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Feature Article

A novel approach to evaluate the effects of offshore energy infrastructure on the northern Gulf of America shrimp fleet

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ABSTRACT

Objective: The existence of offshore energy infrastructure in U.S. federal waters requires an understanding of how artificial structures impact regional fisheries. The Louisiana and Texas continental shelf in the northwestern Gulf of America (also known as the Gulf of Mexico) has a long history of offshore oil and natural gas development and harbors the penaeid shrimp fishery, the highest-valued commercial fishery in the region. Proposed wind energy areas (WEAs) on the shelf for offshore wind energy may disrupt this fishery due to spatial overlap with historical shrimping grounds and the fishery's use of bottom trawls.

Methods: We used high-resolution spatiotemporal data on shrimp fishery effort developed from vessel monitoring data to investigate how development of proposed WEAs might affect the shrimp fleet. We quantified patterns of shrimp fishing effort at multiple spatiotemporal scales. We also investigated the attraction and avoidance response by shrimp vessels to existing oil and natural gas rigs to infer how future construction of fixed structures affects the spatial dynamics and behavior of the shrimp fleet.

Results: Less than 2.5% of the total annual shrimping effort between 2015 and 2019 occurred within the proposed WEAs in the region, and while rigs were generally avoided, shrimper trawling behavior was modified in certain regions due to spatial constrictions. The density of rigs largely controlled how closely shrimp vessels operated near platforms. In areas with high rig density, most effort occurred at distances nearly equal to the horizon, suggesting that line of sight was an important factor driving shrimper fishing behavior.

Conclusions: Further consideration of the responses of the fishing fleet to structures will enhance our understanding of how ocean development for multiple uses will affect regional bottom trawl fisheries and provide insight into the applicability of these methods for future marine spatial planning in and beyond this region.

KEYWORDS: Atlantic white shrimp, bottom trawl, *Farfantepenaeus aztecus*, *Litopenaeus setiferus*, marine spatial planning, mixed effects regression, northern brown shrimp, spatial ecology, vessel monitoring system

LAY SUMMARY

Offshore rigs affect the behavior of shrimp trawling vessels on the Louisiana–Texas continental shelf, with vessels generally avoiding rigs by modifying their trawling in areas with high rig densities. Understanding these responses can assist future marine planning to balance energy development and fisheries sustainability.

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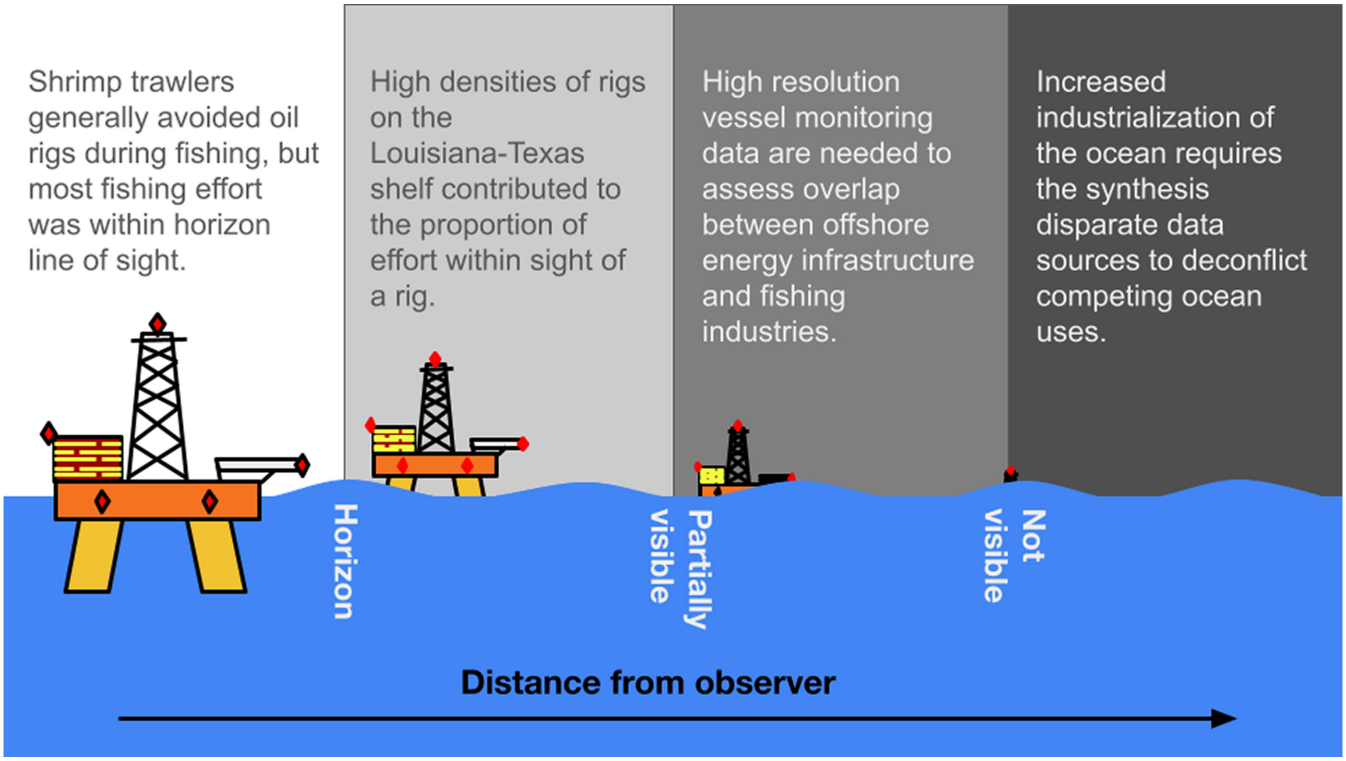
GRAPHICAL ABSTRACT



INTRODUCTION

The global development of offshore energy infrastructure has been rapidly advancing in the past decade from the construction of natural gas and offshore wind (OSW) platforms as a means to diversify energy production and expand Blue Economy initiatives (Gourvenec et al., 2022). Investment in OSW is regarded as a key part of many national and international decarbonization goals and over the past decade has become a factor in U.S. federal and state waters (Haggett et al., 2020). While the former U.S. Executive Branch led by President Biden set a goal of doubling OSW production by 2030 (Exec. Order No. 14,008, 2021), recent actions by the U.S. Executive Branch have put a pause on OSW leasing and have called for more research into the potential impacts of OSW infrastructure (Executive Office of the President, 2025). As of May 2024, the U.S. OSW energy operating capacity was approximately 174 megawatts (MW) generated by three projects (Block Island Wind [30 MW], Coastal Virginia Offshore Wind [12 MW], and South Fork Wind [132 MW]) and another 4,097 MW under construction in the U.S. Northeast and mid-Atlantic regions (McCoy et al., 2024). The effects of the growth of the OSW industry, which is on track to become a major use of marine space and a source of potential obstacles for humans and habitat for biota, are not well understood and vary locally and regionally (Methratta et al., 2023). There is a need to understand the effects of offshore energy infrastructure, including OSW, on marine fisheries from a historical perspective and during the planning phase before large-scale operational projects are completed to minimize conflicts among these sectors.

In previous evaluations of marine space use, a common approach has been to evaluate the historical distribution of harvested species or coarse-scale fishery footprints relative to areas that are proposed for development to infer their potential effects on fisheries (Gusatu et al., 2020; Randall et al., 2022). However, research concerning the effects of offshore infrastructure, particularly OSW development, on fisheries has previously been constrained to analyses of effort, catch, or abundance inside of a proposed wind energy area (WEA) versus outside of the proposed WEA (Randall et al., 2022). Many studies have focused on the potential disruptions to regional socioeconomics and recreational fisheries in prospective or existing OSW areas (Kirkpatrick et al., 2017; Navarro et al., 2022; Smythe et al., 2021; Stelzenmüller et al., 2021) or perceptions about multiple concurrent uses of ocean space (Haggett et al., 2020; Schupp et al., 2021). Other studies have speculated about potential effects on fisheries populations, but they have not conducted quantitative analyses due to insufficient monitoring data (Hooper & Austen, 2014; Perry & Heyman, 2020). Commonly, studies focus exclusively on effects on commercially valuable fish species in singular OSW areas (Jech et al., 2023) or using a single-species approach (Fayram & de Risi, 2007; Thatcher et al., 2025). Stanley and Wilson (1990) employed a fisheries-dependent approach to examine the species composition and relative abundance of fish that are associated with oil and gas structures in the U.S. Gulf of America (also known as the Gulf of Mexico; hereafter, referred to as "Gulf") from 1987 to 1988. There is limited research on the effects of fixed marine structures on spatiotemporal fishing effort or harvest due to the lack of high-resolution spatial data for most fisheries.

The effects of WEAs on the distribution of fishing effort are likely a more direct indicator of potential effects on fisheries, but the spatial dynamics of mobile fishing vessels are not widely available and thus are rarely considered. Therefore, information about the effects of fixed structures on the spatiotemporal dynamics of fisheries is rare. The effects of WEAs may vary spatially and temporally due to the typically high spatiotemporal heterogeneity that characterizes seasonally prosecuted and highly mobile fishing fleets. Inside versus outside analyses are limited because they (1) implicitly assume (future) behavioral responses that have not been observed and (2) do not consider the potential effects of spatial displacement that could occur beyond the boundaries of the proposed WEA. Therefore, quantifying the spatiotemporal responses of fishing fleets to current fixed structures in the marine environment could be a useful surrogate for how proposed future structures will likely affect fisheries.

The penaeid shrimp fishery is the highest-valued commercial fishery and ranks second in commercial landings in the Gulf (National Marine Fisheries Service, 2024). Landings are dominated by three species of shrimp: northern brown shrimp *Farfantepenaeus aztecus*, Atlantic white shrimp *Litopenaeus setiferus*, and northern pink shrimp *Farfantepenaeus duorarum*. The potential WEAs on the Louisiana–Texas (LA–TX) continental shelf (hereafter, "LA–TX shelf") in the northwestern Gulf overlaps with the distributions of brown shrimp and white shrimp, which are found in abundance in shallow (inshore) to medium depths (about 150 m) on the LA–TX shelf (Montero et al., 2016). Pink shrimp can be found in the southern Texas shelf but are primarily distributed off the Gulf coast of Florida (Etzold & Christmas, 1977). Brown shrimp and white shrimp dominate the LA–TX penaeid fishery, with white shrimp generally occupying shallower habitats (Zimmerman & Nance, 2001) and brown shrimp occupying shallow to medium-depth temperate waters (Etzold & Christmas, 1977) with abundant oxygen (Renaud, 1986). The Gulf shrimp fleet has been outfitted with vessel monitoring systems (VMS) since the early 2000s, allowing for detailed tracking of their movement throughout the Gulf.

The seasonal variability of Gulf shrimp fishery effort is partially driven by the timing of the annual Texas closure, which typically occurs from May 15 through July 15 (Gulf of Mexico Fishery Management Council [GMFMC], 1981). During this time, state and federal waters are closed to all shrimp fishing to allow newly recruiting shrimp to grow to larger sizes and thus contribute to higher exvessel revenues and reduced discards (Griffin et al., 1993). The closure of waters off Texas has the regional effect of concentrating brown and white shrimping effort off the Alabama, Mississippi, and Louisiana coasts. In the weeks before the opener, vessels will return to port to offload, restock supplies, and steam to Texas federal waters for what essentially is a fishing derby (Nance et al., 1991). This fervor of shrimping activity lasts a few weeks to a month before the fleet redistributes across the LA–TX shelf. There is some flexibility by the shrimp fishery participants to switch between species (i.e., brown, pink, and white) because the trawling gear is similar, and as a result, the regional distribution of shrimping effort is a function of the seasonal distribution of shrimp species. Some federally permitted shrimp vessels spend part of the winter months fishing for pink shrimp northwest of the Florida Keys (Scott-Denton et al., 2012).

The industrial evolution of the LA–TX shelf has progressed since the mid-20th century, adding structure to the otherwise relatively flat continental shelf. The extensive offshore oil and natural gas (ONG) industry on the LA–TX shelf may be used to infer potential effects of OSW development on the distribution of the shrimp fleet due to the similar nature of the structures. From 1947 to 2023, 7,165 documented rig structures and other infrastructure, including well heads and pipelines, were constructed across the LA–TX shelf (Bureau of Ocean Energy Management [BOEM], 2024; Shipp & Bortone, 2009; Yergin, 1991). The construction, space occupied, and eventual decommissioning of these platforms have affected and have been affected by recreational, subsistence, and commercial fishing activities, most notably the culturally and economically significant penaeid shrimp fishery (Priest, 2016). The underwater structures of the rigs are ecologically diverse and biologically productive (Kaiser & Pulsipher, 2005; Schulze et al., 2020), functioning similarly to artificial reefs. Whether the rigs are active or decommissioned and turned into artificial reefs, they are frequently visited by recreational fishermen and divers, significantly contributing to the recreational economy in a region (Brashier, 1988; Gordon, 1993; Kaiser & Pulsipher, 2005).

Starting in 2021, the U.S. Department of the Interior (DOI) began exploring the viability of OSW infrastructure development in the federal waters of the Gulf (DOI, 2021). Throughout the siting and environmental assessment phases of exploration, BOEM, with the support of the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Coastal and Ocean Science (NCCOS), conducted spatial suitability modeling (the NCCOS/BOEM suitability model [NBSM]) to determine optimal locations for future WEAs in the Gulf. The initial round of analyses resulted in 14 suitable WEAs (Randall et. al., 2022), and the approach has since been expanded to other basins in the U.S. exclusive economic zone that are being considered for OSW development. Following assessment and public comment, BOEM selected two Gulf WEAs for the first round of advancement, leading to a public lease offering of three areas within those blocks. In August 2023, BOEM held the first-ever OSW energy lease auction in the Gulf in the federal waters off of LA–TX, resulting in one lease to RWE Inc. (DOI, 2023).

Marine Spatial Planning (MSP) is an approach to organizing uses of marine space and has been used for numerous offshore development activities on the LA–TX shelf; however, the sheer number of sectors—including oil and gas extraction, economically important fisheries, and shipping activities—and planning efforts has resulted in an overall negative impression of MSP by stakeholders in the region (Collier, 2013). Due to the historic use of the LA–TX shelf by the shrimp fishery, there was a concern that any OSW development may disrupt the fishery due to the potential spatial overlap of the two industries (Randall et al., 2022). The NBSM included spatial patterns of shrimping effort as one of several human-use, biological, and political factors aggregated across seasonal and annual time scales to identify areas that minimize multiuse conflicts. The development of additional offshore infrastructure creates inherent trade-offs because the structures may limit the types of fishing gear due to operational hazards, but refuge effects may translate into spillover, boosting the overall population productivity (Craig & Link, 2023). The specific effects of offshore infrastructure such as OSW farms in the region are not fully understood, and new offshore infrastructure must compete for space with existing industries.

This article's overarching objective was to understand how the offshore infrastructure affects the shrimp fishery on the LA–TX shelf. Evaluating the potential effects of OSW on marine capture fisheries requires information on the likely responses of fishing fleets to fixed artificial structures in the environment. Our goal was to analyze the spatial scale at which shrimp vessels respond to offshore oil rigs during normal fishing operations to gain insight into the effects that structure has on shrimping effort and thus infer how the fleet might respond to OSW. Our study approach was broadly divided into two research directions. First, we quantify the spatiotemporal patterns of shrimp effort inside versus outside the currently proposed WEAs at multiple spatial (0.5 km to shelfwide) and temporal (seasonal to annual) scales to understand how proposed WEAs potentially affect the fishery. Second, we analyze the spatial responses of shrimp vessels to existing oil rigs in the Gulf at different spatial scales to infer how fixed structures in the marine environment affect the spatial dynamics of the shrimp fleet.

METHODS

Data

Shrimp fishery effort

The shrimp fishery effort estimation method described here used the same raw VMS data that was used for the NBSM (Randall et al., 2022) and prior studies (Gallaway et al., 2003a, 2003b; Purcell et al., 2017). For our analyses, an algorithm that was developed by Dettloff (2024) determined shrimping effort in hours fished as described here. Raw position pings were filtered to retain pings within the Gulf the occurred at less than a specific depth (150 m), and vessel speed was calculated using time and distance traveled. Pings with unrealistic speeds (>21.3 kph or 11.5 knots) were removed, and vessel speeds of less than 1.9 knots were considered stopping or idling. Effort was identified as consecutive pings at trawling speed (3.5 to 6.6 kph or 1.9 to 3.6 knots) for a minimum of 1 h with a minimum transition time of 10 min between trawling activities. Shrimp vessels were selected for the VMS program using a spatially stratified random sample that was weighted toward vessels with more landings in the years before selection. The randomized nature of the federal VMS program vessel selection process lends support to our assumption that the spatial distribution of the VMS data within strata is representative of the federally permitted shrimp fleet.

Wind energy areas

The NBSM identified 14 WEAs consisting of 2,398,150 acres (9,705 km^2) of suitable ocean area, with WEAs ranging in size from 39,836 to 546,645 acres (161 to 2,212 km^2, Randall et al., 2022). The total area that was considered in the suitability model was 29,693,940 acres (120,167 km^2). The 14 potential WEAs on the LA–TX shelf represent about 6% of the area that is typically trawled by shrimp vessels, with the majority in Texas federal waters (Figure 1). Each WEA contains at least seven potential lease blocks, based on the space that is needed to produce an economically viable amount of energy (Randall et al., 2022). The shapefiles for the WEAs, the RWE lease block (awarded in August 2023, within WEA M), and other lease areas that are currently being considered in the public sale notice as of December 2024 (within WEAs C and D) were accessed directly from NCCOS (Figure 1; BOEM, 2024). Shrimp trawling activity was 1 of about 75 data layers that were considered; other layers included military operating areas, other commercial fishing activity, protected species distributions, vessel traffic and shipping fairways, marine protected areas, and oil and natural gas leases, among others. The NBSM identified shrimp trawling activity using raw VMS data from January 1, 2015, to December 31, 2019, binned to a 100- × 100-m grid, and summed per day, and the mean days trawled per year was calculated. Cells with more than 4.5 mean days of active trawling were considered unsuitable for OSW development due to "moderate to high" shrimping effort (Randall et al., 2022).

Bureau of Ocean Energy Management platform data

Data on the offshore ONG infrastructure on the LA–TX shelf were obtained from BOEM's data repository (BOEM, 2024). We limited our analysis to the platform structure database, which is a comprehensive list of all offshore rigs that are located within the outer continental shelf of the Gulf, stretching across the U.S. exclusive economic zone (i.e., 12 nautical miles [nmi] territorial sea to 200 nmi offshore). The platform database contains coordinates, installation date, removal date, site clearance date, structure type, water depth, and whether the structure is connected to other platforms by a walkway (https://www.data.boem.gov/Platform/PlatformStructures/FieldDefinitions.aspx). To match the shrimp VMS data, we retained the rigs that were constructed before the year of matching VMS data and removed the rigs that were listed as cleared before the year of interest. Additionally, we counted rigs that were attached by a walkway as one structure.

Analysis

Spatiotemporal patterns in shrimping effort

We restricted our analyses to shrimp effort within the LA–TX shelf, statistical zones (StatZones) 13–21, where WEAs are proposed and the majority of the shrimp fishing has been conducted (Figure 1). Only the years from 2015 to 2019 were used for the analysis because the pre-2015 and post-2019 data were subject to reporting inconsistencies. The total number of self-reported shrimp vessels that were active per year (Smith & Williams, 2023) was used to calculate the proportion of the shrimp fleet with VMS installed. Shrimp vessel activity was aggregated to assess the spatiotemporal patterns of shrimping effort and the number of vessels in both StatZones and WEAs per month and per year. We use StatZones as a consistent unit of spatial aggregation because they are the spatial zones in which shrimp effort and landings have historically been reported (Patella, 1975). Total effort (hours trawled) was summed per year for each StatZone, and median vessel effort was calculated per month per StatZone. The corresponding quantities were also calculated for each WEA. The effort per month for both StatZones and WEAs were divided by the area of interest in

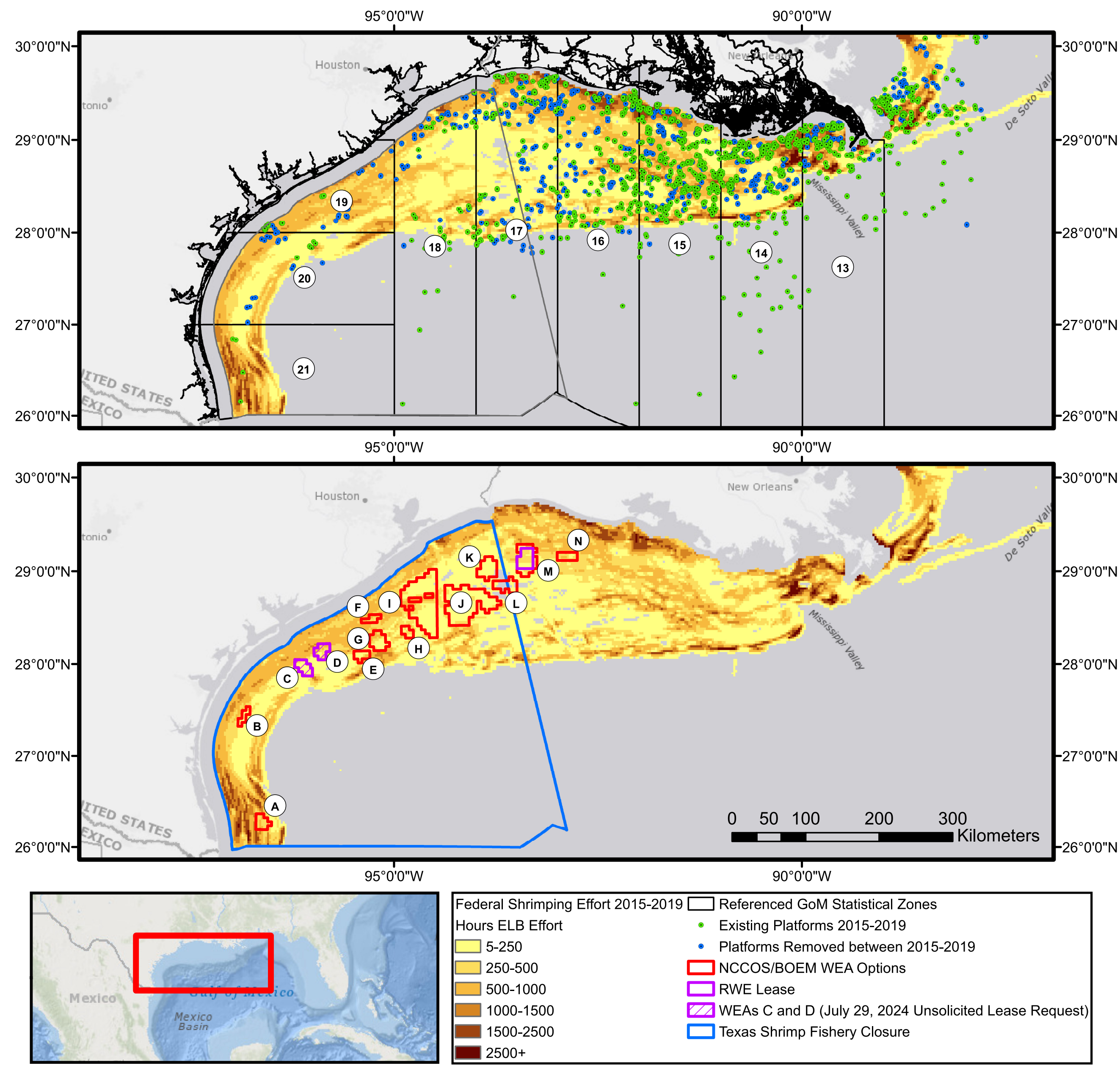


Figure 1. Spatial domain of the vessel monitoring system data used in this analysis, overlaid with information about active and removed oil and natural gas rigs from 2015 to 2019 and Gulf statistical zones (top) and the distribution of Gulf wind energy area (WEA) options identified by the National Centers for Coastal and Ocean Science (NCCOS)/Bureau of Ocean Energy Management (BOEM) suitability model, the RWE lease, and the Hecate noncompetitive lease request (bottom). Total shrimping effort in hours trawled from 2015 to 2019 is displayed on both top and bottom maps. The boundary of the Texas federal waters is displayed in blue, indicating where shrimping is prohibited during the annual Texas closure.

square kilometers to obtain effort density (h/km^2) to compare between the areas.

Shrimping effort near oil rigs

We performed several analyses to assess the spatial scale at which shrimp vessels engage in fishing operations near rigs. The first analysis applied a series of circular buffers that varied in size (i.e., 0.5, 1, 2, 3, 5, 7.5, 10, 12.5, 15, 17.5, 20, 25, 30, 40 km) around each ONG rig and then summed the shrimping effort (hours spent trawling) within each buffer per StatZones (Figure 1) by year. These summations were then converted to proportions by dividing by the total effort within each StatZone per year. We summed all the vessels that spent any amount of time fishing in the same buffers to capture the proportion of the instrumented vessels that approached rigs within the respective buffer during trawling. When the size of the buffer was large enough to touch another buffer, the summation was a union of the buffers so that the summation of effort was not duplicative. We used the data for shrimp effort to create subsets for federal waters that were 3 (Louisiana) or 9 (Texas) nmi

(5.6 or 16.7 km, respectively) from shore to the 150-m isobath, which represents the limit of shelf that is fished by the shrimp industry for penaeid shrimp species. Buffers were clipped to the StatZones of interest and federal waters to prevent counting effort outside the StatZones.

We also performed a series of randomization analyses to assess the association between shrimping effort and the distribution of rigs. First, we selected a random sample of VMS pings ($n = 90{,}000$ or 10,000 per StatZone) and then summed the number of rigs within the previously used buffer distances from each ping. We then repeated the analysis by selecting random points ($n = 90{,}000$ or 10,000 per StatZone) and then summing the number of rigs within the buffer distances to estimate a null distribution. The difference in rig encounter rate between the subsampled VMS data and random points approximates avoidance or attraction behavior. The results of these analyses are referred to herein as the rig encounter metric.

We did not know the spatial scales over which shrimp vessels are able to locate and potentially respond to rigs. As a result, we developed a method to approximate which of the spatial scales (i.e., buffers) that we described earlier are potentially the most relevant to shrimpers. We then calculated several line-of-sight distances to put the buffer analysis into a context that is relevant to the shrimp fleet. These distances are based on an estimate of how far the horizon would be as observed from the wheelhouse of a shrimp vessel. We also calculated several distances that were slightly beyond the horizon because rigs are tall structures that can still be seen if they are over the horizon. Distance to the horizon was calculated as follows:

$$Dh = \sqrt{2 \times Re \times hw}, \qquad (1)$$

where Dh is the distance to the horizon from the shrimp vessel; Re is the radius of the earth, which was assumed to be 6,367.45 km; and hw is the height of the wheelhouse, which was assumed to be 15 ft (4.572×10^{-3} km). We also calculated the distance between the shrimp vessel and a partly visible rig and when just the very top was visible. The latter assumes that the rig has a light at its peak and is visible primarily at night when most shrimp trawling occurs. These distances were calculated as follows:

$$Db = Dh + \sqrt{2 \times Re \times hr}, \qquad (2)$$

where Db is the distance between the shrimp vessels and rigs, Dh is Equation 1, and hr is the height of the rig, which was assumed to be 150 ft (4.572×10^{-2} km). The rig height was multiplied by one-third and one-half to get the distance at which the top two-thirds and top half were visible, respectively, and the full height was used to calculate the distance when just the top of the rig was visible. These distances were 7.6, 21.6, 24.7, and 31.8 km for the horizon, top two-thirds, top half, and just the top being visible, respectively. These calculations neglect what can be seen on radar and electronic charts, and we assumed that sight is the primary driver of shrimp vessel behavior during trawling around rigs. Additionally, these calculations assume perfect conditions and disregard sea state such as wave height and any refraction effects that can further affect visibility.

Response of shrimpers to rigs

To further characterize the response of shrimpers to fixed structures, we analyzed the change in shrimping effort before versus after the removal of oil rigs at two spatial scales (1 and 7.5 km). These two distances were chosen to capture effort at relatively small scales and relatively large scales to cover a range of decision-making time frames. A shrimp boat will move 1 km in approximately 15 min moving at 4.63 kph (2.5 knots a typical trawling speed), whereas a shrimp boat will reach the horizon (7.5 km) in approximately 1 h and 40 min if moving in a straight line. We expected effort to be higher in the year after removal relative to the year before removal if fixed structures (e.g., oil rigs) significantly alter the spatial distribution of shrimping effort. The original intent of this research was to examine changes in shrimp effort in response to the construction of new rigs on the LA–TX shelf as a proxy for OSW farm construction. However, preliminary investigations showed that only six ONG rigs were installed during the period of our analysis (i.e., 2015–2019; BOEM, 2024). After filtering for removals that had effort in the years before and after (2016, 2017, and 2018), only two rigs remained for analysis. Therefore, we decided to characterize changes in shrimp effort before and after the removals of rigs to gain insight into how fixed structures affect the spatial dynamics of the shrimp fleet.

We compared shrimp effort within a rig removal site in the year prior and the year postremoval using generalized linear mixed-effects regression models. We filtered the data to include rigs that were removed in the years of interest (2016, 2017, and 2018), applied a buffer around each rig, and summed the effort in the year prior and the year after removal (referred to as treatment and coded as pre- and postremoval). Effort during the year of removal was not included in the calculations because we assumed there would be a lag between removal and shrimpers taking advantage of new territory. Total effort was summed by StatZone pre- and postremoval and included in models as a fixed effect to control for overall differences in effort between years. The data were filtered using a 1-km buffer and a 7.5-km buffer (the horizon distance) and modeled separately. Shrimp effort near the rigs was highly right-skewed, with some mass at zero. Thus, effort was assumed to follow a Tweedie distribution, with mean μ and variance $= \phi\mu^p$ where ϕ is the dispersion parameter and p the power parameter, both estimated by maximum likelihood. Fixed effects included StatZone (categorical with eight levels), total StatZone effort (continuous), and treatment (categorical with two levels; preremoval and postremoval). The interaction terms were StatZone × total StatZone effort and treatment × StatZone. We modeled complexID (a unique identifier for each rig complex) as a random effect to account for the nonindependence of observations that are obtained from the same rig complex removal site. The full generalized linear mixed-effects regression model was defined as follows:

$$\begin{aligned}&\text{Effort}_{ijk} \sim \text{Tweedie}(\mu_{ijk})\\&\log(\mu_{ijk}) \sim \text{StatZone}_i + \text{TotalEffortStatZone}_{ij} + \text{Treatment}_{ijk}\\&+ \text{StatZone}_i \times \text{TotalEffortStatZone}_{ij} + \text{StatZone}_i\\&\times \text{Treatment}_{ijk} + (1|\text{ComplexID}_i)\ \text{ComplexID}_i \sim N(0,\sigma^2),\end{aligned} \tag{3}$$

where Effort_{ijk} is the *j*th observation in complex *i* for each buffer *k* and ComplexID_i is the random intercept, which was assumed to be normally distributed with a mean 0 and variance σ^2. Two reduced models ("treatment" model and null model) were tested per buffer area to assess the significance of individual terms. The "treatment" model was the full model (Equation 3) including the main effect of treatment but with the interaction between StatZone and treatment removed,

$$\begin{aligned}&\text{Effort} \sim \text{StatZone} + \text{TotalEffortStatZone} + \text{Treatment}\\&+ \text{StatZone} \times \text{TotalEffortStatZone} + (1|\text{ComplexID}),\end{aligned} \tag{4}$$

and the null model removed the treatment effect entirely.

$$\begin{aligned}&\text{Effort} \sim \text{StatZone} + \text{TotalEffortStatZone} + \text{StatZone}\\&\times \text{TotalEffortStatZone} + (1|\text{ComplexID}).\end{aligned} \tag{5}$$

Likelihood ratio tests were performed on the nested models to test for differences at alpha = 0.05 in the removal effect by StatZone and an overall removal effect, respectively. The model in Equation 3 and nested models were fit using the glmmTMB package, version 1.1.9 (Brooks et al., 2017). Diagnostic tests were performed using the DHARMa package, version 0.4.6 (Hartig, 2022), and contrasts were calculated using the *glht* function in the multcomp package, version 1.4-26 (Hothorn et al., 2008) in R version 4.4.0 (R Core Team, 2024).

RESULTS

Shrimp fishery effort

The total shrimping effort per year estimated from the VMS data was relatively constant across the years examined (median 597,488 h, range 546,765 [2019] to 614,159 [2016] h; Table 1). The number of vessels participating in the VMS program was also relatively constant (median 42%, range 40% [2015 and 2017] to 47% [2018]; Table 1). The proportion of the shrimp fleet participating in the VMS program increased from 41% (2017) to 47% (2018) as the number of self-reported active shrimp vessels decreased (Smith & Williams, 2023; Table 1). There was some vessel turnover with approximately 47% of vessels fishing all 5 years and approximately 10% of vessels fishing only 1 year.

Overall, the distribution of shrimp effort across the LA–TX shelf followed distinct patterns that were partially controlled by the depth of the shelf break (Figure 1). Near the mouth of the Mississippi River, the shelf is narrow, constraining the fishable bottom and increasing the densities of effort. As the shelf widens west of the Mississippi River, the spatial distribution of shrimp effort spread out and a bimodal distribution was observed with a distinct nearshore and offshore effort distribution, especially off the Texas coast (StatZones 19–21). An exception to this general pattern was StatZone 21, in which lanes of relatively high effort were observed distributed throughout the depth range (Figure 1); however, the effort was bimodally distributed across StatZones 19–21 in the months right after the Texas opener (July–August), and effort shifted closer to shore (StatZones 19–20) and consolidated in the latter months of the year (September–December in StatZone 21) (see online Supplementary Material, Figure S1).

Shrimping effort followed a seasonal pattern with low effort across all StatZones in the LA–TX shelf (StatZones 13–21) during January–April, which then increased in StatZones off the Louisiana coast (StatZones 13–16) during May–June, coinciding with the Texas closure on May 15th (Figure 2A; see Figure S2 for individual years). Effort increased in mid-July in the StatZones off of Texas (StatZones 17–21) concurrently with the Texas opener on July 15th (Figure 2A) as effort decreased in the Louisiana StatZones during the same period. The number of vessels per StatZone (and per WEA) per month followed similar patterns to the effort results, translating to a relatively constant effort per vessel per StatZone (not shown) per month.

Wind energy areas

The area occupied by the WEAs contained about 3.5% of all effort (or about 104,000 h out of 2,950,000 h) within the LA–TX shelf (StatZones 13–21) from 2015 to 2019 in federal waters out to the 150-m isobath. The proportion of shrimping effort per StatZone that occurred within the WEAs was low (median 3.7%, range 0.9% to 16.1%), and WEAs within StatZone 18 (H, I, and J) had the highest proportion of total shrimping effort per StatZone (16.1%, Table 2). The annual effort within the WEAs was relatively constant (Figure S2), and the majority of the effort within the proposed WEAs was concentrated in the two largest WEAs (WEAs I and J; see online Supplementary Material, Table S1).

Shrimping effort in the WEAs followed a seasonal pattern (Figure 2B) that was consistent with the seasonal effort in the StatZones. For example, effort in the Louisiana WEAs (M and N) was highest in the spring and summer, coinciding with the

Table 1. Annual summary of vessel monitoring system (VMS) data. Proportion VMS corresponds to the number of active shrimping vessels with VMS units divided by the total active federally permitted shrimp vessels.

Year	Total effort (h)	Total VMS vessels	Total vessels	Proportion VMS
2015	602,435	409	1,012	0.40
2016	614,159	422	1,015	0.42
2017	597,488	413	1,009	0.41
2018	588,446	452	963	0.47
2019	546,765	403	911	0.44

Table 2. Summary of active oil and natural gas rigs, vessel managment system (VMS) effort, and wind energy area (WEA) distribution sorted by statistical zone (SZ); N/A = not applicable.

SZ	SZ area (km²)	Rigs per SZ	Rig density (1/100 km²)	Median rig nearest neighbor (km)	Total VMS effort 2015–2019 (h)	Effort density (h/km²)	WEAs within SZ	SZ effort proportion within WEA
13	4,113	227	5.52	0.96	194,431	47.3	0	N/A
14	9,730	396	4.07	0.98	298,860	30.7	0	N/A
15	14,181	508	3.58	1.15	423,824	29.9	0	N/A
16	17,375	312	1.80	1.73	469,391	27.0	1	0.01
17	19,683	263	1.34	2.11	346,716	17.6	4[a]	0.05
18	15,407	79	0.51	2.68	291,347	18.9	3[a]	0.16
19	8,799	42	0.48	1.88	315,707	35.9	5[b]	0.08
20	12,178	23	0.19	3.64	233,936	19.2	2[b]	0.01
21	7,658	3	0.04	4.13	375,049	49.0	1	0.02

[a]StatZones 17 and 18 share WEA option J.
[b]StatZones 19 and 20 share WAE option C.

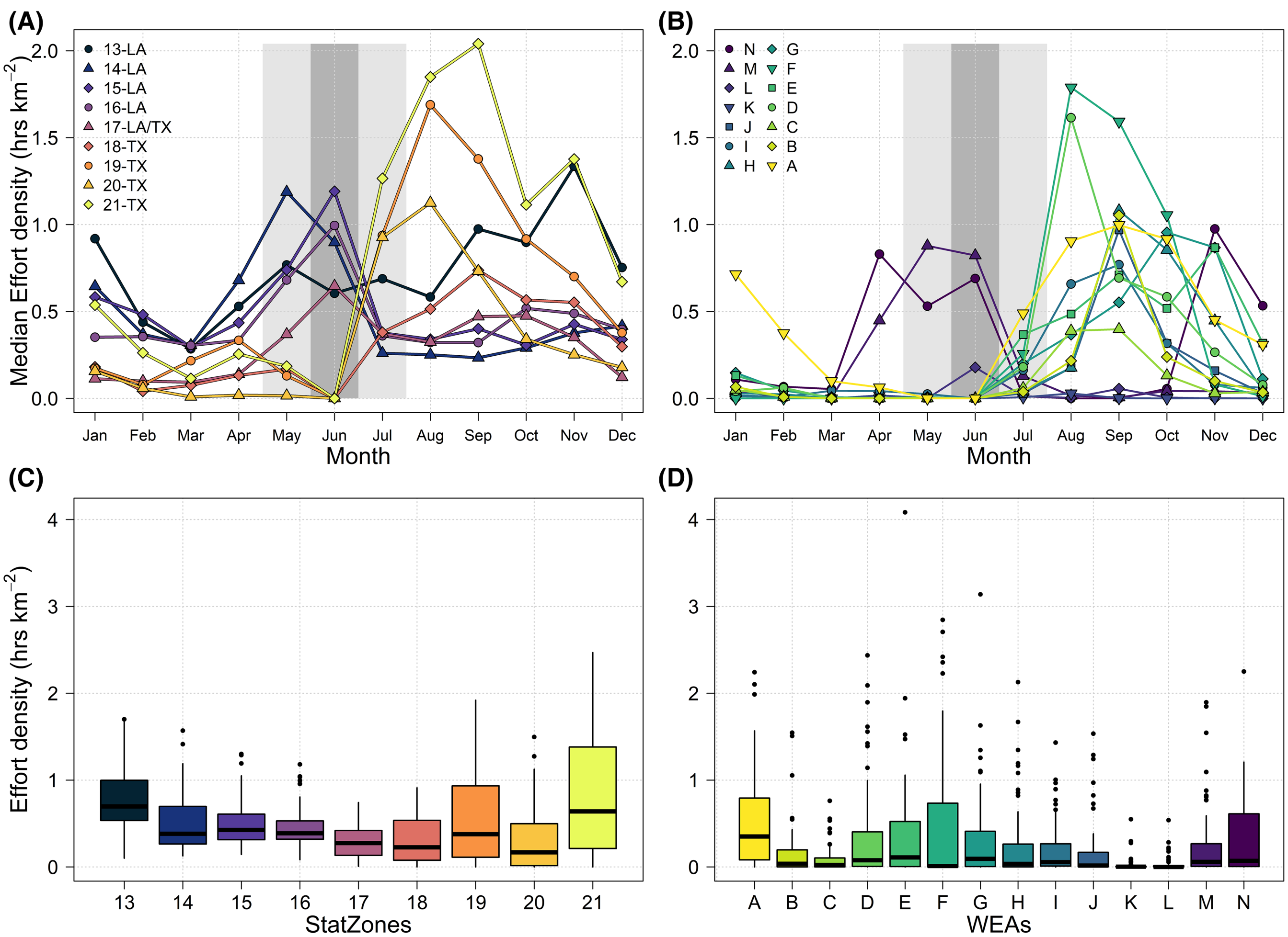


Figure 2. The plots display seasonal patterns of median shrimping effort density (h/km²) per (A) statistical zone (StatZone) and (B) wind energy area (WEA). The box plots display the monthly effort densities (h/km²) per (C) StatZone and (D) WEA. The gray bars represent the timing of the Texas closure (May 15–July 15). Note that the ranges of the ordinate axes differ between the top and bottom panels.

Texas closure (Figure 2B). Then, the effort shifted westward into the WEAs in Texas federal waters (A–L) after the Texas opener (Figure 2B; Figure S4). The number of vessels per WEA per month followed patterns that were similar to the effort results, translating to a relatively constant effort per vessel per WEA (not shown).

In the areas where leasing is actively occurring or being pursued (RWE lease area in WEA M, WEAs C and D as of July 29, 2024), the total VMS effort was about 14,000 h (or about 6,700 h in RWE lease, 1,700 h in WEA C, and 6,000 h in WEA D) from 2015 to 2019. The RWE lease and WEAs C and D account for only 0.5% of the total effort on the LA–TX shelf between 2015 and 2019 (or about 0.02% for RWE, 0.001% for WEA C, and 0.02% for WEA D).

Shrimping effort near rigs

From 2015 to 2019, 6 rigs were constructed and 585 rigs were removed, with 1,480 rigs remaining on the LA–TX shelf at the end of 2019. The median nearest neighbor distance between rigs that was not linked by a walkway was 1.9 km (range 1.0 km [StatZone 13] to 4.1 km [StatZone 21]). The median number of rigs per StatZone was 227 (range 3 [StatZone 21] to 508 [StatZone 15]), and the StatZones with the highest densities of rigs were offshore Louisiana (StatZones 13–16; Figure 1; Table 2). The rigs tended to be distributed across the continental shelf, the median depth distribution was less than 50 m, and the depth distribution of rigs tended to be shallower than the depth distribution of shrimping effort per StatZone except for StatZones 20 and 21.

Total shrimping effort was highest in StatZones 16 and 15 (469,391 and 423,824 h, respectively), coinciding with the some of the most rigs (312 and 508, respectively) and some of the greatest densities of rigs per StatZone (1.8 and 3.6 per 100 km^2 [10- × 10-km grid], respectively; Table 2).

On the LA–TX shelf, the cumulative proportion of shrimping effort relative to rigs generally fell into three categories. The first category's cumulative effort, which includes StatZones 13 through 17, reached more than 60% within the distance of the horizon (7.6 km; Figure 3A). These StatZones also had the highest rig densities and some of the highest effort densities (Table 2). Furthermore, there was considerable spatial overlap between rig locations and effort density (Figure 1A). The second category's cumulative effort, StatZones 18–20, reached 50% cumulative effort when the top third of the rig was visible from the wheelhouse (24.7 km; Figure 3A). These StatZones had lower rig densities and lower (StatZones 18 and 20) to high (StatZone 19) effort densities (Table 2). The spatial overlap of rigs to effort was quite varied for these StatZones (Figure 1). The overlap was such that lanes of high effort coincided with rigs in StatZone 18; however, in StatZones 19 and 20 there were few rigs and they occurred in areas of relatively low effort. The

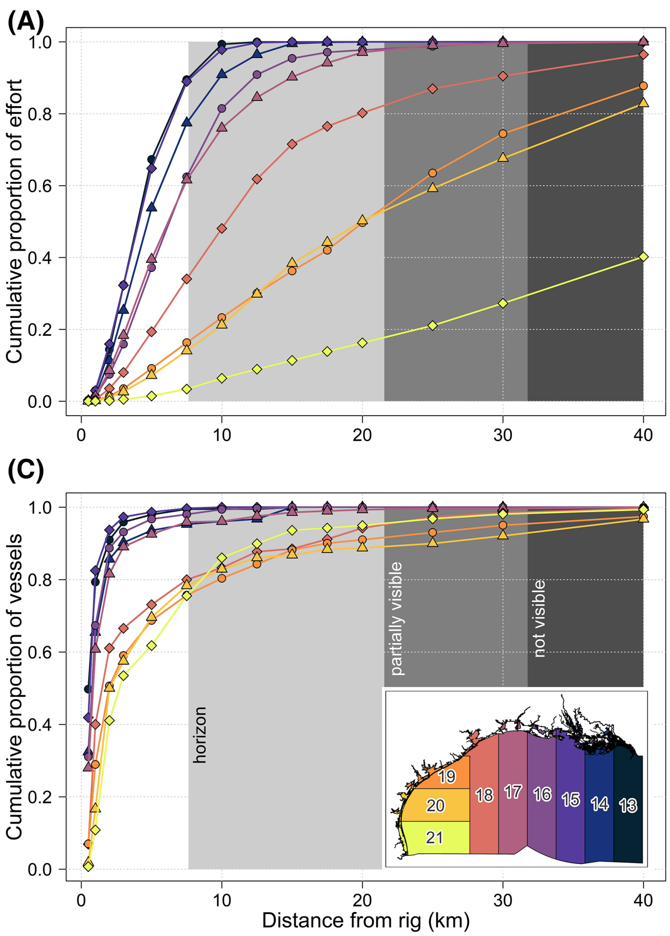


Figure 3. Results from the buffer analysis displaying the cumulative proportion of (A) shrimping effort and (C) vessels as a function of distance from oil and natural gas rigs. (B) The proportion of shrimping effort is the derivative of the cumulative proportion of effort. The inset map in panel C is a color key indicating which color denotes which StatZone. (D) Rig encounter metric per statistical zone from random points analysis. Negative values denote a reduction of effort relative to randomization, and positive values indicate increased effort. The white-to-gray regions indicate distances that rigs are fully to partially visible from the wheelhouse of a shrimp vessel. The lines (from left to right) are the horizon at 7.6 km, partially visible at 24.7 km, and not visible at 31.8 km. The divisions between regions (from left to right) are the horizon at 7.6 km, partially visible or when the upper two-thirds are visible at 21.6 km, and not visible at 31.8 km.

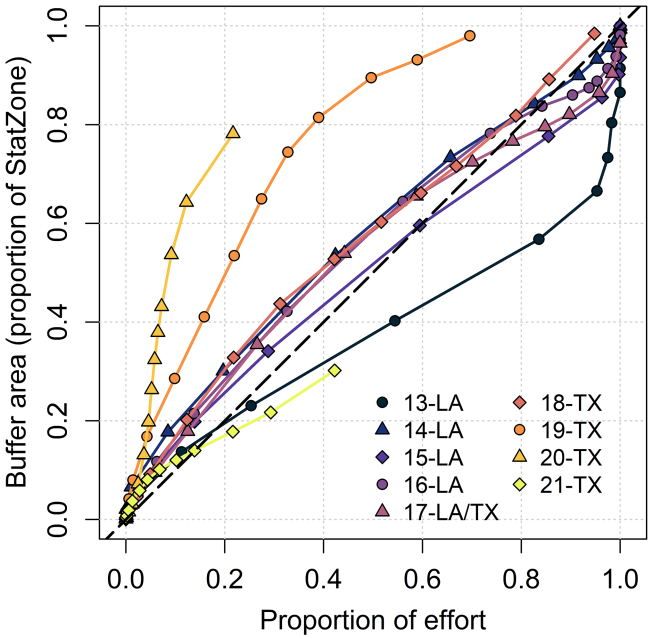


Figure 4. As buffer size increases, the buffer occupies an increasing proportion of the statistical zone (StatZone) area, as shown on the *y*-axis. The *x*-axis shows the proportion of shrimp effort within the buffer area per StatZone. Each point represents a buffer size that was used in the buffer analysis (e.g., 0.5, 1, 2, 3, 5, 7.5, 10, 12.5, 15, 17.5, 20, 25, 30, 40 km). This figure demonstrates that the amount of effort relative to rigs is a function of the space.

cumulative effort for StatZone 21, which is the third category, differed partially because it never reached 50% when rigs may be visible from the wheelhouse (Figure 3A). This StatZone was unique because it had multiple lanes of high effort that were parallel to the shore throughout the depth range (Figure 1). There were only three rigs in StatZone 21 during the period of study (Table 2). The proportion of effort showed a nearly linear relationship with the buffer area as a proportion of the StatZone area, with only minor deviations (Figure 4), which may suggest that the amount of effort relative to rigs was a function of the space. For example, the largest buffer size of 40 km takes up nearly 80% of StatZone 20 but shrimpers spend only around 20% of their effort in the buffer area. In contrast, StatZone 21 has fewer rigs, so only ~30% of the area is encompassed in the buffer area but more than 40% of the effort takes place in this buffer area. The interannual variability of the effort in the buffers around rigs was relatively constant with minor variability between years (Figure S3).

The derivative of the cumulative proportion of shrimping effort relative to rigs demonstrates that the highest proportion of shrimping effort occurred within distances of 5–10 km of an oil rig (17 to 30%; Figure 3B) in StatZones 13 through 17, which is similar to the distance of the horizon. The proportion of effort in StatZone 18 has a broader peak between 5 and 12 km. StatZones 19 through 21 maximums were 40 km and may be higher beyond that (Figure 3B), but larger distances were not investigated. Vessel size per StatZone was not expected to cause an effect, as vessels transverse many StatZones on a single trip. Furthermore, vessel size of the offshore fleet was constant and has not changed in decades, other than a limited amount of skimmer trawling happening off nearshore Louisiana. The mean size distribution of vessels holding a Gulf of Mexico Shrimp Permit were Alabama: 75 ft (22.8 m; SD 11), Florida: 73 ft (22.5 m; SD 13), Louisiana: 73 ft (22.5 m; SD 25), Mississippi: 73 ft (22.5 m; SD 12), TX: 76 ft (23.2 m; SD 22).

In StatZones with high densities of rigs (13 through 17), more than 50% of the vessels with VMS had some level of effort within 1 km of a rig. Within 2 km, the percentage increased to more than 75% (Figure 3C). The cumulative proportion of vessels near rigs peaked at shorter distances (<5 km; Figure 3C) than the amount of effort spent trawling. For example, for most StatZones, 75–100% of vessels were within the horizon distance from the rigs (<7.6 km), whereas the amount of time spent trawling only reached this level (75–100%) over much greater (15–20 km) distances. For all StatZones, 50% of vessels operating in each StatZone had some effort at distances that were <5 km to the nearest rig (Figure 3C), which was within the distance to the horizon. Generally, the results per StatZone could be classified into two groups that were categorized by vessels operating off Louisiana and vessels operating off Texas (Figure 3C). The first group off Louisiana had a higher proportion of vessels that had some effort closer to rigs reaching 80% within 5 km. The Texas group reached 80% at larger distances (greater than 12 km, Figure 3C).

For the rig encounter metric, all StatZones displayed negative encounter values at distances that were less than the horizon (Figure 3D). StatZones 13 through 18 displayed minimum values at less than or approximately at the horizon. These minimum values represent decreased rig encounters of about 12% (StatZone 13), 13% (StatZone 14), 7% (StatZone 15), 13% (StatZone 16), 4% (StatZone 17), and 4% (StatZone 18) relative to randomized points (Figure 3D). Several of these StatZones encounter values became positive at larger distances and reached maximums between 10 and 20 km (4% [StatZones 13 and 15], 5% [StatZone 17], and 9% [StatZone 18]; Figure 3D). The encounter values for StatZones 14, 16, 19, and 20 never became positive. The encounter values in StatZone 19 were always negative, having the lowest minimum for all the StatZones at about −32% at 20 km (Figure 3D). At increasing distances, the rig encounter metric approached zero for most StatZones (13–17 and 21), meaning there was neither attraction nor avoidance at these distances.

Response of shrimpers to rigs

Of the six rigs that were constructed during 2015 to 2019 in the study region, three were in 2015 (two in StatZone 14 and one in StatZone 17), one was in 2017 (StatZone 16), one was in 2018 (StatZone 13), and one was in 2019 (StatZone 15). However, only the rigs that were constructed in 2017 and 2018 were examined more closely because they had effort data in the years pre- and postconstruction. For both rigs at a 1-km distance, there was 0 h effort pre- and postconstruction. For both rigs at 7.5-km distance, there was a reduction of effort from pre- to postconstruction (191 [2017] and 196 [2018] fewer hours of shrimping effort; Figure S4). The proportional reduction, which was the effort in the buffer around the rig that was constructed divided by the total effort in the StatZone for that year, was on the same order of magnitude between the 2 years; however, the proportion for 2017 was less than half of

Table 3. Likelihood ratio tests for the 1- and 7.5-km removal models. The Tweedie power parameter (p) is given in parentheses for each model; AIC = Akaike informatoin criterion.

Model	Model scale	df	AIC	LogLik	Deviance	χ^2	df	*P*-value
Reduced ($p = 1.46$)	1 km	19	3,798.5	−1,880.3	3,760.5			
Treatment ($p = 1.46$)	1 km	20	3,790.2	−1,875.1	3,750.2	10.33	1	0.001
Full ($p = 1.44$)	1 km	27	3,789	−1,867.5	3,735	15.18	7	0.034
Reduced ($p = 1.43$)	7.5 km	19	12,113	−6,037.6	12,075			
Treatment ($p = 1.43$)	7.5 km	20	12,112	−6,036	12,072	3.26	1	0.071
Full ($p = 1.44$)	7.5 km	27	12,232	−6,026	12,052	19.98	7	0.006

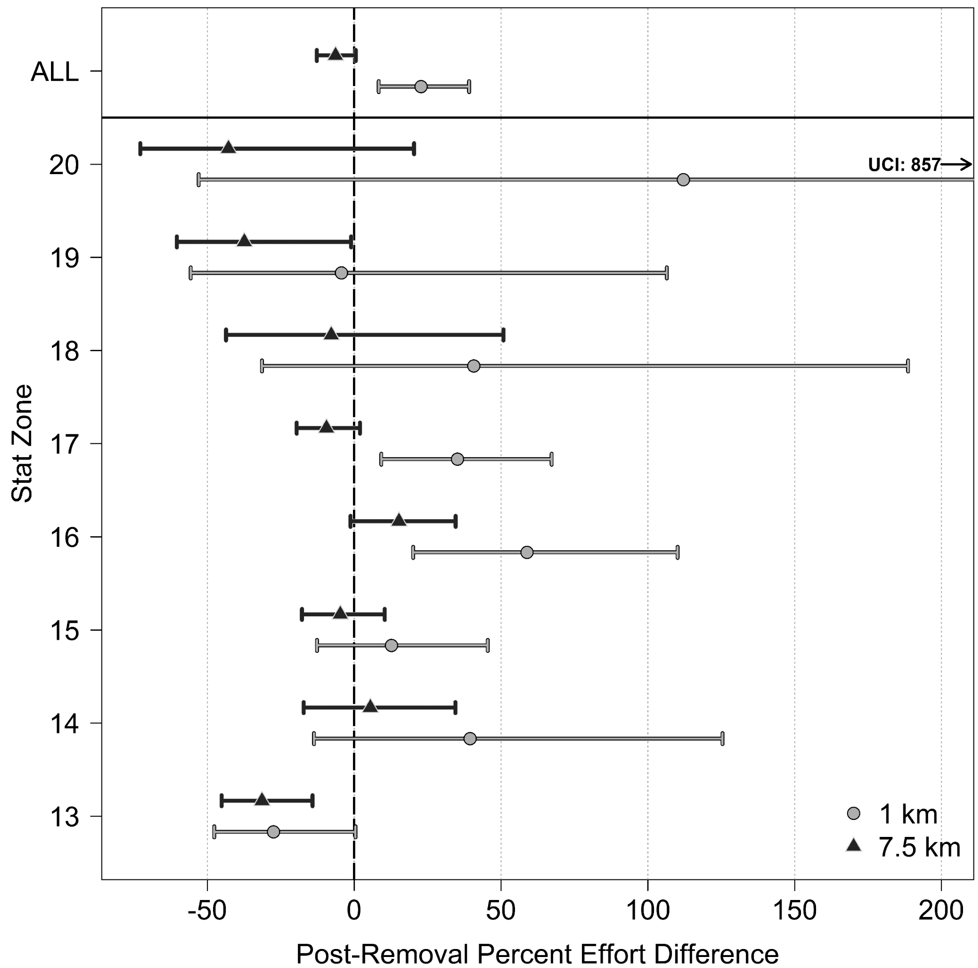


Figure 5. Effect of rig removal on vessel monitoring system effort by statistical zone (StatZone) for both buffer distances. The overall effect is on the top of the plot separated by a thick, horizontal, black line. The values are model-estimated percentages of change in shrimping effort after rig removal, with 95% confidence intervals (CIs) based on the 1- and 7.5-km generalized linear mixed models. A dashed, vertical, black line at zero denotes no change in effort due to rig removals. Significance at $\alpha = 0.05$ can be inferred if the CI does not cross the line at zero.

the proportion for 2018 (0.0021 [2017] versus 0.0050 [2018]; Figure S4).

From 2015 to 2019, 587 rigs were removed on the LA–TX shelf in federal waters that were less than 150 m. The most rigs (maximum = 182) were removed in 2016 (minimum = 76 [2019]), with most being removed from StatZone 17, at 140 rigs (minimum = 16 [StatZone 20]). For the years 2016 to 2018, there were 400 rigs that were removed that were used as the basis for the linear mixed-effects regression. The full 1- and 7.5-km models had the best fits to the data relative to the nested models (likelihood-ratio tests [LRT]; Table 3; see Tables S2 and S3 for estimated model parameters, SEs, and CIs). There was clear evidence of an association between effort near rigs and removal at the 1-km level (LRT, *P*-value = 0.001) but less so at the 7.5-km level (LRT, *P*-value = 0.07). For the 1-km model, the coefficient for treatment translate into an estimated 22.8% increase in effort postremoval (95% CI = [8.3%, 39.1%]; Figure 5). For the 7.5-km model, the coefficient for treatment was nonsignificant at alpha = 0.05 (estimate = −6.3%, 95% CI = [12.8%, 0.5%]; Figure 5). There was also evidence that the association between effort near rigs and removal varied by StatZone in both the 1-km (LRT, *P*-value = 0.03) and 7.5-km

(LRT, *P*-value = 0.006) models. The model diagnostics found that the assumptions were adequately met in both the 1- and 7.5-km models (Figures S5 and S6, respectively).

DISCUSSION

The WEAs that were identified as low-conflict areas by the NBSM were developed using coarse aggregate time scales (e.g., across 5 years). An inspection of more finely resolved annual and monthly time scales further confirmed that the WEAs avoided areas of high shrimping effort. If the WEAs are further developed into OSW farms, it is likely that their effects on the shrimp industry, on the whole, will be relatively minor and primarily on the brown shrimp fishing effort. While this study and the NBSM used a time series of only 5 years, the effort across years was consistent, suggesting some confidence that the results were a fair approximation of the shrimping fleet's expected usage of the LA–TX shelf and the WEAs. This study did not distinguish targeted effort between shrimp species due to the lack of species information on an equivalent spatial resolution; however, the general distribution of brown shrimp tends to be midshelf toward the shelf break (Dettloff, 2024; Montero et al., 2016), which overlaps with the location of the WEAs. There could be some disruptions to both the brown and white shrimp effort due to the construction of the cables that bring the power onshore. The general distribution of commercial shrimp species (brown and white) in the Gulf is seasonally driven by ontogenetic migration, with juveniles found in estuaries and smaller size-classes found nearer to shore (Turner & Brody, 1983). Broadly, white shrimp reside closer to shore and brown shrimp reside closer to shore during the summer and then shift their distribution from midshelf to near the shelf break later in the year (Montero et al., 2016).

While the WEAs largely avoided areas of high shrimping effort, the use of these regions by the shrimp fleet varied seasonally and was largely driven by the Texas closure. Shrimping effort increased in the WEAs that were located on the Louisiana shelf in the months preceding the Texas opener due to spatiotemporal nature of shrimp recruitment out of the estuaries (Turner & Brody, 1983). After the Texas opener, most of the effort shifted to Texas federal waters. There was more effort in the WEAs that were closer to shore in Texas federal waters right after the opener, and then that effort shifted offshore as the fleet chased larger shrimp and nearshore areas became relatively depleted. Because WEA use varies seasonally, there is a possibility that a spatial shift of effort could increase fishing pressure to other regions if the WEAs are developed. For example, the WEAs M and N were used more frequently in the months of April and May before the Texas opener; however, if those WEAs were developed and effectively became no longer viable for shrimping, the vessels will have to trawl elsewhere. Moreover, the hypoxic and anoxic areas expand westward from the Mississippi and Atchafalaya rivers in the summer months (Morey et al., 2003; Rabalais & Turner, 2019). During these events, the shrimp fleet was largely displaced from regions of anoxia and the fleet trawled the edges of where shrimp may aggregate to escape the hypoxia (Craig et al., 2005; Craig & Crowder, 2005; Purcell et al., 2017). If effort is displaced from active WEA leases on the Louisiana shelf, shrimpers may be forced to operate closer to rigs, increasing potential conflict with offshore fossil fuel extraction and shipping lanes. While the WEAs currently represent areas that are not heavily fished, these areas could become prime shrimp habitats in the future, increasing interactions between shrimpers and OSW energy infrastructure. Because the shrimp fleet responds dynamically to resource distribution, the fishery is potentially vulnerable to changes to the redistribution of shrimp population if OSW farms tend to aggregate shrimp distributions.

In areas with the highest densities of rigs, shrimp vessels trawl primarily at distances within the horizon (e.g., 5 to 7 km). This suggests that the shrimpers use the rigs as navigation cues in these regions. In regions with high densities of rigs that are primarily on the Louisiana shelf, the trawlable shelf can get narrow eastward toward the Mississippi River. As a result of increasing rig density and decreasing space without rigs, there is a "sweet spot" distance from rigs where the shrimpers tend to operate. This result combined with the absence of large areas without rigs explains why the portion of shrimping effort goes to near zero at distances that are greater than 20 km. In other words, there are few trawlable areas that are farther than 20 km from any rig in StatZones with high rig densities. The Gulf offshore shrimp fishery relies on a variety of information sources, including visual cues such as navigation lights, radar, and electronic charts, to avoid collisions. In the areas with high densities of rigs, there are also pipelines, submarine wellheads, and other vessels, including shrimpers that are actively trawling (Anderson et al., 1949; Scott-Denton et al., 2012). As a result, adequate space to maneuver can be limited, necessitating optimal distances at which shrimping operations are likely to occur near static infrastructure. The patterns of effort near rigs differed on the Texas shelf due to a combination of fewer rigs and a wider continental shelf allowing the fleet to spread out. The majority of the vessels throughout the study region demonstrated some effort within a few kilometers of rigs in areas with relatively high and low rig densities. The pattern suggests that the shrimp vessel operators were comfortable trawling near these structures or did so out of necessity. While shrimpers avoided rigs at smaller distances within the horizon, there seemed to be a preference for areas at larger distances (e.g., 7.5 to 20 km) from rigs. This was likely due to the coincidence of where shrimp were found and where the rigs are located. Thus, shrimpers can avoid rigs as navigational hazards but generally prefer the same areas due to the spatial overlap of the two industries' interests. The Texas shelf was different from that of Louisiana because there was not the same overlap of shrimping effort and rigs off Texas, making it more difficult to infer a behavioral response.

Shrimping effort increased on small spatial scales (1 km) after rigs were removed from an area, but not at larger spatial scales (7.5 km). The significant shift at 1 km suggests a localized response, where shrimpers were likely moving short distances into these areas the year after rigs were removed. The lack of a response in shrimping effort due to rig removal at the larger spatial scale of 7.5 km was likely due to the observed peak in effort between distances of 5 and 7 km. This optimal operating distance would be invariant with respect to rig removal or if anything might have a negative response (decreasing effort at the larger scale), as vessels moved into areas that were previously avoided on smaller spatial scales (in fact, the response at 7.5 km was negative but nonsignificant).

As the results of this study have demonstrated, shrimping effort around rigs on the LA–TX shelf occurred in distinct patterns. It is difficult to attribute a behavioral response by shrimpers to structures from a purely analytical perspective without direct knowledge concerning vessel operators' decision making. On the other hand, it is likely that the shrimpers were responding to rigs during fishing operations, especially in areas that have high densities of rigs and high densities of shrimping effort. The spacing between wind turbines is a trade-off between generating enough power to be profitable and adherence to offshore safety guidelines, but the distance will likely be approximately 1 nmi apart (~1.9 km; Mulas Hernando et al., 2023). It is difficult to predict whether shrimpers will trawl in areas with a high density of structures because individual operators' tolerance to risk occurs on a spectrum with unknown variability. There are notable differences in the layout of rigs engaging in fossil fuel extraction (nonrandom, clusters of rigs) versus OSW farms (regular spacing between turbines), so shrimpers will respond differently to these industries. Most shrimpers will likely avoid trawling in areas with high structure density given the restricted ability to maneuver; however, some shrimpers may try to "thread the needle" between closely spaced structures, as was observed in the VMS data in areas of high rig densities.

Overall, our analyses demonstrate the complex seascape that shrimpers must navigate to avoid collisions and successfully conduct trawl operations. Each vessel operator (i.e., captain or crew standing watch) will likely have a "sweet spot" distance in which they feel comfortable trawling near a rig while considering other factors, such as the proximity and density of other vessels (fishing or nonfishing), environmental conditions (e.g., visibility, rain, wind, or wave height), time of day (crepuscular versus nighttime trawling), fatigue of vessel operators, and other unknown factors. The maneuvering requirements of a shrimp vessel will also influence the distance between the shrimp vessel and offshore infrastructure. With trawl nets deployed, a shrimp vessel is restricted in its ability to maneuver, meaning that turning requires a large radius to avoid tangling the nets or capsizing the vessel. The typical offshore shrimp vessel uses two double rigs for a total of four trawl nets that have an operational spread of 45 to 60 m (GMFMC, 2005). Furthermore, a shrimp boat captain will typically let out 3–5 times the water depth in cable to fish optimally (Pereyra, 1963). This means that the distance between obstacles and depth are factors in maneuverability and influence vessel operators in finding a "sweet spot" distance from offshore infrastructure during shrimp trawling operations.

The shrimping effort within the WEAs represents a small fraction of the total shrimping effort on the LA–TX shelf; however, this potential loss of fishable ground may disproportionately affect certain vessels or ports. Methods to derive VMS effort estimates on the scale of individual tows are ongoing. Once these data become available, a finer-scale analysis that examines which vessels and ports are most likely to be affected by OSW development in the WEAs could assist in identifying the most heavily affected communities. This information could then be used to target stakeholder engagement and fishery compensation funds. These details would provide valuable context to better understand how WEAs may affect individual vessels.

We did not explore the effects that WEAs could have on transit between Louisiana and Texas, especially in response to the Texas closure. This is relevant, as the WEAs occupy regions that sit between productive shrimping grounds in Louisiana and Texas. While the WEAs are generally expected to be open to transit, even if they are effectively fishing exclusion zones, there may be some displacement during construction or decommissioning. As profits can be constrained by fluctuating prices of fuel and exvessel prices for shrimp, increasing transit times could have the effect of displacing effort to keep costs roughly stable between years. Fishing footprints are dynamic and are likely to change as environmental and socioeconomic conditions change in the future.

The penaeid shrimp fishery on the LA–TX shelf continues to be an economically and culturally significant part of life in the U.S. Gulf Coast (Griffith et al., 2023). The distribution of shrimp populations is a major influence on the decision to allocate shrimping effort. On smaller spatiotemporal scales, several factors influence the allocation of shrimper effort, including bottom suitability (areas without large obstructions), prior knowledge of productive shrimping grounds, the seascape as perceived from the wheelhouse (rigs, other vessels, and fairways), and the distribution of the target species as assessed by individual shrimpers in real time. Individual decision making is also affected by macroeconomic forces such as the global shrimp supply and exvessel prices in addition to the price of consumables such as diesel fuel and food (Liese & Travis, 2010). Each of these factors operates at different spatiotemporal scales and contributes to the decision-making process that is used to select where and when a shrimper will allocate effort. However, localized differences in shrimp density on daily time scales are likely the most influential with respect to effort allocation, as shrimpers employ a smaller trawl net, called a "try net," to more frequently sample potential shrimping areas and assess catch per unit effort in real time (GMFMC, 1981). Thus, the fleet responds dynamically to resource distribution, making the fishery potentially vulnerable to changes to shrimp population redistribution, especially in the context of new multiuse activities in the Gulf (e.g., OSW).

As new marine spatial uses, like OSW, mature in the region, additional research is needed to better understand how the fishery and other activities could be affected by increased vessel traffic, new structure, and the potential for spatiotemporal closures (temporary or permanent) (Sura et al., 2025). The NBSM identified 14 WEA options by spatially weighting multiple data layers, including areas of "high" shrimping effort (4.5 d per year or more, Randall et al., 2022). The results of the NBSM produced several spatial blocks that might not be practical for the offshore commercial shrimp fishery. For example, WEA option I has several "cutouts" that are recommended to be removed from consideration for OSW development. These cutouts are areas of higher shrimp effort and serve to deconflict multiuse in the region (Randall et al., 2022). Additionally, several WEAs, including WEA I with the cutouts, are adjacent to a major shipping fairway leading into Galveston Bay. Our work has shown that shrimpers rely heavily on visual cues to inform navigation, and these cutouts, which are 4.8 km wide, may not be used by shrimpers once they are surrounded on three sides by OSW infrastructure in addition to being bounded by shipping fairways. Additional information on turning radius during trawling and consultation with active shrimpers would help address the potential limitations of these cutouts and could be used to design realistic concessions that are suited to the shrimp fishery. The results of the suitability modeling, which included aggregate shrimp VMS data into a presence/absence of high effort, have initially proven to be successful because major stakeholders, such as the Southern Shrimp Alliance (SSA), seem broadly satisfied by the placement of the WEAs (SSA, 2022); however, finer details on transmission lines are lacking as of July 2025. Our work suggests that some of the MSP decisions that are based on shrimping effort data may not be practical once applied. Future spatial modeling efforts may want to consider the use of a visual buffer threshold, higher resolution VMS data, and individual vessel behavior and maneuverability.

In the northeastern USA and mid-Atlantic, where MSP methods like the NBSM were not used for initial OSW siting, managers are navigating considerable stakeholder pushback on existing and planned projects that are related to multisectoral conflict. Although some of the processes that are used in these regions accounted for existing ocean uses and spatial information (example: BOEM, 2018), the siting methods that were used in the Northeast and mid-Atlantic were much less robust than the NBSM that was used in the Gulf. The resulting projects have faced fierce opposition based on coastal and landscape aesthetic damage, inadequate biological surveying, and conflict with commercial and recreational fishing (Sokoloski et al., 2018). While there is some opposition in the Gulf—and it should be noted that the Gulf has an extensive history of stakeholder engagement in the offshore energy siting process (Priest, 2016)—early feedback from stakeholders and special interest groups (like the SSA) suggests that the spatial modeling approach may lead to increased satisfaction with siting activities (SSA, 2022).

By examining shrimpers' responses to rigs as surrogates for wind farms, this study provides some insight into the dynamics between two existing offshore industries that operate in a shared spatial domain. There are many unknowns in how the wind industry will affect existing fisheries, but the strength of this study is the data-driven approach to understanding interactions between industries. The study had several caveats that limit the broader application of the methods and results in predicting interactions between the shrimp industry and offshore wind farms. Rigs are imperfect surrogates because they are spatially distributed more heterogeneously. Individual turbines in wind farms will be regularly spaced, producing a different seascape than is currently encountered by shrimp vessels in the Gulf. Furthermore, the use of rig removals instead of construction is less ideal to infer a response to construction because construction will likely cause an immediate response because the space is occupied, whereas after decommissioning and rig removal, there is likely a lagged response because shrimpers may be wary of unknown obstacles on the seafloor in addition to some other unquantified behavioral response. In reality, a nearly 100% reduction in effort due to wind farm construction is likely on small spatial scales, especially when we consider that the regular nature of wind turbine spacing will likely act as trawling exclusion zones. Additionally, consideration of the spatial distribution of shrimp on patterns in shrimping effort, better information on the inshore (not federally permitted) component of the fleet, and the potential effect of the ancillary structures that are associated with oil rigs and/or OSWs (e.g., pipelines) are needed. Despite these limitations, our analysis provides a fine-scale understanding of how shrimp vessels navigate the complex seascape to effectively engage in shrimp trawling.

The use of MSP methods to the Gulf offshore energy siting and development processes represents a shift from the traditional approach to ONG infrastructure siting. Previous approaches in the region, which focused primarily on single-sectoral concerns (Smythe & McCann, 2019), have shifted to multisectoral concerns and thus a more holistic process. Historically, ONG infrastructure was positioned based on immediate access and availability to oil and gas deposits and potential conflicts with other sectors were rarely considered. While commercial shrimp fisheries have been included in environmental impact statements for ONG leasing in the Gulf (BOEM, 2017), the cumulative effects are trending toward some industries being excluded due to insufficient space to operate. With the anticipated expansion of the blue economy, new marine spatial uses—including OSW, offshore hydrogen production, and aquaculture—mean that ocean space will become increasingly contested. The novel application of MSP in the Gulf through the NBSM holds considerable promise for the deconfliction of potentially competing sectors. This relatively new approach to MSP, which does have caveats as mentioned above, considers and theoretically optimizes economic viability for offshore energy or aquaculture, and mitigates interactions between infrastructure, human activities, and natural resources.

SUPPLEMENTARY MATERIAL

Supplementary Material is available at *Marine and Coastal Fisheries* online.

DATA AVAILABILITY

Platform database is publicly accessible on the BOEM website (https://www.data.boem.gov/Platform/PlatformStructures/Default.aspx). The WEA shapefile may be request from the NOAA–NCCOS Marine and Coastal Planning division (https://coastalscience.noaa.gov/science-areas/coastal-and-marine-planning/). The shrimp VMS data are confidential and cannot be released with a signed nondisclosure agreement. All code used in analysis and to create plots are available on GitHub (https://github.com/BrendanTurley-NOAA/US_Shrimp_ONG).

ETHICS STATEMENT

To the best of our knowledge, our work and practices fully comply with the ethics guidelines set by this journal and general scientific and academic standards.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

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