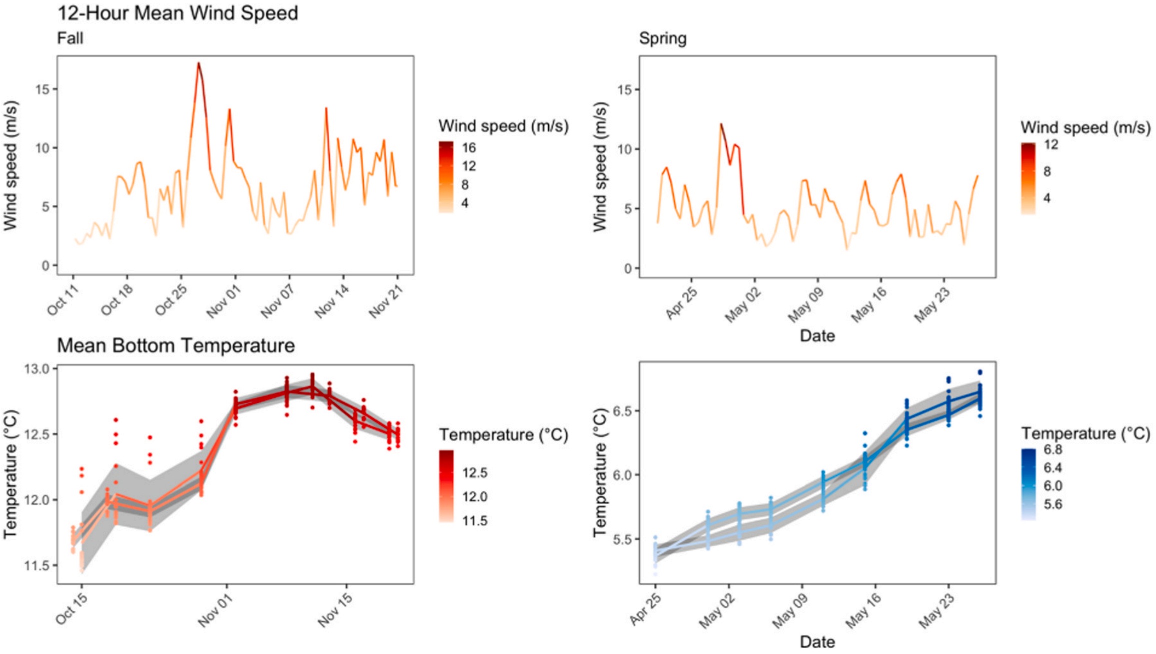

Fig. 5. Time series of mean bottom temperature (°C) (Left) and mean wind speed (m/s) (Right) during Fall (Top) and Spring (Bottom) surveys at control (Inner Left) and test (Inner Right) sites. Bottom temperature is monitored with HOBO sensors on each pair of deployed traps and averaged over each soak duration. Individual points represent trap-level mean temperature, while line values plot the site-level mean temperature and the shaded region represents the site-level mean +/- standard deviation over the soak duration. Wind speed was collected by University of Maine Ocean Observing System (UMOOS) Buoy E, accessed via http://gyre.umeoce.maine.edu/ and averaged into 12 hour bins to remove noise.

3.2. Environmental conditions

We observed increases in catch per trap between survey day 23 and 29 following a wind-mixing event. Wind speed was higher in the fall than spring with means and standard deviations of 6.65 ± 0.35 m s^{-1} and 5.02 ± 0.25 m s^{-1}, respectively (Fig. 5). Bottom temperature increased over the course of both surveys; fall survey bottom temperature ranged between 11.5 and 13 °C, and spring bottom temperatures ranged from 5.5 to 7 °C. During spring, the timing of increases in wind speed and increases in bottom temperature did not generally coincide. However, in the fall, wind mixing events and changes in bottom temperature co-occurred. Fall bottom temperature was sensitive to wind mixing due to the development of a well-mixed water column following summer temperature-driven stratification over the course of the survey. Spring bottom temperature was not sensitive to wind mixing due to the stratification between surface and bottom water indicated by differences between surface and bottom temperature (Fig. 6). We observed a fall catch per trap increase of 49 % at both sites following a major wind mixing event. This event resulted in a bottom temperature change of + 1 °C, and we hypothesize fall overturn events are a major functional driver of fall lobster catch dynamics; which Monhegan fishermen on board corroborated.

3.3. Model selection

Cross-validation demonstrated that the fully-developed Tweedie GAM made higher quality predictions and was tightly fit to the 1:1 line over the full range of data in comparison to the other models (Fig. 7). R^2 values from our cross validation approach were higher in the two-stage versus the Tweedie GAM (0.33 and 0.24 respectively); however, these models overpredict data between 0 and 2 legal lobsters per trap with higher percent error relative to the Tweedie GAM (52 and 11 mean % error respectively for observed values = 1; Fig. 7). Thus the Tweedie GAM was selected as the model with the lowest percent error when relating fitted values to observed values.

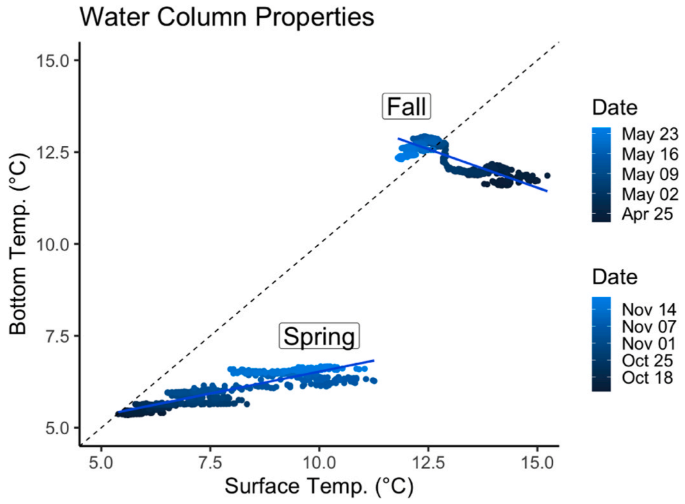

Fig. 6. Surface to bottom temperature (°C) relationship for Fall and Spring surveys. Fall data is from survey day: 1–42 (Oct. 11 - Nov. 21, 2021) while Spring data is from survey day 1–33 (April 22 - May 25, 2022). Bottom temperature is calculated as the 12-hour mean temperature averaged across HOBO temperature loggers at both sites (n = 36 and 35 in Fall and Spring). Surface temperature is from University of Maine Ocean Observing System (UMOOS) Buoy E, accessed via http://gyre.umeoce.maine.edu/ and is averaged into the same 12-hour bins. The 1:1 line is a gray dotted line; when points fall on or near this line, the water column is well-mixed resulting in similar surface and bottom temperatures, while column stratification results in points falling off away from the 1:1 line.

3.4. Model description

The fall legal Tweedie GAM used the full suite of available covariates, describing both linear and non-linear relationships between catch per trap and abiotic conditions. All available covariates were used in the GAM since the removal of any decreased the model's AIC score (Table 2). Partial effects from the covariates were used to understand how catch responded to changes in each covariate assuming other factors remain constant. Temperature, soak time, temperature anomaly, depth and slope generally exhibit positive linear relationships to the partial effect on catch per trap (edf ~ 1.00 for all, Fig. 8). However, the magnitude of associated effects on predicted catch per trap were not equal. For example, for each additional day of soak time past the standard 3-days, we expect an additional 0.1 legal lobsters per trap hauled (3.6 additional lobsters per site over 36 traps), while for each degree of temperature increase, we predict an additional 0.5 lobsters per trap hauled (18 additional lobsters per site over 36 traps). Fall legal catch was particularly sensitive to changes in temperature and temperature anomaly consistent with our observation of increased catch following rapid bottom temperature change from water column mixing. However, depth features the largest range of partial-effect catch responses with a decrease in catch per trap as depth shoals of about + 0.01 legal lobsters per trap per meter increase in depth. Generally, legal lobsters per trap increased when deployed on bottom between 0 and 20° in slope (as we excluded values greater than 20° from this analysis due to poor setting conditions and low data density). We deployed fewer traps at locations greater than 7° slope, but legal catch per trap was highly variable under these conditions, making it difficult to determine whether this relationship was connected to habitat, low sample density, or how well the gear fished on these bottom types. The tidal height covariate describes a parabolic relationship with $2 < \text{edf} < 3$. Tidal height has a minor-to-modest impact on catch, resulting in a slightly increased expected catch per trap when tidal height is at its maximum observed. There is high uncertainty in the tails of modeled relationships between temperature anomaly, slope, and depth to legal catch per trap. The uncertainty arises from continually changing data density along each function, represented by rugs in each subplot, and increased variability of catch observations at extreme values–combining to balloon standard error estimates.

In addition to single term continuous smooth functions, longitude and latitude were included in the model to describe remaining unexplained impacts to catch that may arise due to site differences. The model was initially developed with a categorical effect to describe site differences, but it was improved with the thin plate spline, which describes spatial differences with up to 10 knots. The inclusion of an undefined spatial effect increased the quality of the model, indicating that there was an additional spatially-varying term impacting catch that we did not measure for example, a spatial relation to habitat. In the control site, the dominant catch gradient increased from west to east while at the test site the gradient increased from south to north (Fig. 9). While the slopes of these gradients are perpendicular to one another, they generally follow an orientation of decreasing catch with distance from shore. Including this covariate interaction improves deviance explained from 23.4 % to 26.3 % by providing a representation of spatial dynamics not captured in the other model terms.

The final effect included in the full model described a difference in expected catch per trap due to trap type as linear intercepts. While controlling for the other covariates, legal catch was slightly lower in ventless traps than vented traps. For example, under baseline model conditions, there were 0.33 ± 0.05 fewer legal lobsters per trap in ventless traps than vented traps potentially indicating avoidance of ventless traps by legal lobsters which could arise due to inter or intra-specific competition.

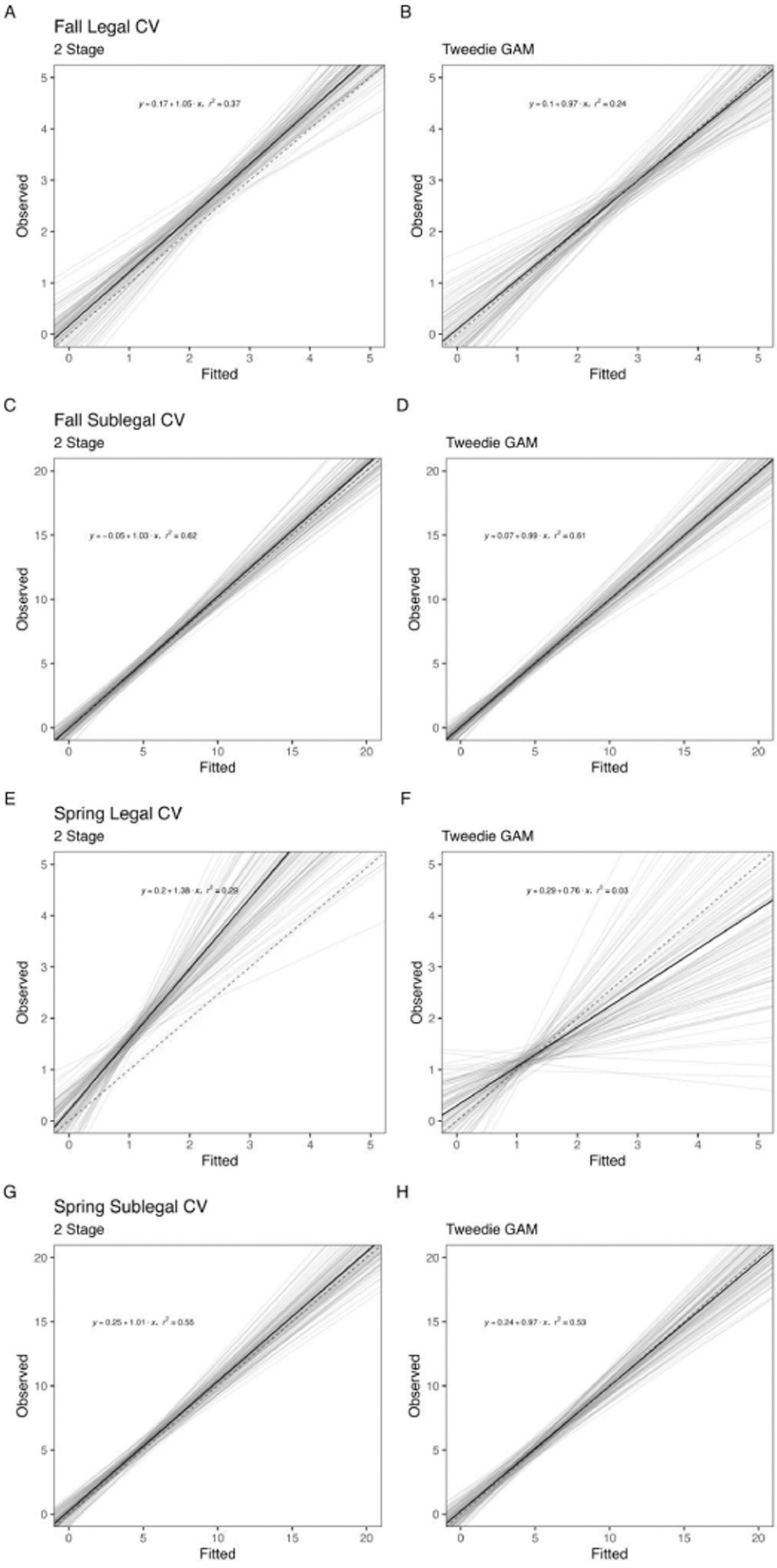

Fig. 7. Cross-validation of all fully-developed 2 Stage GAM and Tweedie GAM for all model response groups, (A-B) Fall Legal, (C-D) Spring Legal, (E-F) Fall Sublegal and (G-H) Spring Sublegal. Each model is cross-validated by comparing observed and predicted values of test data via linear regression 100 times. Mean intercept, slope and R-squared value of the regressions are calculated and presented on the panels. Individual validation fits are plotted in light gray. The mean slope-intercept line between observed and fitted values is plotted in black. The 1:1 line is plotted in dotted red.

Table 2
Fully Developed models describing Fall, Legal catch per trap for each refinement approach used. Model equations are described with s(variable, $k = x$) representing a spline function describing the relationship between the variable and response term with up to x knots, or turning points in the function.

Approach	Group	Iteration	Response Variable	AIC	Dev.Ex.	Equation
2 Stage GAM	Fall, Legal	6	*Presence*	397.16	5.45 %	$Presence \sim s(Temp\ Anom, k = 5) + s(Temps, k = 5)$
2 Stage GAM	Fall, Legal	3	*Catch*	1937.61	44.20 %	$Catch \sim Trap\ Type + s(Effort, k = 3) + s(Molt, Sex, k = 5) + s(Depth, k = 5) + s(Temps, k = 5) + s(TideHeight, k = 5) + s(Lon, Lat, k = 10)$
Tweedie GAM	Fall, Legal	3	*Catch*	1513.52	26.30 %	$Catch \sim s(Lon, Lat, k = 10) + Trap\ Type + s(Depth, k = 5) + s(Effort, k = 3) + s(Slope, k = 5) + s(Temps, k = 5) + s(TempAnom, k = 5) + s(Tide\ Height, k = 5)$

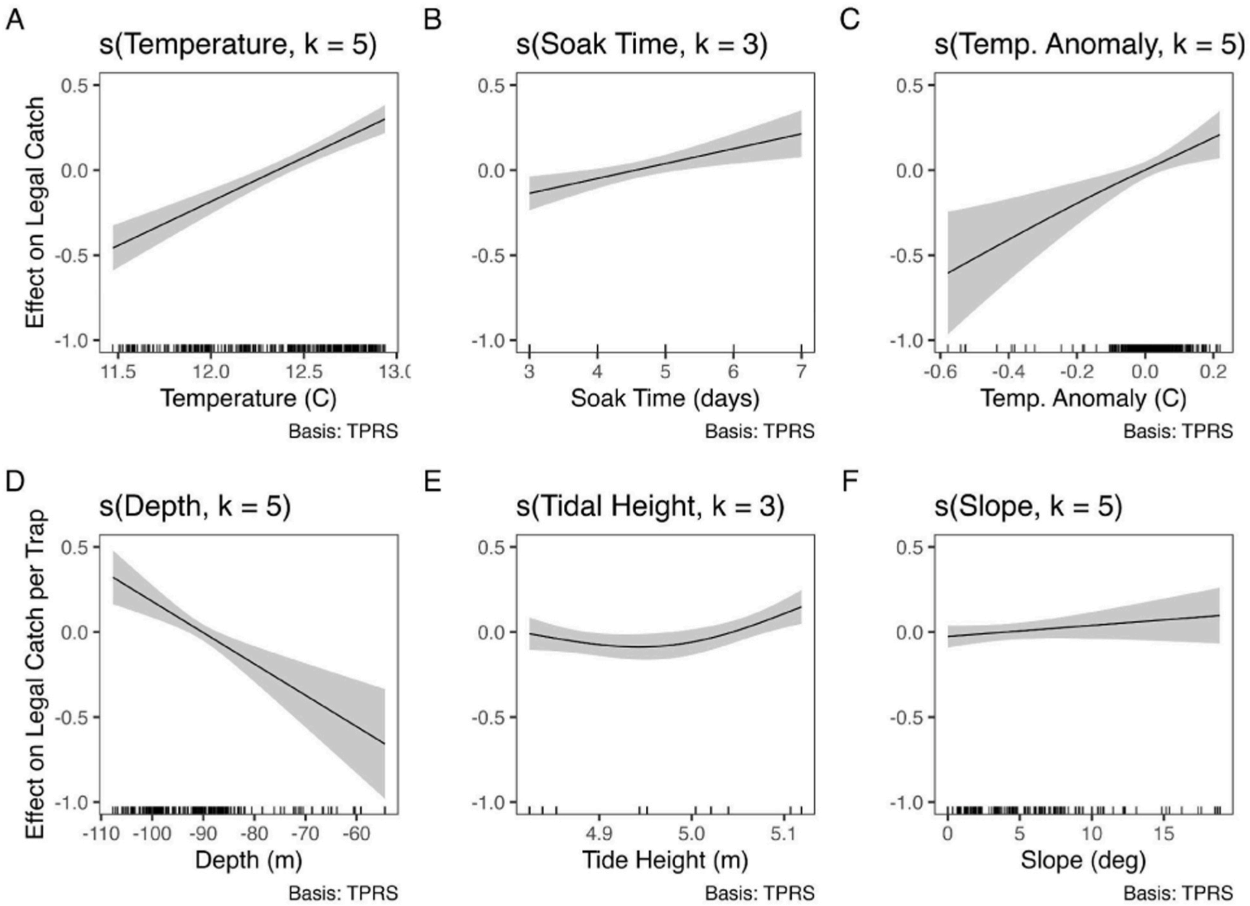

Fig. 8. Partial effects on legal catch per trap of covariates (A) Temperature, (B) Soak Time, (C) Temp Anomaly, (D) Depth, (E) Tide Height and (F) Slope modeled with smooth spline functions from the fully-developed Fall Legal Tweedie GAM model. Standard error estimates over the smooth function are described by the gray shadow around each line. Data rugs along the x-axis represent the density of observations.

4. Discussion

4.1. Fishery mortality, movement ecology, population density, bottom temperature and survey catch

Catch dynamics in trap surveys integrate processes related to catchability, fishery removal, seasonal migration and population density. Consequently, disentangling these components is complicated. However, some attempt at disentanglement is important since characterizing changes in population density, rather than catchability and migratory patterns, before and after offshore wind farm deployments is generally the objective of studies assessing project impacts. The most significant outcome of our survey was the striking reduction in legal catch per trap from fall to spring across sites and trap types (80 % more legal lobsters caught in fall compared to spring; Fig. 3). To effectively describe catch dynamics of a trap survey, we must consider changes in catchability as well as those affecting actual population density. American lobster catchability is often associated with changes in temperature, allowing seasonal cycles to affect expected catch (Miller, 1990; Bell et al., 2001; Courchene and Stokesbury, 2011; Jury and Watson, 2013; McManus et al., 2021).

The MILCA has a restricted fishing season (October 1 - June 7) that does not operate in the summer, a limited number of permits with access, and a lower trap limit than the inshore Maine lobster fishery management zones (i.e., 400 vs. 800 traps [600 traps in Zone E]; ME DMR Ch. 25.95, Ch. 25.10). This has created unique fishery dynamics, allowing the MILCA to be used as a lower fishing mortality reference area for comparisons with adjacent areas fished heavily in the summer (Grabowski et al., 2010; Wilson et al., 2010). Fishery participants are restricted to fishing within the conservation area, creating an even more spatially restricted and localized fishery than frequently seen along the coast of Maine. While OSW development is occurring over large spatial

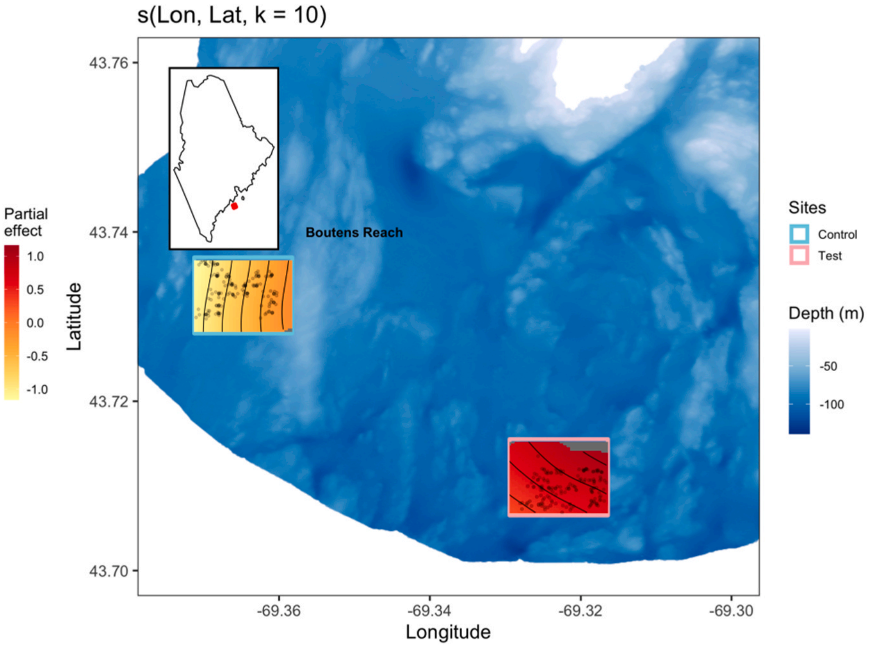

Fig. 9. Continuous spatial partial effect on catch described by longitude and latitude overlain on bathymetry map of MILCA. Sample locations of each location are plotted.

areas, fishing behavior is often inherently local and it is important to disentangle project effects from the impacts of local fishery dynamics to assess future fishing opportunities (Allen-Jacobson et al., 2023).

Legal catch changes co-occurred with bottom temperature changes between seasons, as well as intraseasonal changes during the warmer fall period, while sublegal catch remained relatively consistent across temperature regimes. Much of the difference in legal catch between seasons was attributable to a large change in catch during a relatively short period of time in fall. The Fall survey occurred in a temperature regime 5–7 °C warmer than the spring (11.5–13 °C and 5–7 °C fall and spring temperature ranges, respectively). Importantly, temperature actually increased during the survey due to a fall overturn event that warmed local bottom water. This change in bottom temperature was associated with a subsequent 49 % increase in legal catch across sites (Fig. 4). While it may have been ideal to assess salinity changes during the survey period, these sensors failed during deployment. However, we do not feel that a lack of salinity data takes away from the study in whole as stratification is generally temperature driven in the Western Gulf of Maine (Townsend and Spinrad, 1986, Townsend et al., 1992, Townsend et al., 2023).

If we contextualize observed temperature ranges to lobster habitat suitability work we can additionally understand catchability differences between seasons. The fall temperature ranges were found to be consistent with previously established optimal temperatures (11.6–14.3 °C and 10.9–14.3 °C) for both adult and juvenile lobsters, respectively (Tanaka and Chen, 2016). In contrast, spring temperatures were outside of optimal ranges for adults and only minimally in the optimal range found for juveniles (8.4–10.6 °C and 6.6–10.1 °C, respectively) (Tanaka and Chen, 2016). The combined less-than-optimal thermal habitat and seasonal fishery mortality likely resulted in lower adult lobster population density and catch during the following spring's survey. On the other hand, ideal thermal habitat and lack of removal by the fishery due to size regulations likely allowed the sublegal population and subsequent catch to remain relatively consistent between surveys. Many previous studies demonstrate that lobster activity increases from approximately 2 to 12 °C (McLeese and Wilder, 1958; Miller, 1990; Drinkwater et al., 2006; Bowlby et al., 2007; Jury and Watson, 2013; Collie and King, 2016). Therefore, when temperature increases, lobster movement increases and the effective area fished (m^2) by a trap (catchability) increases as lobsters are likely to travel further before encountering it (Miller, 1990; Bell et al., 2001; Courchene and Stokesbury, 2011; Jury and Watson, 2013; McManus et al., 2021).

The effect of fishing mortality on our study is difficult to directly calculate at our spatial scale because state landings were aggregated to the zone level during the study period but we know immigration and emigration plays a role in seasonal population dynamics in the MILCA. The ASMFC Stock Assessment assumes the exploitation rate (total catch abundance^{-1}) on the GOM lobster stock to be ~ 50 % (ASMFC, 2015; ASMFC, 2020). Therefore, fishery removal due to high fall fishing pressure on lobster in the region could also play a role in the observed catch dynamics (Chen et al., 2005; ASMFC, 2015; Tanaka et al., 2019a; ASMFC, 2020). Due to the seasonal migratory behavior of lobsters, legal individuals captured during the fall survey are subject to the reduced Monhegan fishery as well as the larger offshore GOM federal lobster fishery between surveys (Mazur et al., 2020). While tagging results were outside the scope of this study, individuals were recaptured and reported by the federal fishery over 30 km from release during the first winter following tagging. Legal lobster catch was > 80 % higher in fall relative to spring and it is likely the Spring legal lobster population was depleted to some degree by both the local and offshore fall and winter lobster fisheries. Another hypothesis is that while sublegal lobsters were captured at peak molt during the spring survey, the legal lobsters did not reach this point during the survey (Figure S2). Therefore, following the previous fishing season, the next year-class had not fully recruited into the fishery by the spring survey, potentially resulting in low spring legal catch rates.

In addition to removal via fishing mortality, population density changes in American lobster are inherently related to regional-scale migratory movements. Tagging studies have previously characterized local to regional scale inshore-offshore migration in conjunction with seasonal changes between summer and winter in and outside the GOM (Bowlby et al., 2007; Collie and King, 2016; Henninger et al., 2020). Monhegan Island's lobster fishery, located 21 km offshore, is affected by transient populations of lobsters migrating between inshore and offshore habitats and timing of inshore-offshore movements therefore, impacts the catch per trap in the MILCA seasonally with population density differences due to thermal habitat (Jury and Watson, 2013). This process can in turn influence large changes in catch over short periods of time allowing for rapid changes in catch dynamics in response to bottom temperature events. We observed this process during the fall survey when legal catch increased 49 % following fall overturn warming bottom water and is likely in part responsible for baseline seasonal catch differences of > 80 %. Additionally, McLeese and Wilder (1958) observed that catchability was directly related to water temperature with the slope of this relationship mediated by lobster population density. This relationship supports the proposition that both increased catchability and population density due to optimal thermal habitat in the fall allow for the seasonal differences in expected legal catch per trap.

4.2. Functional drivers of catch

The difference between fall and spring legal catch per trap indicates that resolving the drivers of dynamics for fall lobster fishing in the MILCA is necessary to discern any measurable impact on the local fishery due to the installation and operation of NEAV I. Despite the seasonal differences revealed by this survey, it is often desirable to describe dynamics of multiple seasons with a single size-structured model, allowing previous seasonal time steps to inform model output (Chen et al., 2005; Tanaka et al., 2019a). In this case, by splitting models up between seasons, we ensured that the large difference in seasonal temperature range did not mask effects from additional processes or potential future shifts in catch dynamics between the control and test site that could arise from the installation and operation of NEAV I. Additionally, better characterization of the drivers of catch dynamics will prevent falsely relating an impact on catch to wind turbine operations that may have occurred due to an unrelated change in the system. Previous studies have frequently taken a season and size specific modeling approach for explaining lobster population dynamics (Dunnington et al., 2005; Tanaka and Chen, 2015; Tanaka and Chen, 2016). With this approach, differences in models can be attributed to the preferences lobsters have for environmental conditions within a season and at a particular life stage (Tanaka and Chen, 2016). However, it should be noted that in each season models have been developed based on survey results from a single year and therefore, cannot account for interannual variability in resource abundance, survey performance and environmental conditions.

Temperature was the most consistent and important covariate explaining catch dynamics, particularly intraseasonal fall catch dynamics. At least one temperature derived covariate, either site-specific temperature or trap-specific temperature anomaly, was included in each fully developed model (Table S1). We should note that within the lower spring temperature regime, temperature dynamics did not affect catch dynamics to the extent observed in the fall. Of the abiotic covariates included in the Fall Legal model, temperature was the largest partial effect ranging from −0.5 to +0.3 legal lobsters per trap, or a potential difference of 0.8 legal lobsters per trap over a range of 1.5 °C. Interestingly, temperature anomaly, defined here as the site-specific temperature minus the trap-specific temperature, was consistently included in final models (Table S1). The inclusion of local (10 s of meters) temperature anomalies is supported by Jury et al., (2019), who observed that lobsters acclimated to different temperature regimes exhibited different preferences for ambient water temperature: cold-acclimated lobsters preferring higher relative ambient temperature to a warm-acclimated lobsters. Similarly, the partial effect on catch as a function of temperature anomaly indicates that catch was higher (0.15 legal lobsters per trap higher for a 0.25 °C increase in local temperature) in traps that were relatively warmer than surrounding traps. Including both temperature and temperature anomaly in the Pre-Deployment Model provides a relationship to catch that can inform how a hypothetical post-deployment survey may be constructed.

We used tide height as a proxy for tidal velocity and the observed effects may represent lobsters' responses to changes in current velocity. We chose to calculate mean tidal heights for each soak from NOAA's Portland Tide Station which provided a well-correlated proxy for current speed measurements when they were available (CO-OPS, 2022). In the Fall Legal Model, the tide height partial effect may represent increased trap encounters under higher tidal velocity conditions. Previous studies have observed that increased tidal velocity influences chemotaxis as lobsters respond to increased bait plume odor diffusion (Moore et al., 1991; Kozlowski et al., 2001). Increased diffusion effectively increases the area of influence for each trap, allowing more lobsters to be influenced by the plume and ultimately increasing the trap's effective trapping area (Bell et al., 2001; Watson, 2009). The inclusion of this term was explored following conversations with fishermen conducting the survey who were considering moon/tidal patterns in setting their own fishing schedules; further emphasizing the benefits of stakeholder engaged fisheries research (Hillyer et al., 2021). In future surveys, including *in situ* measurements of current at each site by equipping single traps with tilt current meters could significantly improve our understanding of this process.

We used slope as a coarse descriptor of benthic habitat. The relationship between slope and catch was consistent with past observations of lobster behavior in which lobsters were found to be more mobile on low-complexity bathymetry (*i.e.,* sand or gravel paths, a low slope environment), but present in higher density on high-complexity bathymetry (*i.e.,* ledge, a relatively higher slope environment) (Geraldi et al., 2009). These behavioral responses to habitat complexity would result in higher trap encounter rates at low and high slope values than intermediate slope values, creating the observed partial effect (Fig. 8). Floating offshore wind infrastructure will increase the 3-D complexity of the benthos in relatively featureless locations with the potential to introduce high-quality, complex habitat for lobsters, and it is possible that catch around mooring anchors could be locally boosted.

Depth is included in previous Generalized Additive Models describing lobster catch and can be considered as a marker of abundance across the sampling range (Collie and King, 2016; McHenry et al., 2017; Tanaka et al., 2017). From this interpretation in the MILCA during fall, legal lobster abundance is high between 90 and 110 m and decreases in depth shallower than 90, reflected by differences in catch of 0.6 legal lobsters per trap (all else equal). Depth varies across both the control and test sites with a shoaling west to east gradient in the control site and a general south to north gradient in the test site. The spatial covariate representing longitude and latitude varied along similar gradients to those observed in depth resulting in an effect that decreases with increasing distance from shore. Similar to this study, Li et al. (2018) included latitude and longitude as a covariate after developing a covariate model with clear mechanistic impacts on American lobster catch dynamics, as this effect describes underlying spatial patterns in catch unexplained by those other covariates. In this way, it may act as an adjustment factor on the model and it does not necessarily describe a specific abiotic variable. While the smooth surfaces vary similarly to depth gradients at each site, the partial effects are opposite to that of depth. Light correlation between the depth and longitude and latitude terms indicate that the longitude and latitude effect generally describe spatial variance in catch that correspond with differences in depth (Table S2).

We did not include a bottom type classification in our models due to a lack of available high resolution data however this type of variation may play a role in our latitude-longitude effect. Bottom-type is commonly included as a categorical effect in GAMs describing lobster catch and this inclusion could improve the interpretive capabilities of these models with regard to lobster behavior (Collie and King, 2016; Tanaka et al., 2017). Benthic features are highly complex in the GOM and are known to vary mosaically on a scale of < 10 m (Barnhardt et al., 1998). Since high resolution geophysical surveys (HRG) will be required at all offshore wind sites, we recommend better data integration with environmental and ecological monitoring. For example, to better assess project impacts, HRG surveys of control sites should be coordinated even if they are not the target for current and future development efforts. The ability to include additional information about bottom-type in future studies of offshore wind development sites would greatly refine our understanding and interpretation of benthic and spatial covariates.

Our inclusion of survey design terms, soak time, and trap type in the model standardized catch-to-survey effort. The partial effect of soak time on catch was unsurprisingly a positive linear relationship (Fig. 8). However, the fact that catch linearly increased with soak time over all observed soak times implies that traps did not typically reach a point of saturation during surveying (Miller, 1979; Miller and Rodger; 1996; Skerritt, 2015). The time to reach trap saturation likely varies between the seasons and size ranges examined, as soak time or survey effort is not contained in every final model (Table S1). For example, Miller and Rodger (1996) found that saturation can occur within 24 hours, and Løkkeborg (1990) found that bait attraction may rapidly decrease following trap deployment (< 6 hour). Trap saturation can result in an underestimation of potential catch and should be assessed in any trap survey. We were unable to calculate decay coefficients to relate catch to soak time and do not believe we reached catch asymptotes. In this case, we followed the lead of our partner fishermen to determine soak time, and results indicate trap saturation was not a pervasive source of underestimation of catch.

While fall traps did not appear to reach saturation with legal lobsters, trap type was included as a small but significant linear effect, favoring standard vented lobster traps. The inclusion of this covariate accounts for differences in trap type size selectivity that arise due to behavioral interactions around and within traps (Jury et al., 2001; Courchene and Stokesbury, 2011). Ventless traps largely prevent the escape of sublegal lobsters which increase the number of conspecifics in the traps. Although traps did not necessarily saturate with legal lobsters, the entrance rate of legal lobsters into ventless traps was likely lower due to antagonistic interactions with conspecifics around and within ventless traps stemming from the increased retention of sublegal lobsters (Courchene and Stokesbury, 2011; Clark et al., 2015). Legal lobsters that do enter ventless traps are less likely to be retained and captured due to these antagonistic interactions with smaller lobsters both in and around traps (Jury et al., 2001).

4.3. Model approach in the FOSW context

Previous BACI commercial trapping surveys to assess potential changes in lobster resources at Block Island Wind Farm (BIWF) and Westernmost Rough Wind Farm have used study areas and survey years to define how catch functionally changes over time. At BIWF, commercial trap surveys used two near-field and two far-field sites. The study found that reference site selection may have influenced or confounded the interpretation of project impacts due to differences in depth and temperature that are inherently connected with the large spatial difference (Wilber et al., 2021). While they developed GLMs to describe catch, they noted that GAMs could be used in the future to model non-linear effects. The HFIG conducted the BACI study at Westernmost Rough Wind Farm, where interannual changes at both test and control sites indicated regional shifts in resource quality year-to-year (Roach et al., 2022). Neither of these previous surveys used environmental information to inform catch modeling. It is often assumed that BACI design projects cannot account for spatial heterogeneity (Methratta, 2021). In reality, despite the prevalence of non-random before-after style studies, it has been noted that this study design is subject to high bias and randomized BACI studies generally detect change with lower bias (Christie et al., 2020). We have demonstrated that by collecting environmental data *in situ* when possible, or as proxy terms to complement catch data, we can account for more deviance in response variables and model underlying differences between a test and control site to take the lobster's ecology into account when assessing resource health.

Similar to previous studies, we could have developed GLMs rather than GAMs, but this approach would have its own restrictions. For example, while the majority of 1D responses are near linear, we would not have considered the flexible 2D spatial term used to describe underlying distributional differences. Additionally, projected environmental conditions could result in future non-linear resource responses to changes post-construction making a non-linear approach during power analysis and pre-construction surveying favorable. Overall, we aim to provide a useful demonstration integrating *in situ* environmental data into offshore wind fishery modeling; but to operationalize this approach responsibly for a commercial-scale FOSW project would require multiple years of pre-construction surveying and environmental characterization as done at the BIWF and Westernmost Rough Wind Farm projects.

While the vast majority of OSW development thus far has used fixed bottom foundations, as we saturate nearshore shallow options, economically feasible development in deep waters requires floating offshore wind (FOSW) platforms (Beiter et al., 2016; Lopez et al., 2022). Thus past research on OSW fixed gear fishery impacts has focused on fixed bottom projects, however FOSW development is progressing rapidly globally. In Europe, two Equinor-backed FOSW projects, Hywind Scotland and Hywind Tampen, have been successfully producing 30 and 88 MW since 2021 and 2022 respectively (Equinor, 2024)., Similarly, the first floating commercial scale FOSW turbine (11.4 MW) offshore wind turbine in the western hemisphere, New England Aqua Ventus I (NEAV I), is proposed for deployment in the Monhegan Island Lobster Conservation Area (MILCA), < 5 km south of Monhegan Island, ME. Previously a 1:8 scale FOSW turbine using similar technology was temporarily deployed in a demonstration project off of Castine, ME (Viselli et al., 2015). The state of Maine has additionally submitted a Research Lease Application to deploy ≤ 12 floating turbines in federal waters (MERA, Governor's Energy Office, 2021). In parallel, the Bureau of Ocean Energy Management (BOEM) has gauged commercial interest in developing the GOM and is planning for lease auctions in mid-2024 (Theuerkauf, 2023). Given the foreseeable timeline of development, understanding potential impacts from the installation and operation of a FOSW turbine on the lobster fishery is necessary for responsible commercial wind energy development in the GOM. The demonstration scale projects in the GOM give us the opportunity to examine small-scale fishery impacts from a single turbine before floating offshore wind development in the GOM scales up through MERA and commercial development.

From beginning to end, including pre-construction surveying, construction and operation, stakeholders may expect FOSW projects to be active in leased areas for up to 35 years Therefore, resource monitoring must consider disentangling climate change and fishery responses from development impacts. Current lobster resource productivity increased as the GOM approached temperature optima for recruitment and growth from 1970 to 2016; however, long term resource projections predict 40–60 % reductions in GOM lobster abundance by 2050 as stressful conditions including high temperature and extreme events such as hypoxia increase in frequency (LeBris et al., 2018; Goode et al., 2019). The predicted decreases in lobster abundance have already begun to be reflected in landings. Lobster landings by the Maine fishery peaked in 2016 and have already declined steadily across Zones A, B, C and D where landings are highest. This survey took place in the MILCA which is located within the larger Zone D during this decline and thus represents a small-scale snapshot of a fishery in change (Figure S3). The ultimate timeline of expected major abundance decrease is consistent with the decommissioning of initial FOSW projects emphasizing the necessity to consider environmental impacts in conjunction with project effects. The modeling scheme presented here allows us to consider the impacts of environmental variables as well as factors related to survey design that affect catch over a restricted spatial scale. When a turbine is ultimately deployed off of Monhegan Island we can use these established relationships to determine whether the deployment and operation of the turbine has introduced a new factor impacting catch in the region.

5. Conclusions

Offshore wind projects have an expected operation period of 20–25 years and resource monitoring must consider disentangling climate change and fishery responses from development impacts. To begin this process, we must first contextualize baseline fishery catch relative to current conditions using tools that can incorporate environmental heterogeneity over time. This survey provides the necessary characterization of seasonal Legal lobster catch and factors driving catch variance in the local fishery preceding deployment of a demonstration scale offshore wind project. This type of characterization is necessary to complete later post-deployment impact analysis which will determine whether or not a measurable impact is detectable on lobster catch due to the installation and operation of NEAV I. Beyond the demonstration-scale project, this study developed analytical methods for fixed gear fishery surveys that will be effectively scalable to novel offshore wind scenarios for example, the Maine Research Array (MERA) or future commercial scale floating wind arrays.

We used this survey's results to model lobster catch as a function of environmental survey design and, when feasible, biological covariates. Models were developed for four survey response groups: Fall, Legal; Spring, Legal; Fall, Sublegal; Spring, Sublegal. A robust model development process was used to reduce the terms in each model based on AIC scores and term significance before a final model was selected based on cross validation and biological feasibility. This process allows for models to be predictive of variance rather than descriptive of biases. Legal catch dynamics were strongly influenced by bottom temperature, especially temperature changes associated with fall overturn, but habitat complexity, depth, and survey effort also played a role in observed catch. We encourage post-deployment surveys to incorporate these covariates when assessing project impacts in the future. Establishing analyses to quantify resources that leverage environmental data is a key step in determining the impact of offshore wind development on existing marine uses. Offshore wind development is a necessarily lengthy process beginning pre-site selection and continuing until decommissioning. Therefore, tools must be developed to resolve impacts that are easily translated over time by accounting for a variety of factors that may change over space and time. Having these types of analyses available will become increasingly beneficial over the lifecycle of a project, which is likely to exist through environmental change.

Funding

This research is supported by the Department of Energy grant DE-EE0009426.0000 awarded to the University of Maine.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Everett J Rzeszowski, Damian C Brady reports financial support was provided by US Department of Energy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgments

This work would not be possible without the contributions of expertise, gear, and time by multiple Monhegan Island fishermen. Sampling was completed from multiple commercial vessels. We extend our gratitude to not only direct project participants but to the Monhegan community within which our researchers are guests treated as family. Thank you to A.G. whose expertise and feedback at different stages of analysis has helped to refine our approach to the data. Thank you to C.C. for making introductions between researchers and the Monhegan community fishery participants.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2024.107163.

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