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American lobster *Homarus americanus* responses to construction and operation of an offshore wind farm in southern New England

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ABSTRACT: Construction and operation of the Block Island Wind Farm (BIWF) has occurred against a background of declining American lobster *Homarus americanus* abundance and harvests in southern New England (SNE), USA. Potential effects of BIWF on a portion of the SNE stock were assessed with a ventless trap survey conducted at 2 blocks near BIWF and 2 blocks at a reference location located 22 km northeast from May through October, 2013–2019. Collaboration with the fishing industry to select sampling locations yielded a reference location on favored fishing grounds to document potential effects on the fishery. Results of the before–after–control–impact (BACI) design revealed American lobster catches decreased between the baseline and operation time periods at the wind farm (−30%) and reference (−18%) locations, and this decrease was greater as a proportion of the overall catch near the wind farm (BACI interaction [$\alpha = 0.10$]), but similar in absolute numbers (−0.8 vs. −0.9 lobsters trap^{-1}). Catch rates of females carrying late-stage eggs were relatively high in the reference location where bottom water temperatures were lowest. An adverse impact of turbine installation activities on lobster catches was not apparent. Temporal variation in lobster catch rates was similar to that observed in other regional ventless trap surveys. The design decision to document lobster metrics on the deeper fishing grounds satisfied fishing industry concerns. However, potential BIWF effects cannot be separated from regional shifts in lobster distributions to deeper, colder habitat, which reflects one limitation of using a BACI design when effects, if present, likely follow a spatial gradient.

KEY WORDS: Block Island Wind Farm · American lobster · *Homarus americanus* · Ovigery · Shell disease · Before–after–control–impact · BACI · Before–after–gradient · BAG

1. INTRODUCTION

Thermally stressed fisheries on the northeastern US continental shelf are faced with potential effects of offshore wind (OSW) farm construction and operation before any eventual benefits from a transition to renewable energy sources can be realized. One such fishery in southern New England (SNE) targets the American lobster *Homarus americanus*, an ecologically important benthic consumer. Historically, American lobsters were an important food source for native Americans and were abundant enough to be used as fertilizer and bait (ASMFC 2020). Currently, American lobsters support one of the most productive fisheries on the northeastern coast of the USA (Wahle et al. 2015, Carloni & Watson 2018, NOAA 2020, Zou et al. 2021), with 2019 coastwide landings worth $636 million USD in ex-vessel value (ACCSP Data Warehouse 2002–). Although lobster abundances are increasing throughout the northern extent of its range, the SNE stock is declining, which has been attributed to lower recruitment and higher natural

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mortality over the last several decades (ASMFC 2010, 2020, Castro & Somers 2012, Howell 2012, Wahle et al. 2015, Mazur et al. 2020). Potential impacts of OSW farm construction and operation within the SNE stock are therefore of particular concern.

Before installation of the first OSW turbines in North America, resources for predicting potential impacts on lobsters were limited to studies conducted in Europe, where OSW has been in commercial use since 2002 (Bailey et al. 2014). Lobsters are attracted to hard substrata, and in Europe, *H. gammarus* occur in relatively high abundances in the structurally complex habitat created at wind turbine foundations (Hooper & Austen 2014, Griffin et al. 2016) and near the concrete mattresses used to stabilize sub-marine power cables (Taormina et al. 2020). Concrete mattresses are an engineered protection system for seabed cable installation. The mattresses are made with articulated concrete slabs connected by cables to allow the mattress to drape over an exposed or insufficiently buried electrical cable or to separate cables at a crossing point. Fishing regulations vary across European wind farms, ranging from complete exclusion within a wind farm of all vessels not involved in wind farm maintenance (Rasenberg et al. 2015, van Hal et al. 2017) to temporary prohibitions during construction (Gray et al. 2016, Roach et al. 2018) to variable access based on gear type (Rasenberg et al. 2015). In areas where fishing activity was stopped during construction of a wind farm, European lobster abundances increased (Roach et al. 2018, 2022), benefiting from the creation of de facto marine protected areas (Coates et al. 2016, Dannheim et al. 2020). In the USA, commercial fishing is not excluded from wind farm areas; therefore, potential wind farm impacts on American lobster catch rates cannot be directly inferred from the results of European studies. Additionally, American lobsters are more migratory and occur at higher densities than European lobsters, which exhibit limited home ranges (Moland et al. 2011, Phillips 2013); thus patterns of prey and shelter utilization around wind farms are not comparable (Rozemeijer & van de Wolfshaar 2019).

The Block Island Wind Farm (BIWF) ventless trap survey, a monitoring activity required by Rhode Island State agencies, was conducted near the wind farm and at a more distant (reference) location that was selected based on guidance provided during multiple meetings with the fishing industry (Rhode Island Coastal Resources Management Council Fishery Advisory Board and open meetings conducted over a 3 yr period). The reference location was requested to serve as a general index of lobster abundance in an area specifically targeted by lobster fishermen well outside the direct influence of the wind farm project. Thus, the ventless trap survey documented lobster catches on local fishing grounds with relatively high value to the fishery to provide evidence of potential construction and operation impacts on the fishery. Another study objective was to assess whether lobster metrics (i.e. catch rates, ovigery rates, shell disease prevalence, and cull status) changed in a way consistent with a wind farm impact based on spatial (wind farm vs. reference areas) and temporal (baseline, construction, and operation time periods) variation in these metrics. A consequence of using the fishing ground as a reference location was that lobster metrics were contrasted between favored (fishing) and sub-optimal (near wind farm) habitats, which complicated the interpretation of potential BIWF effects on catch rates. The temporal scale of impacts may manifest as either short-term pulse impacts or longer-term sustained impacts. Short-term impacts were considered for the partial years when construction phases were on-going, while longer-term impacts were limited to the 3 years of this monitoring program during which the wind farm was in operation.

2. MATERIALS AND METHODS

Ventless trap surveys are commonly used across coastal New England states to assess American lobster populations (e.g. Chen et al. 2006, Courchene & Stokesbury 2011, Collie & King 2016, Goldstein et al. 2017, McManus et al. 2021). To better understand potential OSW effects on American lobsters, a 7 yr ventless trap study was conducted at BIWF, the first OSW constructed in North America. In addition to lobster catch rates, other biological metrics including ovigery status, shell disease prevalence, and cull (claw loss) status were examined to explore potential physiological effects of construction and operation that may not be reflected in changes to catch rates. Analyzing ovigery rates and the rates of females that recently released (spent) eggs provides valuable information on locations that may have favorable conditions for egg development and hatching (Goldstein & Watson 2015, Carloni & Watson 2018), as well as whether wind farm construction and/or operation may have affected reproductive activity. Because shell disease is associated with physical stressors (Shields 2013, Barris et al. 2018, Groner et al. 2018), examining shell disease prevalence rates at locations near and distant from the wind farm, before and after wind farm operation, could indicate potential wind farm impacts affecting lobster physiology. Claw loss rates provide an additional metric to assess potential stress on lobsters. Claw autotomy, a reflexive mechanism of claw loss, can occur in response to interactions with predators, other lobsters, handling in the fishery, or severe environmental conditions, such as extreme cold (Scakratt 1973, Juanes & Smith 1995).

2.1. Field methods

The BIWF consists of 5 wind turbine generators (6 MW each) with steel jacket foundations located approximately 5 km southeast of Block Island, Rhode Island (Fig. 1), over predominantly sandy−gravel sediments adjacent to a cobble/boulder field (Guarinello & Carey 2022). This area historically was fished using gillnets, trawls, lobster pots, and hook-and-line. The overall turbine height is 150 m, and the footprint of each foundation is approximately 576 m^2. This pilot-scale project was sited in coordination with commercial and recreational fisheries representatives, as well as state and federal resource agency personnel, in order to minimize impacts to biological resources and fisheries in the area (Smythe et al. 2016).

The ventless trap survey was conducted twice per month from May through October from 2013 to 2019 at 2 blocks (sites) near the BIWF project location (Near Field North [NN] and Near Field South [NS]) and at 2 reference blocks (Far Field North [FN] and Far Field South [FS]) located 22 km to the northeast (Fig. 1). Near Field sediment characteristics were primarily coarse sand, with some pebble, cobble, and boulder, while Far Field sediments were comprised primarily of sand. Bottom depths were approximately 32 and 34 m at the FN and FS blocks, respectively; and 23 and 24 m at the NN and NS blocks, respectively. Each survey block contained 427 m trawl lines (n = 3) spaced 200−300 m apart and oriented approximately parallel to each other. Trawl lines closest to the wind farm in the Near Field blocks were 1.46 km (NN) and 4.00 km (NS) distant from the nearest turbine. Locations of survey blocks and trawl lines were determined based on experience of the commercial lobstermen contracted to conduct each portion of the

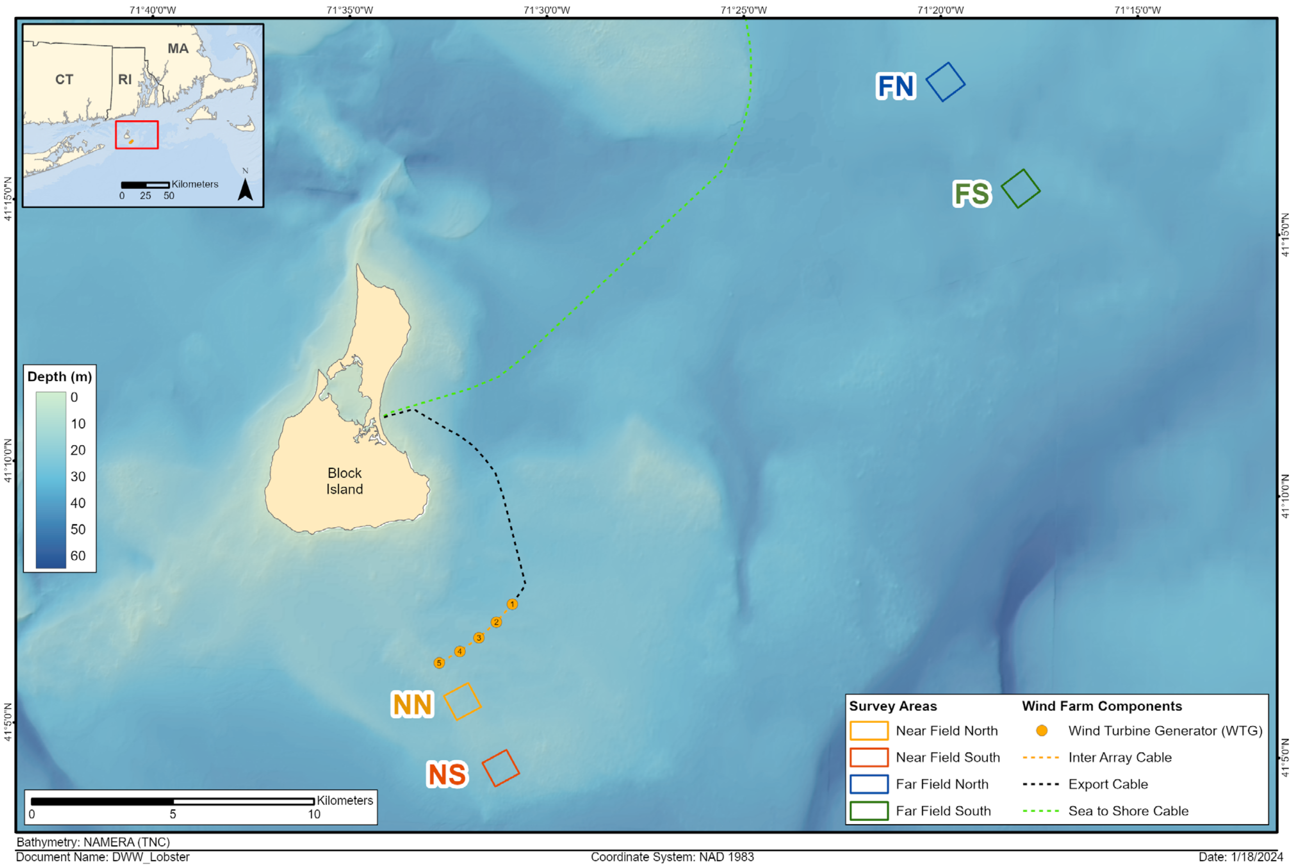

Fig. 1. Location of the Block Island Wind Farm wind turbine generators (WTGs), inter-array cables, Block Island transmission cable, and Near Field South (NS), Near Field North (NN), Far Field South (FS), and Far Field North (FN) survey blocks

survey to avoid gear conflicts and allow harvesting during and after construction. Each trawl line was composed of 2 trawl arrays of 6 traps, 5 ventless and 1 vented, each array connected with 122 m of ground line with traps spaced 30 m apart. A starting point for trawl line placement each year was assigned by randomly selecting 1 of 4 distances from the northeast edge of the block (0, 122, 244, and 366 m) and then spacing 2 additional parallel trawl lines with random starts at intervals of 200–300 m (INSPIRE Environmental 2021). The same trawl locations were resampled for the remainder of each year. Ventless traps were single parlor traps, overall dimensions were 41 × 102 × 53 cm, with 13 cm entrance hoops and constructed with 2.5 cm square rubber-coated 12-gauge wire mesh. Vented traps were the same traps and included rectangular escape vents that measured 14.6 × 4.9 cm, consistent with Rhode Island Department of Environmental Management (RIDEM) and the Massachusetts Division of Marine Fisheries (MADMF) surveys. Traps were constructed with doors that allowed release of lobsters between surveys when the traps were on the bottom, but not actively sampling. The sampling protocol was informed by the methods used by the Atlantic States Marine Fisheries Commission (ASMFC) for their coast-wide ventless trap survey and other surveys (Wahle et al. 2004, O'Donnell et al. 2007, Geraldi et al. 2009). The proposed sampling design was based on a power analysis and study design assessment of SNE lobster catch data (2006–2012) from ASMFC's coast-wide ventless trap survey (see Appendix A in INSPIRE Environmental 2021).

A standard soak time of 5 nights was used, consistent with local fishing practices. Traps were baited with locally available skate at the start of each sampling event. Two consecutive 5 night soaks were conducted each month. After the first soak period of each month, traps were retrieved, the catch was sampled, and traps were rebaited for another 5 night soak. Temperature loggers (HOBO Tidbit V2, Onset Computer) recorded temperature in Celsius every 10 min throughout the duration of sampling each year on 1 trawl within each block. Lobsters were surveyed using commercial fishing vessels with scientists on board to process the catch. Metrics recorded for each lobster included: mortality, sex, carapace length (CL) to nearest 0.1 mm, molt status (shell hardness), shell disease score (reduced to presence/absence for analyses), egg status (eggs present or hatching/spent), and cull status (1 claw missing/bud, both claws missing). Criteria for these metrics were based on the ASMFC protocols used in their ventless trap survey. Egg status included (1) recently extruded (dark green), (2) eyed (dark green with eye spots), and (3) hatching/spent (furry appearance on abdomen, few eggs present, lighter brown/green to orange color). Select bycatch were enumerated and measured (INSPIRE Environmental 2021), but are not analyzed here.

2.2. Analytical approaches

For this before–after–control–impact (BACI) study design, generalized linear models (GLMs) were used to describe each response variable, and *a priori* linear contrasts (e.g. Schad et al. 2020) were used to estimate the mean temporal change in metrics at the Near Field versus change at the Far Field blocks (i.e. the spatiotemporal 'BACI interaction'). For each response, a single model was fit to all 7 years of data, and separate linear contrasts estimating the magnitude of the differences and their confidence intervals (the observed effect size) were constructed for the time periods relevant to each impact phase.

Data collected before construction (the baseline period) were compared to either one of the 2 construction phases, or the wind farm operation phase. 'Baseline' is defined differently for each impact contrast, using only the months corresponding to each construction or operation period. Survey time periods are defined as:

- baseline (May through October, 2013 and 2014, or a subset of these months for the construction contrasts);
- construction phase I (July through October 2015), which included turbine installation and associated disturbances, e.g. pile driving;
- construction phase II (April through September 2016), which included cable installation and turbine assembly, e.g. blade installation, jet plow trenching;
- operation (May through October, 2017, 2018, and 2019).

Although the BIWF ventless trap study was conducted before OSW monitoring guidelines were established, the monitoring duration is consistent with guidelines that have subsequently been released (BOEM 2019, ROSA 2021). Analyses focused on detecting changes in metrics that may be indicative of wind farm construction or operation effects, i.e. a mean temporal change in a metric at the wind farm that did not occur at the reference stations or the reverse. All statistical tests were conducted in R (R Core Team 2021), using the packages 'ggplot2' (Wickham 2016), 'MASS' (Venables & Ripley 2002), 'glmmTMB' (Brooks et al. 2017), and 'DHARMa' (Hartig 2021).

Catch statistics and other biological parameters were evaluated using GLMs. Each model had a unique structure and error distribution appropriate for the response (e.g. a GLM with a zero-inflated negative binomial error distribution and a log-link for catch; a logistic regression with a binomial error distribution for presence/absence metrics like shell disease, ovigerous/spent females, and cull status; all models are presented in Table 1). Lobster catch per unit effort (CPUE) was calculated as the total number of individuals per trawl array. For the catch model, the response was the CPUE for 6 replicate trawl arrays from each survey with the number of traps per trawl as the offset and with 2 surveys per month, May through October, in each block. On 7 survey events, 1 or more trawl arrays were excluded from the model due to loss from weather or potential harvesting prior to sampling. In addition, where more than 2 traps within a trawl array were compromised either due to loss or damage to the trap, the entire trawl array was excluded. In total, 15 out of the 2016 trawl arrays were excluded from the catch model.

For the reproductive models, 2 separate logistic regression models were used to examine the binary (yes/no) reproductive status of females for (1) those carrying eggs (early or late stage) or (2) those with evidence of recently spent eggs. A 2 yr reproductive cycle is typical for SNE female lobsters (Aiken & Waddy 1980, Waddy & Aiken 1992) and occurs when females molt and mate in one summer, store sperm in a seminal receptacle until spawning in the late summer the following year, and carry the eggs for 9 to 12 mo until the third summer when the eggs hatch. Therefore, lobster reproduction (ovigery and spent egg rates) was examined separately for 3 reproductive cohorts: (1) late-stage ovigery rates in females collected in May and June with eggs that were likely to hatch in the coming weeks, (2) spent rates in females collected in June, July, and August, whose eggs had recently hatched, and (3) early-stage ovigery rates for females with eggs collected in September and October with newly spawned egg masses. Separate contrasts were conducted for late-stage and early-stage ovigery analyses using one model, and a second model was used for spent females. All analyses of female reproduction were calculated using only females ⩾79 mm CL to limit the influence of immature female abundances that could vary over time and among blocks. The 79 mm CL size threshold was based on the size at which a 50% maturity rate was observed for lobsters collected in offshore SNE (Ellertson et al. 2022). Data from all 7 years were used in the models, and the respective months and years were used in each contrast, as appropriate: for the construction phase I contrast, ovigery rates were contrasted between September and October in 2015

Table 1. Description of methods used to estimate effects for American lobster catch and other biological metrics in the Block Island Wind Farm (BIWF) study. CPUE: catch per unit effort. In the final models, note that the '*' is short-hand to indicate main effects plus interactions, e.g. Block*Year = Block + Year + Block:Year

Response modeled	Response description	Sample size	Final model
CPUE	Total lobster count per trawl array	2001 (6 trawl arrays × 2 surveys mo^{-1} × 6 mo × 7 yr × 4 blocks; minus missing or incomplete trawls)	glmmTMB (negative binomial, log link, offset = trap count); ~ Block*Year + Month:Year + Block:Month + T + T^2, zi~Month, where T is temperature deviation from mean, to avoid collinearity between T and T^2
Ovigery rates	Binary response for ovigerous status in adult females collected in May, June (late-stage), September, and October (early-stage)	8053 females (from the 4 months of interest, 7 years, 4 blocks)	Logistic regression; ~ Block*Month*Year − Block:Month:Year
Spent rates	Binary response for recently spent eggs in adult females collected June, July, August	10188 females (from the 3 months of interest, 7 years, 4 blocks)	Logistic regression; ~ Block*Month + Year + Month:Year
Shell disease rates — females	Binary response for shell disease in adult females collected in May—July	4085 females (from the 3 months of interest, 7 years, 4 blocks)	Logistic regression; ~ Block + Year
Cull rates — separately by sex	Binary response for cull status of each sex collected throughout each sampling year	17640 males and 27165 females (from 6 months, 7 years, 4 blocks)	Logistic regression; ~ Block + Month + Year

and the same months during the 2 baseline years (early-stage ovigerous females); for the construction phase II contrast, spent egg rates were contrasted between June through August in 2016 and the same months during the 2 baseline years (spent females).

The prevalence of shell disease was examined with a logistic regression only for ovigerous females collected from May through July to standardize for shell age, i.e. the approximate time of the most recent molt. Cull rates were also modeled with a logistic regression for lobsters of both sexes caught throughout the 7 yr study, with sex as a separate factor to determine if cull rates differed between males and females.

Lobster size frequency distributions were plotted for baseline and operation time periods for each survey block. Size bins were <50, 50.1–55, ..., ending with >105 mm CL.

Initially for each GLM, an unconstrained model was fit using the 'MASS::stepAIC' function in R (Venables & Ripley 2002) and included temperature and fixed factors (block, year, month) to identify which models were best supported by the data. This first evaluation allowed all 2-way and 3-way interactions, as well as an association with temperature for each survey event as either linear or quadratic. The lower bound of possible models in this first evaluation was the null model (intercept only) which allowed for temperature to be the only coefficient in the model; this would be possible if environmental variability alone sufficiently described the variability in the data. In the final model, the 'MASS::stepAIC' function was run with a restricted set of possible models which were constrained to include block and year (and month if required to address the *a priori* contrasts) to allow estimation of the effect size for each spatial–temporal (BACI) interaction contrast. The GLM linear predictor (η) for the mean response may be written on the link-scale (i.e. log-link for CPUE or logit for the rates models) as:

$$\eta_{\mathrm{bmy}} = \beta \times \alpha \times \omega + g(T) \qquad (1)$$

where the upper bound of models for η is set as a function of block (β), year (α), month within year ($\omega_{[\mathrm{m}]\mathrm{y}}$), all 2- and 3-way interactions (e.g. $\alpha{:}\beta$, the interaction between year and block; or $\alpha{:}\beta{:}\omega$, the interaction between year, block, and month), and $g(T)$, a linear or quadratic function of standardized temperature (T). Temperature was collected on a single trawl within each block, and is summarized as the monthly mean per block and year; it is standardized (expressed as deviations from the mean) to avoid collinearity between T and T^2.

For the catch model, the i^{th} trawl array (i = 1 to 6) has total catch (as counts), associated with a block–month–year–survey event, i.e. $C_{[b,m,y,s,i]}$ is the observation for block b (b = 1 to 4), month m (m = 1 to 6 for May to October), year y (y = 1 to 7), survey s (s = 1 to 2), and trawl array i (i = 1 to 6); the number of traps per trawl is the offset. For the logistic models, the observation for each lobster is coded as a binary response (yes/no), $L_{[b,m,y]}$, associated with block b, month m, in year y.

For each response, the final model with constraints was selected based on the lowest value of Akaike's information criterion (AIC) and best residual diagnostics (package 'DHARMa,' Hartig 2021). From the final models, *a priori* linear contrasts were constructed to estimate differences in lobster responses between time periods within each area, $(\hat{Y}_{\mathrm{FarField,ImpactPeriod}} - \hat{Y}_{\mathrm{FarField,BaselinePeriod}})$, between areas within each period $(\hat{Y}_{\mathrm{FarField,Period}} - \hat{Y}_{\mathrm{NearField,Period}})$, and the spatial–temporal BACI interaction $(\hat{Y}_{\mathrm{FarField,ImpactPeriod}} - \hat{Y}_{\mathrm{FarField,BaselinePeriod}}) - (\hat{Y}_{\mathrm{NearField,ImpactPeriod}} - \hat{Y}_{\mathrm{NearField,BaselinePeriod}})$, that is, differences between temporal changes in the mean of the Far Field and mean of the Near Field blocks, or equivalently, differences between spatial changes in the baseline and operation time periods. In each contrast, the same months included in the Impact period were used in the Baseline period, specifically: May–October for operation impacts; July–October for construction phase I; May–September for construction phase II. The contrasts focused on changes in means, both as 'pulse' responses with comparisons to the construction phases, and 'press' responses with comparison to the operation phase (e.g. Underwood 1992).

These contrasts were calculated as absolute differences on the original scale for the rates of ovigery, shell disease, and cull status. Contrasts in CPUE data were estimated as linear differences on the log-scale representing proportional change on the original scale, as a relevant way to understand changes across different groups that might have widely different baseline values. A 90% confidence interval (90CI) around each BACI contrast was constructed using Monte Carlo methods (Tofighi & MacKinnon 2016). If the 90CI excludes 0, the interaction is considered statistically significant (2-tailed α = 0.10). This approach provides 90% confidence in the 2-tailed hypothesis of 'no difference,' and 95% confidence in each of the 1-tailed hypotheses.

2.3. Regional context

Interannual variability observed in the BIWF ventless trap survey was compared to data collected in RIDEM and the MADMF surveys, which differed from BIWF sampling in both gear configuration and survey design. This comparison provides a regional context for temporal fluctuations in CPUE at similar depths during the same time period with the SNE stock area. Temporal trends were compared by plotting the annual deviation from the 7 yr (2013–2019) average CPUE established for each survey. Temporal trends in lobster CPUE at BIWF were not directly compared to CPUE in the state surveys because, although a 6-trap trawl array was used as the sampling unit in each study, the state surveys use 3 ventless and 3 vented traps per array compared to the 5 ventless and 1 vented trap array used in the BIWF survey. Years with higher-than-average catches have values above zero and lower-than-average catches fall below zero. Data from the MADMF and RIDEM surveys were sub-sampled to include only those trawls in the 21–40 m depth stratum; only trawls from Block Island Sound were used from the RIDEM survey (McManus et al. 2021), and only those trawls from NMFS area 538 off southern Massachusetts were used from the MADMF survey (Pugh & Glenn 2020; note there was no MADMF survey in 2013).

3. RESULTS

Lobsters (n = 44 844) were collected from 11 923 uncompromised (intact) traps from 2007 trawl arrays. Legal-size lobsters accounted for 14% of the total catch, and the majority (71%) of these individuals were female. Nine trawl arrays were lost, all of which were from the NN block, which is shallower with stronger hydrodynamic conditions and rockier substrata on which trawl lines can get snagged. In addition, 2 trawls sampled in the NS block in June 2017 may have been hauled and harvested prior to sampling; therefore, these 4 trawl arrays were excluded from the analysis. Two additional trawl arrays from the NN block (May 2017 and October 2019) also were excluded from the analysis because less than 4 uncompromised traps were sampled. There were 1923 complete trawl arrays and 78 with 4 or more uncompromised traps for which catch was modeled, with the number of uncompromised traps per trawl array used as an offset in the CPUE model to predict average catch per trap per trawl array.

Bottom water temperatures were lowest in May (averaging approximately 8°C), increased throughout the summer, with the highest average temperatures (approximately 17°C) in October (Fig. 2). Average bottom temperatures were consistently highest at the NN block and lowest in the FS block, with an approximate 2°C difference between these locations. Interannual variation within blocks in mean monthly water temperatures was greatest in May, with an average range of 4.2°C among years compared to an average range of 1.8°C among years for all other months (see figure in Supplement 1 at www.int-res.com/articles/suppl/m727p123_supp1.pdf).

3.1. Seasonal trends

Total lobster CPUE varied among months, with lowest catches in May and highest catches in August (Fig. 3A). The low catch rates in May were similar at all survey blocks, and as summer months progressed, catches at the Far Field blocks exceeded those at the Near Field blocks nearly 3-fold. Ovigery rates ranged from 56 to 78% among survey blocks in May, declining to <6% in July and August, and increasing in September and October, ranging from 16 to 66% (Fig. 3B). In May and June, the percentage of ovigerous females was highest at the FS block and was fairly similar among the other blocks. In October, ovigery rates were more variable (26–66%) spatially, with the lowest rates in the FN block. Percentages of spent females peaked in June and July and were higher at the Far Field blocks (Fig. 3C).

3.2. BIWF operation effects

Figures illustrate seasonal variability in habitat use in the reference and wind farm locations. Ad-

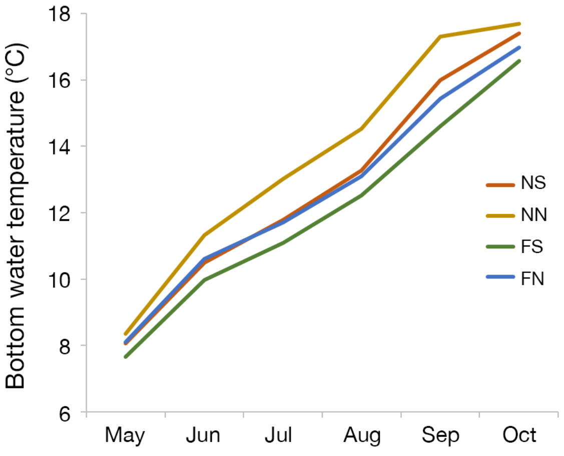

Fig. 2. Average monthly bottom water temperatures (from readings taken at 10 min intervals throughout each sampling year 2013 to 2019) from 1 trawl in each of the 4 survey blocks (NS: Near Field South; NN: Near Field North; FS: Far Field South; FN: Far Field North). Data for each month, year, and block are provided in Supplement 1

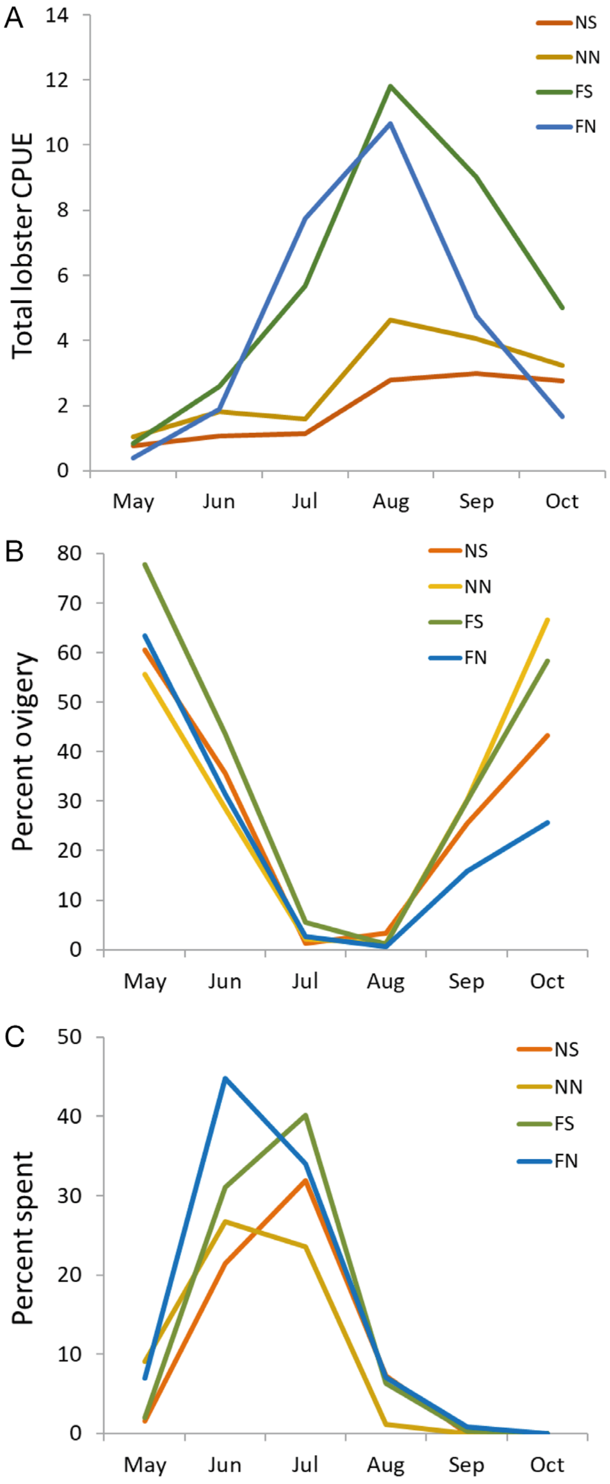

Fig. 3. (A) Total lobster catch per unit effort (CPUE) as average catch per trap per trawl array averaged across all years for each month, and monthly percentages averaged across years of (B) ovigerous and (C) spent females for each survey block (NS: Near Field South; NN: Near Field North; FS: Far Field South; FN: Far Field North). Data for each month, year, and block are provided in Supplement 2

ditionally, figures are provided for all biological metrics with a statistically significant ($\alpha = 0.10$) BACI interaction term. The estimated 90CIs for all contrasts are provided in Table 2. Details and diagnostics for all models are included in Supplement 2 at www.int-res.com/articles/suppl/m727p123_supp2.pdf.

3.2.1. Catch rates

Spatial and temporal variation in catch rates occurred throughout the study period (Fig. 4A), with consistently higher catch rates in the Far Field than the Near Field. The temporal patterns within each year also differed between areas, with Far Field showing a distinct peak in catch rates in late July or August while Near Field tended towards bimodality, with catch rates rising again in October.

The BACI interaction contrast compares the mean temporal change at the Near Field with that at the Far Field. Negative BACI contrast values reflect either a bigger increase, or a smaller decrease in catch between time periods at the wind farm, whereas positive values reflect the reverse situation, i.e. a smaller increase, or bigger decrease in catch at the wind farm. Lobster CPUE decreased between the baseline and operation time periods in all blocks, with a greater proportional decrease in the Near Field (−30%; 90CI = −35 to −26%) compared to the Far Field (−18%; 90CI = −23 to −13%), resulting in a statistically significant BACI contrast (17%; 90CI = 7 to 28%; Fig. 4B). Lobster catch rates were consistently higher in the Far Field, averaging 2.6 and 2.5 more lobsters per trap during the baseline and operation time periods, respectively. The decrease in lobster CPUE between the baseline and operation time periods was similar for the 2 locations, i.e. 0.8 fewer lobsters per trap in the Near Field and 0.9 fewer lobsters per trap in the Far Field, but the decrease accounted for a greater proportion of the Near Field catch. Lobster catch rates were most stable in the FN block, decreasing by 0.11 lobsters trap^{-1} between the baseline and operation time periods, whereas the largest decrease in average catch rate (1.60 lobsters trap^{-1}) occurred at the FS block, revealing considerable variation within the reference location. Temperature was significant ($p < 0.001$ for the linear and $p = 0.005$ for the quadratic term), indicating that temperature had an effect beyond differences between block, month, and year. Therefore, confidence intervals for the estimated effects (Table 2) are adjusted for the influence of temperature.

Table 2. Estimated percent changes between baseline and impact period, between areas, and the spatial–temporal before–after–control–impact (BACI) interaction (90% confidence intervals given in parentheses). Results presented by metric and impact phase. Impact period is compared to baseline, where OP: operation (May through October, 2017–2019); CP1: construction phase I (July through October, 2015); CP2: construction phase II (April through September, 2016). Baseline period data were extracted from Project Years 1 and 2 for the same months as the impact period for each comparison. Model components include: block (B), year (Y), month (M), and bottom water temperature (standardized) (T). Model components indicated with a '*' include the main effects plus the interaction term, e.g. B*Y is Block + Year + Block:Year. For model details, see sections for impact phase by metric in Supplement 2

Impact period	Model	Temporal difference (impact phase − baseline)[a]		Spatial difference (Far Field − Near Field)		Interaction BACI $\text{Impact}_{(\text{Far}-\text{Near})} - \text{Base}_{(\text{Far}-\text{Near})}$ or $\text{Far}_{(\text{Impact}-\text{Base})} - \text{Near}_{(\text{Impact}-\text{Base})}$
		Near Field	Far Field	Baseline	Impact Phase	
Lobster CPUE						
OP	B*M*Y	−30 [−35, −26]	−18 [−23, −13]	100 [80, 121]	134 [114, 156]	17 [7, 28]
CP1	− B:M:Y	50 [36, 65]	−16 [−23, −9]	182 [149, 218]	58 [41, 78]	−44 [−50, −37]
CP2	+ $T + T^2$	62 [49, 76]	108 [91, 125]	125 [102, 150]	189 [156, 227]	28 [15, 43]
Percent ovigery (early- or late-stage adult females)						
Late stage (May–June)						
OP	B*M*Y − B:M:Y	−1.4 [−6.2, 3.2]	17 [14, 21]	−11 [−15, −6.6]	8.2 [4.4, 12]	19 [14, 24]
Early stage (September–October)						
OP	B*M*Y	1.5 [−2.9, 5.8]	9.1 [6.3, 12]	−19 [−22, −15]	−11 [−15, −7.5]	7.6 [3, 12]
CP1	− B:M:Y	5.1 [−0.3, 11]	21 [17, 25]	−19 [−22, −15]	−2.9 [−8.3, 2.6]	16 [9.4, 22]
Percent eggs spent (adult females June–August)						
OP	B*M +Y	−3.9 [−5.6, −2.3]	−12 [−14, −11]	8.7 [6.7, 11]	0.2 [−1.3, 1.7]	−8.5 [−9.6, −7.3]
CP1	+ M:Y	−8.2 [−9.8, −6.6]	−12 [−14, −9.9]	8.0 [5.9, 10]	4.4 [3.1, 5.6]	−3.6 [−4.8, −2.5]
Percent shell disease (ovigerous or spent females May–July)						
OP	B + Y	−1.7 [−2.7, −0.8]	−4.1 [−6.5, −1.8]	−8.8 [−10, −7.2]	−11 [−13, −9.1]	−2.4 [−4, −0.9]
Percent culls in males						
OP	B + M	−1.1 [−2.3, 0.1]	−0.4 [−1.3, 0.6]	−3.1 [−4.0, −2.2]	−2.3 [−3.2, −1.5]	0.8 [0.4, 1.1]
CP1	+ Y	−3.5 [−4.8, −2.1]	−2.2 [−3.3, −1.1]	−3.1 [−4.0, −2.2]	−1.8 [−2.5, −1.1]	1.3 [0.9, 1.7]
CP2		−2.4 [−3.6, −1.2]	−1.1 [−2.1, −0.1]	−3.3 [−4.2, −2.4]	−2.0 [−2.8, −1.2]	1.3 [0.9, 1.7]
Percent culls in females						
OP	B + M	−0.9 [−1.7, −0.1]	−0.2 [−0.8, 0.5]	−2.8 [−3.5, −2.1]	−2.1 [−2.8, −1.4]	0.7 [0.4, 1]
CP1	+ Y	−1.4 [−2.5, −0.3]	−0.4 [−1.2, 0.4]	−3.1 [−3.8, −2.3]	−2.1 [−2.8, −1.4]	1.0 [0.6, 1.3]
CP2		0.4 [−0.5, 1.3]	0.9 [0.2, 1.7]	−2.3 [−3, −1.6]	−1.8 [−2.5, −1.1]	0.5 [0.2, 0.8]

[a] For metrics expressed as percentages (e.g. culls, shell disease) the contrasts were calculated as differences on the original scale, so that results represent differences in percent response. For example, a temporal difference of +5% indicates the impact phase% response was estimated as the baseline phase + 5%. For CPUE, the contrast differences were calculated on the log-scale and back-transformed to the original scale, so results represent proportional change. For example, a temporal difference of −30% for CPUE indicates the impact phase CPUE was 30% of the baseline CPUE (e.g. 3/10). See Supplement 2 for more information for interpreting results

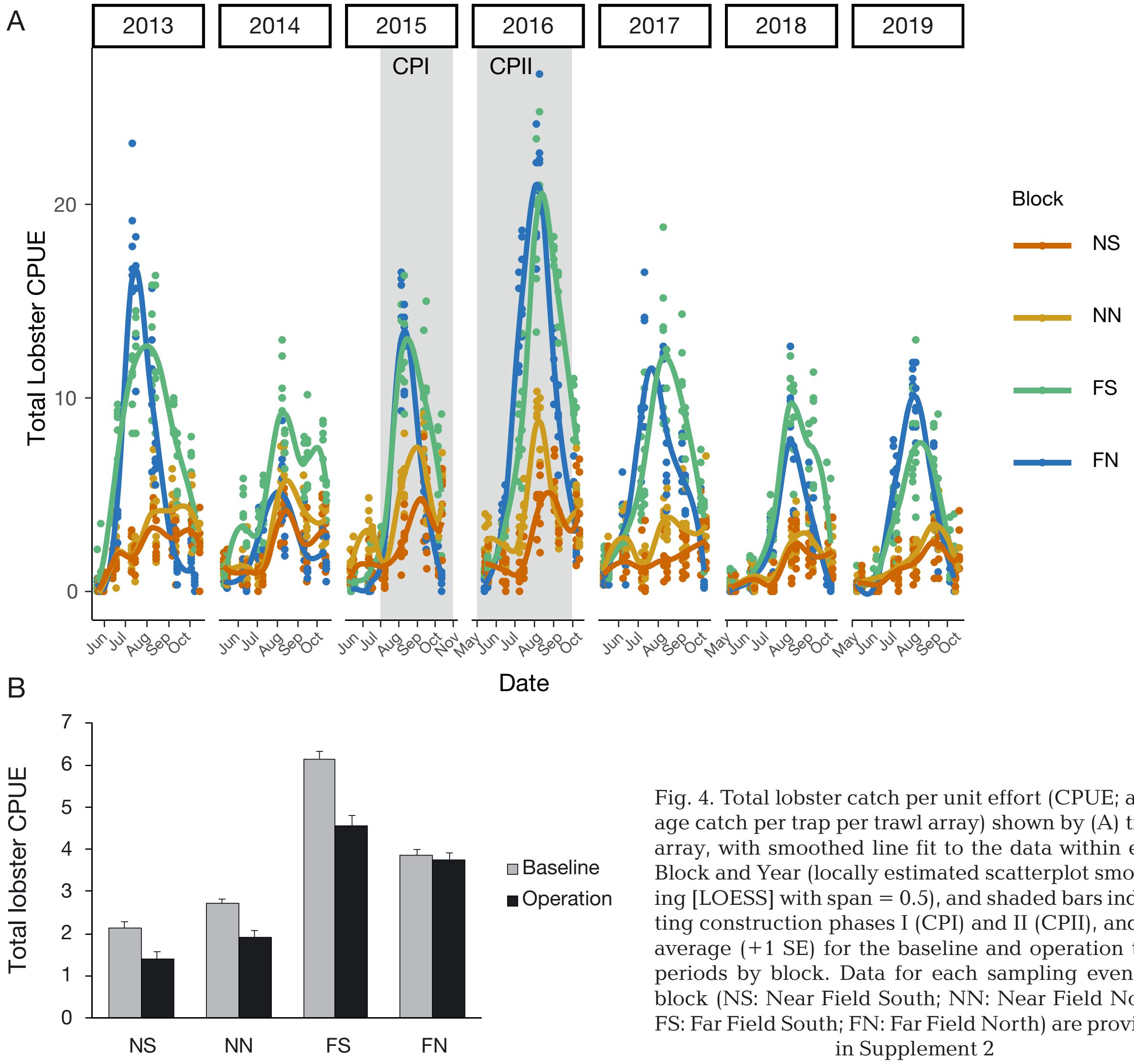

Fig. 4. Total lobster catch per unit effort (CPUE; average catch per trap per trawl array) shown by (A) trawl array, with smoothed line fit to the data within each Block and Year (locally estimated scatterplot smoothing [LOESS] with span = 0.5), and shaded bars indicating construction phases I (CPI) and II (CPII), and (B) average (+1 SE) for the baseline and operation time periods by block. Data for each sampling event by block (NS: Near Field South; NN: Near Field North; FS: Far Field South; FN: Far Field North) are provided in Supplement 2

3.2.2. Ovigery rates

Ovigery rates for late-stage ovigerous females (May and June) increased between the baseline and operation time periods in every survey block, with a greater observed increase in the Far Field (14%) compared to the Near Field (3%), resulting in a statistically significant BACI interaction (19%; 90CI = 14 to 24%). The highest average ovigery rates were in the NS (47%), FN (47%), and FS (59%) blocks for the operation time period (Fig. 5A). Estimated ovigery rates indicated a large increase from baseline to the operation time period in the Far Field blocks (17%; 90CI = 14 to 21%), whereas there was a smaller, and highly variable change in ovigery rates between time periods predicted for the Near Field blocks (−1.4%; 90CI = −6.2 to 3.2%). Temperature did not contribute significantly to the model. Month was a required factor in this model to be able to estimate *a priori* contrasts (Section 2.2). However, month could be considered a surrogate for temperature, and there were interactions between month and both block and year, indicating that the magnitude of the month (or temperature) effect changed depending on block or year, which means it is not possible to completely separate block and time period effects from temperature.

The percentage of females with recently hatched eggs (spent) decreased in all blocks between time periods, with a greater observed average decrease in the Far Field (−13%) compared to the Near Field (−6%) (Fig. 5B), resulting in a statistically significant BACI contrast (−8.5%; 90CI = −9.6 to −7.3%). Temperature was not a significant covariate in the model. Similar to the ovigery model, month was a necessary

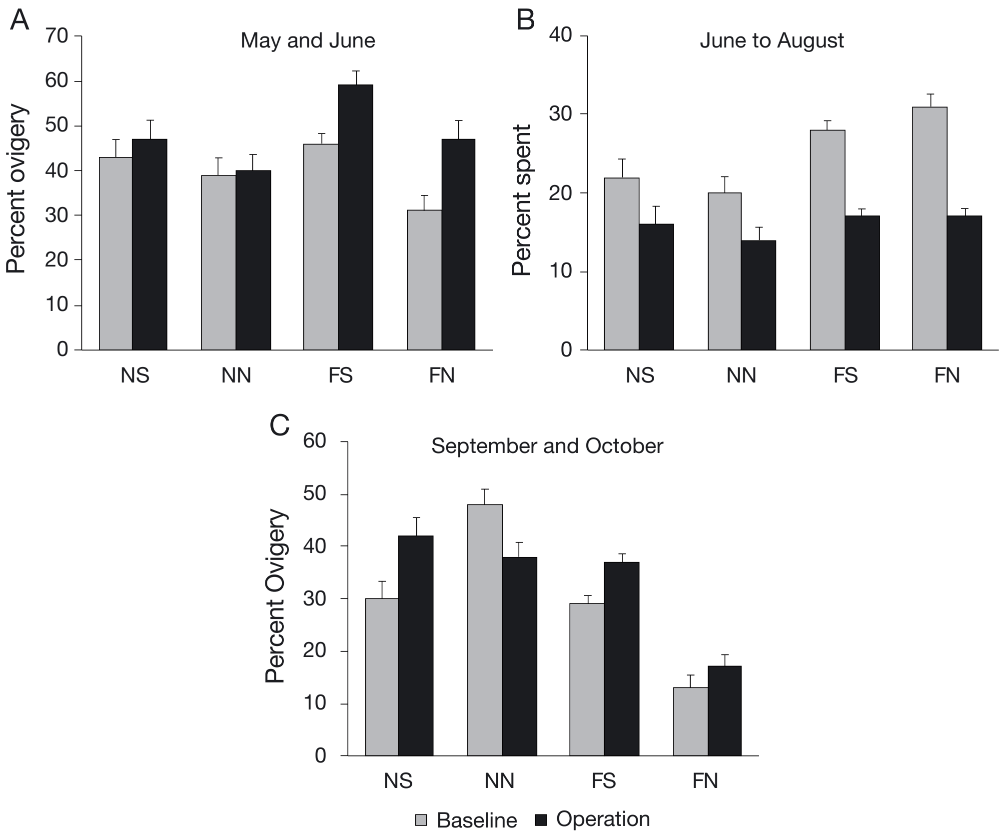

Fig. 5. Percent ovigery (+1 SE) for (A) late-stage female lobsters (collected May and June), (B) spent females (June to August), and (C) early-stage females (September and October) for the baseline and operation time periods for each block (NS: Near Field South; NN: Near Field North; FS: Far Field South; FN: Far Field North)

factor to be able to estimate the *a priori* contrasts (Section 2.2). The interactions between month (correlated with temperature) and both block and year indicate it may not be possible to completely separate block and time period effects from temperature.

There were differences in ovigery rates for early-stage ovigerous females (September and October) between locations and time periods (Fig. 5C), yielding a statistically significant BACI interaction (7.6%; 90CI = 3 to 12%). Estimated ovigery rates were lower in the Far Field compared to Near Field blocks during both the baseline (−19%; 90CI = −22 to −15%) and operation (−11%; 90CI = −15 to −7.5%) time periods. Ovigery rates increased from the baseline to the operation time period in the Far Field (9.1%; 90CI = 6.3 to 12%). Ovigery rates increased between the baseline and operation time periods at every block except NN (Fig. 5C).

3.2.3. Shell disease

The prevalence of shell disease (examined only for ovigerous females collected from May through July) was consistently higher during the baseline time period (Fig. 6). The proportional decrease in disease prevalence between time periods was greater in the Far Field, resulting in a statistically significant BACI contrast (−2.4%; 90CI = −4 to −0.9%). Estimated shell disease prevalence in the Far Field blocks decreased approximately 4% between time periods compared to a 2% decrease in the Near Field blocks. Overall dis-

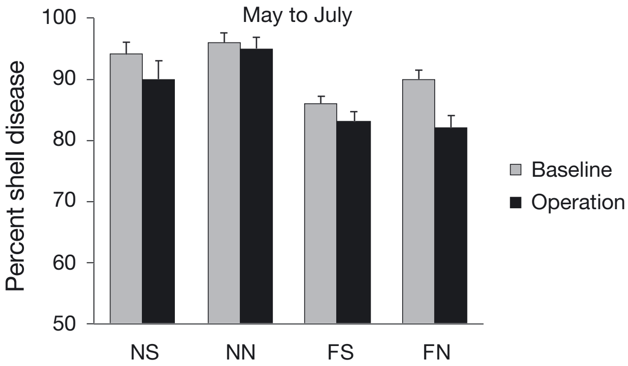

Fig. 6. Shell disease percentages for ovigerous/spent female lobsters collected from May to July depicted as averages (+1 SE) for the baseline and operation time periods for each survey block (NS: Near Field South; NN: Near Field North; FS: Far Field South; FN: Far Field North)

ease prevalence in the Near Field averaged approximately 94% compared to 85% in the Far Field over the baseline and operation time periods (Fig. 6). Temperature was not included in the model because concurrent temperatures are not likely related to shell disease, which develops over time.

3.2.4. Cull status

Cull rates varied between sexes ($p < 0.001$ for sex coefficient), so separate models were constructed for males and females. Male cull rates decreased slightly between the baseline and operation time periods in both the Near Field and Far Field, with a proportionally greater decrease in the Near Field (Fig. 7), resulting in a statistically significant BACI contrast (0.8%; 90CI = 0.4 to 1.1%). Temperature was not a statistically significant covariate in the model. Preliminary modeling indicated that month was not an important factor in the model, and variability in these data could be adequately described by block and year alone. However, month was a necessary factor in the model to be able to estimate the *a priori* contrasts (Section 2.2). Male cull rates across all blocks ranged from 10 to 12.5% during both the baseline and operation time periods (Fig. 7).

Female cull rates exhibited spatial–temporal differences (Fig. 7), with a greater estimated decrease in the Near Field between the baseline and operation time periods than in the Far Field (BACI contrast: 0.7; 90CI = 0.4 to 1.0%). Female cull rates were slightly lower in the Far Field during the baseline (−2.8%; 90CI = −3.5 to −2.1%) and operation (−2.1%; 90CI = −2.8 to −1.4%) time periods. Temperature was not a significant covariate in the model that included block, month, and year — factors which were required to be able to estimate all the *a priori* contrasts. Preliminary modeling indicated that block and temperature together were sufficient to adequately describe the variability in the data. Female cull rates across all blocks ranged from 8 to 10% during the baseline time period and 7 to 10% during the operation time period (Fig. 7).

3.2.5. Size distributions

Lobster size distributions were similar between the baseline and operation time periods in all survey blocks and reached a more pronounced peak for the 80.1–85 mm CL size class at the Far Field blocks compared to the Near Field blocks (Fig. 8). This peak was slightly higher during the operation time period in the Far Field. Smaller lobsters (<65 mm CL) comprised a greater proportion of the catch in the Near Field.

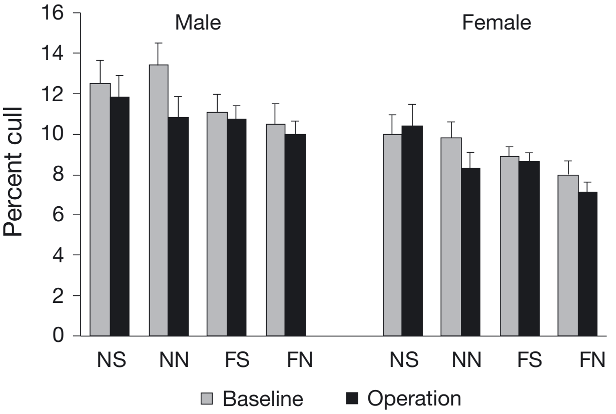

Fig. 7. Cull percentages for male and female lobsters depicted as averages (+1 SE) for the baseline and operation time periods for each survey block (NS: Near Field South; NN: Near Field North; FS: Far Field South; FN: Far Field North)

3.3. BIWF construction effects

3.3.1. Catch rate

For the construction phase I contrast, lobster CPUE increased between baseline and construction phase I time periods at the Near Field (50%; 90CI: 36 to 65%) and decreased in the Far Field (−16%; 90CI: −23 to −9%) (Fig. 9A), resulting in a statistically significant BACI interaction (−44%; 90CI = −50 to −37%). Also, estimated lobster catch rates were greater at the Far Field location compared to the Near Field location during both baseline and construction phase I time periods (Far Field CPUE was nearly 182% higher than Near Field locations during baseline and 58% higher during construction phase I).

Lobster CPUE increased in all blocks between the baseline and construction phase II time periods, with a greater increase in the Far Field (Fig. 9B), resulting in a statistically significant BACI interaction (28%; 90CI = 15 to 43%). The increase in catch between the baseline and construction phase II time periods was, on average, 3.3 lobsters trap^{-1} more at the Far Field location than the increase at the Near Field location.

3.3.2. Ovigery rates

Ovigery rates for early-stage ovigerous females were higher during construction phase I compared to the baseline time period at all blocks except NN (Fig. 10A),

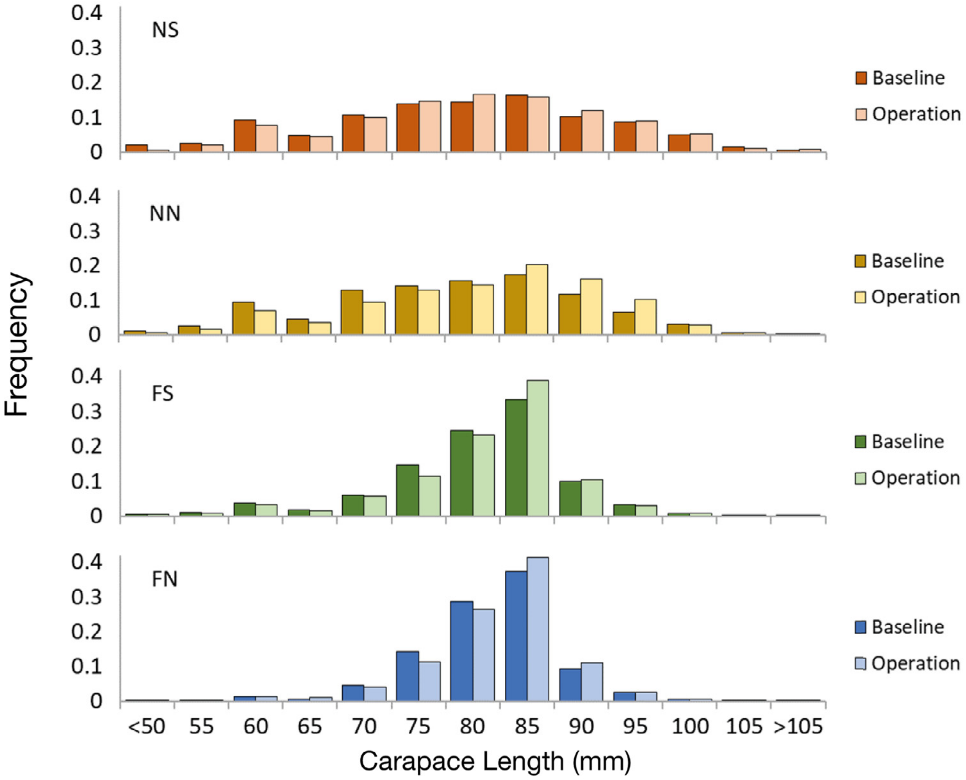

Fig. 8. Frequency of lobster by size category for the baseline and operation time periods for each survey block (NS: Near Field South; NN: Near Field North; FS: Far Field South; FN: Far Field North). The legal size for lobsters in the study area is 85.7 mm carapace length

resulting in a statistically significant BACI interaction (16%; 90CI = 9.4 to 22%). Higher ovigery rates during construction phase I occurred at the Far Field blocks (estimated increase of 21%; 90CI = 17 to 25%).

The percentage of spent females (June through August) was lower in the Near Field (−8.2%; 90CI = −9.6 to −6.6%) and Far Field (−12%; 90CI = −14 to −9.9%) locations during the construction phase II time period compared to baseline (Fig. 10B), with a greater proportional decrease in the Far Field yielding a statistically significant BACI contrast (−3.6%; 90CI = −4.8 to −2.5%). Additionally, the percentage of spent females was higher at the Far Field location during the baseline (8%; 90CI = 5.9 to 10%) and operation (4.4%; 90CI = 3.1 to 5.6%) time periods compared to the Near Field location. On average, the decrease in percentage of spent females between the baseline and construction phase II time periods ranged from a 9% decline in the NN block to a 15% decline in the NS block (Fig. 10B).

3.3.3. Cull status

Male cull rates were slightly lower during construction phase I in all survey blocks than cull rates observed in either of the baseline years, and this decrease was proportionally greater in the Near Field

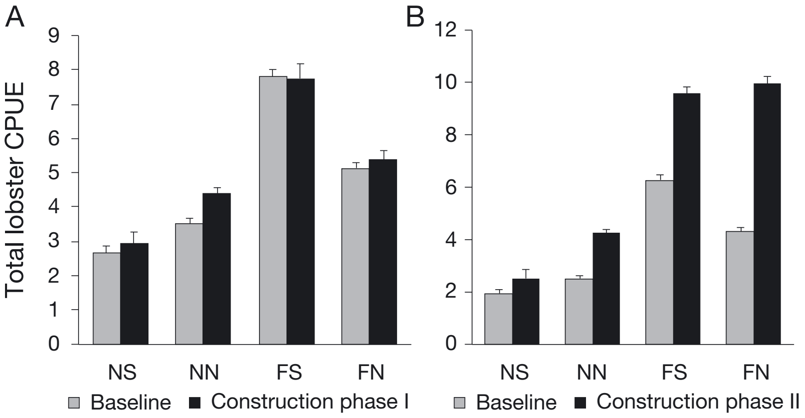

Fig. 9. Total lobster catch per unit effort (CPUE; average annual catch per trap per trawl array) as an average (+1 SE) for total lobsters for (A) the months July to October within baseline and construction phase I (2015) time periods by block, and (B) the months April to September within baseline and construction phase II (2016) time periods by block (NS: Near Field South; NN: Near Field North; FS: Far Field South; FN: Far Field North)

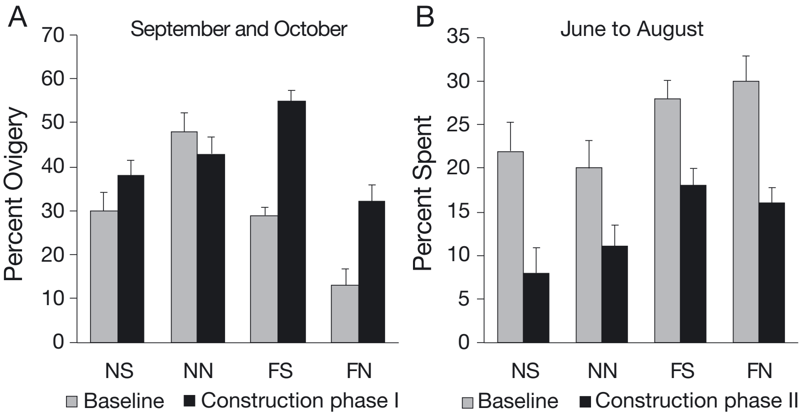

Fig. 10. Percentages (+1 SE) of (A) ovigerous female lobsters with early-stage eggs (September and October) for baseline years and construction phase I time periods, and (B) spent females (June to August) for the baseline years and construction phase II time periods for each survey block (NS: Near Field South; NN: Near Field North; FS: Far Field South; FN: Far Field North)

(BACI interaction: 1.3%; 90CI = 0.9 to 1.7%). The estimated decrease from baseline to the construction phase I time period was −3.5% (90CI = −4.8 to −2.1%) in the Near Field and −2.2% (90CI = −3.3 to −1.1%) in the Far Field.

During construction phase I months, female cull rates exhibited a statistically significant BACI contrast (1.0%; 90 CI = 0.6 to 1.3%) due to lower rates in the Far Field during the baseline time period (−3.1%; 90CI = −3.8 to −02.3%) and construction phase I time period (−2.1%; 90CI = −2.8 to −1.4%).

During construction phase II months, male cull rates also exhibited a statistically significant BACI contrast (1.3%; 90CI: 0.9 to 1.7%), with slightly lower rates in the Far Field blocks during the baseline (−3.3%; 90CI = −4.2 to −2.4%) and the construction phase II (−2.0%; 90CI = −2.8 to −1.2%) time periods. Similar to males, female cull rates were lower in the Far Field blocks during the baseline (−2.3%; 90CI = −3.0 to −1.6%) and the construction phase II (−1.8%; 90CI = −2.5 to −1.1%) time periods.

3.3.4. Regional context

Interannual variation in the catches of lobsters in the BIWF and the 21–40 m depth strata from the RIDEM and MADMF surveys from 2013 to 2019 showed similar patterns (Fig. 11). Catches were higher than average in 2016 in all 3 surveys, decreasing in 2017 regionally, and remaining lower than average in the BIWF and RIDEM surveys in 2018, which is when catches peaked in the MADMF survey. In 2019, catches were lower than average in all 3 surveys. The magnitude of interannual variation was highest in the MADMF survey (coefficient of variation [CV] = 51%), compared to the BIWF (CV = 36%) and RIDEM (29%) surveys.

4. DISCUSSION

Operation of the BIWF has occurred against a background of declining SNE American lobster harvests, standing stock biomass (ASMFC 2020), and abundances in fishery-independent surveys (McManus et al. 2021). Historically, the American lobster supported one of the most productive fisheries on the northeastern coast of the USA (Wahle et al. 2015, Carloni & Watson 2018), but in recent decades, harvests have decreased dramatically in SNE coincident with the onset of shell disease and increasing summer water temperatures (Glenn & Pugh 2006, Wahle et al. 2009). For instance, water temperatures in the northwest Atlantic have increased at a rate ranked in the top 1% globally (Pershing et al. 2015), and this temperature increase is associated with a northern shift in the distributions of lobster stock and fishing effort (Rheuban et al. 2017, Zou et al. 2021).

4.1. BIWF operation effects

At the BIWF, decreases in the lobster catch between the baseline and operation time periods occurred at

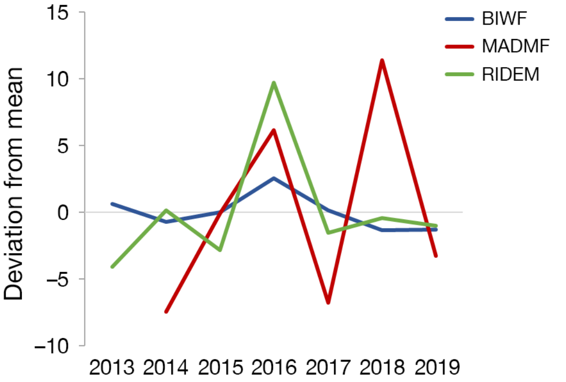

Fig. 11. Temporal variation in lobster catch per unit effort (CPUE) indices among the Block Island Wind Farm (BIWF), Rhode Island Department of Environmental Management (RIDEM), and Massachusetts Division of Marine Fisheries (MADMF) surveys depicted as the deviation from the mean for each survey

both the wind farm and reference locations, with very similar decreases in CPUE. However, because mean catch rates were lower at the wind farm, this decline was proportionally greater, yielding a statistically significant result with unclear ecological meaning because this finding is consistent with both an effect of wind farm operation and the regional shift in lobster distributions to cooler habitat. The wind farm is located in suboptimal lobster habitat with shallower depths and warmer water than the reference location. Average lobster catches decreased between the baseline and operation time periods at the wind farm (−30%; 90CI: −35 to −26%) and reference locations (−18%; 90CI: −23 to −13%), and catches were consistently higher at the reference location throughout the 7 yr study period. A greater proportional decline in catches in suboptimal habitat may reflect a tendency for aggregations to be more stable in favored habitat (Vidal et al. 2018), similar to the phenomenon of hyperstability in fisheries-dependent data, i.e. aggregations on favored habitat can buffer CPUE as the population declines elsewhere (Rose & Kulka 1999, Dassow et al. 2020). The more pronounced truncation of lobster size distributions at the legal-size limit (i.e. >85 mm CL [legal size = 85.7 mm CL]) at the reference location is consistent with higher fishing pressure (sensu Collie et al. 2016, Pugh & Glenn 2020) in this area, which was acknowledged as part of the study design. Results of this study, therefore, satisfy the objective of chronicling lobster responses to wind farm construction and operation on the local fishing grounds; however, lobster catch results cannot be clearly interpreted regarding a direct wind farm effect in the Near Field. In contrast, changes in other lobster metrics (ovigery, shell disease, and cull status) are not subject to the potential complication of hyperstability in favored habitat because these metrics were assessed as a proportion of the catch. Interpretations of significant BACI contrasts should focus on distinguishing between statistically vs. ecologically meaningful results. In the case of shell disease and cull rates, differences in temporal change between the wind farm and reference locations were a few percentage points and unlikely to be ecologically relevant. Ovigery contrasts yielded larger relative differences that merit future investigation via directed research.

Ovigery rates for females carrying late-stage eggs (May and June) increased between the baseline and operation time periods in all survey blocks and to a greater extent in the reference location. During both time periods, the proportion of these pre-hatch females was highest at the FS block, which had the coolest, average bottom water temperatures and the greatest bottom depths, indicating some habitat selection may occur at spatial scales of several kilometers. In the southern Gulf of Maine, where bottom water temperatures are generally lower than in SNE, females carrying late-stage eggs move to deeper, cooler water approximately 2 wk before hatching, where proximity to favorable currents may aid in the dispersal and survival of larvae (Carloni et al. 2021). Thus, females with eggs in the process of hatching tend to occupy deeper habitat (Carloni & Watson 2018).

The higher proportion of spent females (eggs recently hatched) during the baseline time period at the reference location was consistent with this area serving as a hatching site, which warrants further investigation to potentially inform larval transport models (e.g. Casey et al. 2023). The proportion of spent females was lower in all survey blocks during the operation time period and notably lower in the reference location. The use of spent female distributions as an indicator of hatching locations may not be as reliable as late-stage-egg female distributions because the visible duration of the spent phase is shorter, and therefore, more easily missed. Additionally, the identification of spent females can be somewhat subjective depending on the threshold of deteriorating cementum that is recognized as an indicator of this metric. The cementum on the pleopods of females that makes them identifiable as recently hatched is estimated to remain visible for approximately 2 to 3 wk (J. Carloni pers. comm. reported by Pugh & Glenn 2020).

The percentage of ovigerous females in September and October was consistently lower at the FN block, which was located furthest inshore, which is consistent with an offshore movement of newly-spawned females. Aggregations of ovigerous female lobsters occur in shallow waters in the spring and summer (Campbell 1990) and move offshore in the fall and winter where temperatures are warmer and more stable, thus maximizing their exposure to water temperatures that promote egg development (Aiken & Waddy 1986, Waddy & Aiken 1995, Cowan et al. 2007, Goldstein & Watson 2015). Female migrations may also improve proximity to favorable larval settlement habitat (Goldstein & Watson 2015) as egg-bearing females shift larval release seaward away from warming coastal habitat that exceeds their thermal preferences and that of larvae and early benthic-stage lobsters (Casey et al. 2023). The decrease in percentage of early-stage ovigerous females between the baseline and operation time periods only at the NN block is similar to the late-stage ovigerous female results and will require directed research to determine whether the distribution patterns are related to wind farm operation.

Shell disease prevalence also varied spatially and temporally, with a greater proportional decrease in the reference location between the baseline and operation time periods compared to the Near Field, where prevalence rates were higher. However, these changes were minor, i.e. only a few percent. The prevalence of shell disease was high (average = 90%) for the subpopulation assessed (females with late-stage or spent eggs), which was expected given higher disease prevalence prior to molting (e.g. Glenn & Pugh 2006). Shell disease may reflect an individual's weakened immune defenses, and increasing water temperatures can impair host defense responses (Barris et al. 2018). The association between shell disease progression and increasing temperature has been demonstrated with controlled experiments (Barris et al. 2018) and field studies demonstrating a latitudinal trend (Glenn & Pugh 2006, Castro & Somers 2012, Groner et al. 2018). In Long Island Sound, shell disease prevalence is related to temperature-induced molting and is highest in the fall (sampling from May to October), ranging from 30 to 80% following cooler vs. hotter summers, respectively (Groner et al. 2018). These percentages should not be compared to the percentages analyzed in the present study because only females carrying late-stage eggs and spent females were assessed for the BIWF analysis to control for shell age. Shell disease was not related to female fecundity in SNE (Goldstein et al. 2022).

Cull rates decreased during the operation time period relative to the baseline time period and were consistently higher in the wind farm than at the reference location. Spatiotemporal changes were consistent, but small in magnitude. The cull rates of male and female lobsters averaged 11.5 and 9.0%, respectively, in this study, which are similar to rates reported in other studies. Rates of claw loss near Prince Edward Island, Canada, ranged from 5 to 19% in the early 1970s (Scakratt 1973) and 7% in 2007 (Pickering & Quijon 2010). Fishery studies cited by Pickering & Quijon (2010) reported cull rates of 8 and 14% for the Maine lobster fishery, 8–15% in western Long Island Sound (LIS), and 18–21% off the coast of Massachusetts. Similar to this study, cull rates in LIS (Pickering & Quijon 2010) were higher for males than females.

4.2. BIWF construction effects

The higher lobster catches during construction phase I (when pile driving occurred) compared to the baseline time period at the wind farm location suggest that lobsters did not avoid the project area during turbine installation. In fact, the temporal increase in lobster catches in the Far Field was substantially smaller compared to the Near Field (BACI interaction: −44%; 90CI: −37 to −50%). Pile driving produces a loud (high-amplitude), impulsive, low-frequency sound that can propagate over long distances (Bailey et al. 2010) and overlaps with the hearing ranges of marine animals (Madsen et al. 2006, Hawkins et al. 2015), including lobsters (Jézéquel et al. 2021). The higher lobster catches at the reference location during the second phase of construction reflect regional trends. Catches throughout the region (BIWF, RIDEM, and MADMF surveys) were highest during 2016 when cable placement occurred. Catches also increased at the Near Field site during construction phase II (2016), but the increases were less pronounced than those observed at the Far Field site. The interaction may reflect less favorable conditions near the wind farm or more favorable conditions at the reference location for lobsters during the period of cable placement. Cable placement reduces sediment compaction over the pathway of the cable, elevates suspended sediments, and causes vibrations and noise. These disturbances are expected to be short term and localized near the cable route, which at its closest was 1.4 km from the sampling block NN. Cable installation required 2 periods of cable placement, from the Rhode Island shore to Block Island and from Block Island to the wind farm, including inter-array cables.

Ovigery rates for females with early-stage eggs were higher at all blocks during construction phase I compared to the baseline time period, except the NN block, which is the block closest to the wind farm. This difference may be due to fine-scale interannual variability in distribution. Although lower than the baseline time period, the percentage of ovigerous females at the NN block (44%) during construction phase I was higher than that at the NS (35%) and FN (32%) blocks.

4.3. Regional context

Interannual variation in BIWF lobster catches was similar to regional variation documented by RIDEM and MADMF state surveys in terms of the direction of deviation from each study's overall average catch; however, the magnitude of variation in the state surveys (MADMF overall and RIDEM in 2016) was considerably greater than observed at BIWF. The difference in sampling designs may have contributed to lower levels of variation in the BIWF study, i.e. state surveys use completely random designs within each depth stratum, whereas random samples in the BIWF study were restricted to fixed trawl lines within a smaller area. In addition, the state surveys sample over more varied bottom habitat. Relatively high catches occurred in all 3 surveys in 2016, but these catches were low relative to the early years (2006–2008) of the SNE lobster index (McManus et al. 2021).

A common challenge of monitoring studies conducted in recent decades is to distinguish between local anthropogenic effects and a shifting baseline related to climate change (Little et al. 2017, Sanford et al. 2019). In the case of American lobsters, warming temperatures coupled with increasing abundances of warm-tolerant predators, e.g. smooth dogfish *Mustelus canis* and striped bass *Morone saxatilis*, are associated with a northerly shift in the central biomass of SNE lobsters, with varying effects across their range (Boudreau et al. 2015). In this study, potential impacts of BIWF construction and operation were assessed using reference locations mutually selected with representatives of the fishing industry, which ensured that the survey design included important lobster fishing grounds. Siting the reference location in deeper, cooler water allowed the survey to chronicle potential changes in lobster metrics on fishing grounds relative to the wind farm site over the baseline, construction, and operation time periods. However, the difference in depths and temperature between the Near Field and Far Field locations may have confounded project impacts with unrelated temporal shifts in lobster distributions. Monitoring at BIWF is the first of its kind in North America and the design decision to document lobster metrics on fishing grounds was valuable to satisfy concerns of an important stakeholder; therefore, future OSW monitoring can concentrate on using comparable reference areas or gradient designs.

5. CONCLUSIONS AND LESSONS LEARNED

The BIWF ventless trap survey results demonstrate the regional trend of declining lobster catch rates, which were more pronounced at the shallower wind farm site. Although a potential effect of wind farm operation cannot be separated from regional shifts in lobster distributions to deeper, colder habitat, the study design effectively demonstrates that no major impacts of wind farm construction and operation on lobster catch were apparent in an area where the lobster fishery is locally concentrated. Despite tradeoffs in the study design, survey results provide important information and a robust data set to support design of future wind farm monitoring studies.

Monitoring efforts related to the burgeoning OSW industry in North America are changing, with the focus shifting to non-extractive sampling designs to reduce impacts from the monitoring itself on fisheries resources. For instance, a bottom trawl survey that monitored potential BIWF effects on demersal fish and invertebrates collected over 750 000 individuals over a 7 yr period (Wilber et al. 2022). Alternative monitoring methods for potential wind farm effects on lobster include acoustic telemetry, which can be used to track habitat use within wind farms (Thatcher et al. 2023) and movements of ovigerous and non-ovigerous females (e.g. Goldstein & Watson 2015, Skerritt et al. 2015, Carloni et al. 2021). There also is a growing concern about survey-related impacts on endangered/threatened species (e.g. right whales, sturgeons, sea turtles). It is important, therefore, to understand the strengths and weaknesses of the BIWF ventless trap study to leverage these results to enhance future monitoring efforts.

Although a BACI design is a standard approach to examine potential effects of OSW farms (e.g. Lindeboom et al. 2011, van Deurs et al. 2012, Degraer et al. 2016, Buyse et al. 2022) and for BIWF, was generated by representatives from multiple agencies, the fishing industry, and academia, it can have several limitations (sensu Methratta 2020), some of which were realized in the present study. Among our lessons learned are:

- Not all concerns about OSW impacts can be addressed with a single monitoring study. By assessing potential BIWF impacts on the lobster fishing grounds, study results were confounded with a potential hyperstability response in a region where the lobster population is declining.
- Finding an appropriate reference area with comparable habitat to a wind farm site that is beyond the spatial influence of potential wind farm effects can be challenging, thus a before–after–gradient (BAG) design for studies that use stationary gear may be more appropriate.
- The Near Field blocks were designed to measure effects adjacent to, but not within, the wind farm. With larger wind farm installations, a design that measures effects within a wind farm should be considered to address potential mechanisms of effects.
- Because several of the potential mechanisms of effect, e.g. responses to noise, vibration, EMF, and changes to benthic habitat are related to proximity to the wind turbines, a BAG design that targets sampling close to and progressively distant from wind turbine foundations may prove more effective.

- Collaborating with commercial lobstermen to harvest the BIWF catch provided an opportunity to remain engaged with the fishing industry, while retaining a consistent sampling protocol over the 7 yr study period.

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