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Localized and temporary vessel traffic changes from offshore wind development on the US East Coast pose limited risk to large whales

Ana L. Bishop[1,4,*], Erin L. Meyer-Gutbrod[2], Douglas P. Nowacek[1,3], Andrew J. Read[1]

[1]Duke University Marine Lab, Nicholas School of the Environment, Beaufort, NC 28516, USA
[2]School of the Earth, Ocean, and Environment, University of South Carolina, Columbia, SC 29208, USA
[3]Duke University Pratt School of Engineering, Beaufort, NC 28516, USA

[4]*Present Address:* ERT, 6404 Ivy Lane, Suite 650, Greenbelt, MD 20770, USA

ABSTRACT: The rapid expansion of offshore wind development along the east coast of the USA has raised concern over its potential effects on large whales, especially the Critically Endangered North Atlantic right whale. This study examines changes in vessel traffic associated with offshore wind development to assess the potential for increased risk of vessel strikes and corresponding noise exposure. Monthly Automatic Identification System (AIS) vessel data were obtained from before, during, and after the construction of 3 wind energy projects: the Block Island Wind Farm, Coastal Virginia Offshore Wind Pilot Project, and Vineyard Wind I. We then conducted a spatio-temporal analysis of vessel density on monthly rasters of vessel occupancy time. Vessel density increased in very localized regions surrounding wind turbine generator (WTG) sites (i.e. within 2 km) during the active construction period by up to 36.41 additional monthly (h km^{-2}) on average, although notable increases in vessel density only occurred during a subset of months within the broader construction window. Increases in post-construction vessel traffic at WTG sites were minimal (up to 4.98 monthly h km^{-2} on average compared to pre-construction vessel traffic) and on par with the general increase in vessel traffic that has occurred along the eastern seaboard in the past decade. Our results indicate that the threat of increased vessel traffic associated with offshore wind development is temporally limited to the construction period and spatially limited to the areas directly adjacent to the WTGs. This constrained risk can be mitigated by employing restrictions on vessel speed and by restricting active construction to seasons when North Atlantic right whales are not present.

KEY WORDS: Offshore wind · Vessel traffic · Renewable energy · Large whales · North Atlantic right whale · *Eubalaena glacialis*

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1. INTRODUCTION

The offshore wind industry has grown rapidly in the USA, with new advancements occurring on a near-daily basis. The transition to more renewable energy sources is necessary to reduce carbon emissions and combat climate change, but the impacts that offshore wind development will have on coastal environments are not fully understood. A variety of ecological concerns regarding the effects of offshore wind have been raised, including collision risks for birds and bats, acoustic disturbance of marine mammals, modification of habitat, and changes to the air—water interface that could impact oceanographic dynamics (Farr et al. 2021). Many of these potential risks are mitigatable with appropriate measures (Farr et al. 2021). However, the novel nature of this industry in the USA, the speed at which it has developed, and the resultant lack of robust research documenting its impacts limit the ability to comprehensively assess the

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*Corresponding author: ana.bishop@alumni.duke.edu

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environmental effects of offshore wind on large whales (Galparsoro et al. 2022).

To date, few studies have attempted to quantify the impacts of offshore wind on marine mammals in the USA. Most existing work has focused on characterizing the occurrence of whales within specific offshore wind lease sites, and/or quantifying the stressors that those lease sites present (Leiter et al. 2017, Amaral et al. 2020, Quintana-Rizzo et al. 2021, Estabrook et al. 2022). Some studies have examined the impacts of offshore wind from a broader ecosystem perspective (Bailey et al. 2014, Best & Halpin 2019, Farr et al. 2021, Galparsoro et al. 2022, National Academies of Sciences, Engineering, and Medicine 2024). Notably, a recent study examined the causes of recent humpback whale *Megaptera novaeangliae* strandings along the US east coast and found no connection to offshore wind development (Thorne & Wiley 2024).

Here we investigated changes in vessel density patterns resulting from offshore wind development to assess the risk to large whales. Concern has been expressed regarding increased vessel traffic associated with wind farm construction, given the risks that increased vessel activity may present to large whales. Little is known about the influence of offshore wind development on vessel traffic; only a single study in the UK has examined the impact on traffic flow to date (Rawson & Rogers 2015). Most offshore wind-related vessel traffic studies focus on collision risk assessment rather than changes in traffic density (Vanderlaan et al. 2009, Presencia & Shafiee 2018, Yu et al. 2020). Furthermore, these studies have been based on wind farms in other countries and, therefore, do not account for the ecological and logistical dynamics that affect US wind farms. Here we present a new method for quantifying the impact of offshore wind on vessel traffic, describe the potential ecological implications of those impacts at wind lease sites in the USA for the first time, and extrapolate what those impacts might mean for large whales.

Global vessel traffic, tonnage, and speed have all increased rapidly over the past century and are projected to increase more rapidly in the future (Vanderlaan et al. 2009, Tournadre 2014, Sardain et al. 2019). Risks to large whales include a heightened probability of vessel strikes and increased exposure to noise (Thorne & Wiley 2024). Vessel strikes can kill or seriously injure large whales, with nearshore populations having a higher risk due to their presence in major shipping lanes (Vanderlaan & Taggart 2007, van der Hoop et al. 2012). The growth of both vessel traffic and speed is particularly concerning in this context, as both factors are correlated with increased probability of vessel strike morbidity and mortality (Vanderlaan & Taggart 2007, Vanderlaan et al. 2009, van der Hoop et al. 2012, Conn & Silber 2013, Nisi et al. 2024, Redfern et al. 2024, Thorne & Wiley 2024). Additionally, increased vessel traffic, size, and speed have led to substantial increases in low-frequency noise within the underwater soundscape (Haver et al. 2021, Findlay et al. 2023). Potential impacts of such low-frequency noise on the behavior of baleen whales include behavioral disruption, masking, and chronic stress (Moore et al. 2021, Findlay et al. 2023). The low-frequency noise introduced by shipping traffic impacts baleen whales due to the unique characteristics of their vocalization and hearing ranges (Southall et al. 2019).

Five endangered species of large whale inhabit our study area off the northeastern coast of the USA: North Atlantic right whales *Eubalaena glacialis*, sperm whales *Physeter macrocephalus*, sei whales *Balaenoptera borealis*, fin whales *B. physalus*, and blue whales *B. musculus*. The North Atlantic right whale (hereafter 'right whale') is of particular concern within the context of offshore wind development due to the population's small size and consequent vulnerability to extinction. One of the most endangered baleen whales in the world, and currently classified as Critically Endangered on the IUCN Red List, the right whale population is currently estimated at approximately 380 individuals and has been declining since 2011 (Cooke 2020, Linden 2025). Mortalities and morbidities induced by vessel strikes and entanglements are responsible for this decline (Knowlton & Kraus 2001, Sharp et al 2019, Knowlton et al 2022, Reed et al. 2024). Increased mortality associated with these 2 factors resulted in the declaration of an unusual mortality event in 2017 by the National Oceanic and Atmospheric Administration (NOAA), which was still ongoing at the time of writing (spring 2024) (Corkeron et al. 2018, NOAA Fisheries 2024). Climate change is also an indirect but potentially important threat to the species. Climate-mediated drivers of variability in the distribution and abundance of the whales' primary prey species has resulted in major distributional shifts and declines in fecundity (Meyer-Gutbrod et al. 2021, 2023). When right whales respond to these changes by moving to new foraging grounds, they face increased risk of anthropogenic injuries and mortalities due to the geographic specificity of some protective policies (Meyer-Gutbrod et al. 2018, Davies & Brillant 2019). Increased use of the Gulf of St. Lawrence by right whales as foraging habitat after 2010 brought devastating consequences, including increased numbers of whales killed as a result of vessel strikes and entanglement (Crowe et al. 2021, Meyer-Gutbrod et al. 2021). A similar paradigm has also occurred recently for humpback whales along the US east coast (Thorne & Wiley 2024). Additional stressors, such as increasing levels of anthropogenic noise, may also pose substantial threats to both species (Moore et al. 2021).

Right whales use coastal waters off New England and Canada throughout the year, and a subset of the population, predominantly consisting of parturient females and juveniles, migrate to the species' only known calving grounds in the southeastern USA (Gowan et al. 2019). The seasonal distribution of whales within the northern portion of their habitat can vary with shifts in the distribution of their prey. Starting around 2010, right whales decreased their use of historically popular feeding areas (i.e. the Bay of Fundy and Roseway Basin), began occurring in higher densities for longer periods in Cape Cod Bay, and increased their use of other important feeding areas such as the Gulf of St. Lawrence and southern New England (Davis et al. 2017, Leiter et al. 2017, Davies et al. 2019, Ganley et al. 2019, Record et al. 2019, Crowe et al. 2021, Meyer-Gutbrod et al. 2023). These shifts occurred rapidly, likely due to changing prey distributions, making it difficult to predict their long-term distribution trends. Increased right whale presence in southern New England is particularly significant given that the area supports multiple wind farm development projects (including Vineyard Wind I, one of the wind farms that was analyzed in this study) (Leiter et al. 2017, Quintana-Rizzo et al. 2021, O'Brien et al. 2022). The function of the mid-Atlantic region to right whales is less understood, but it is known to be an important migration corridor and supports feeding and social interactions (Whitt et al. 2013, Davis et al. 2017).

During migration, right whales transit relatively close to shore, through a gauntlet of high-density shipping lanes and fishing grounds. Females and their calves spend most of their time near the surface on the calving grounds and while migrating, increasing the risk of vessel strike (Knowlton & Kraus 2001, Vanderlaan et al. 2009, Garrison et al. 2022, Thorne & Wiley 2024). When prey aggregations form near the surface, right whales spend significant amounts of time near the surface skim feeding (Parks et al. 2012). Thus, due to their urban habitat, the risk of vessel strikes for this species is much greater than for other species of large whales (Vanderlaan & Taggart 2007). In the past 8 yr, more than half of right whale mortalities with known causes were attributed to vessel strikes (NOAA Fisheries 2024). Vessel strikes are one of the main threats that offshore wind development may pose to large whales (Farr et al. 2021). To understand this potential risk, we directly measured changes in vessel traffic during and after the construction of wind farms along the US east coast.

2. METHODS

To investigate changes in vessel density related to wind farm construction, we selected 3 study sites: the Block Island Wind Farm ('Block Island'), the Coastal Virginia Pilot Project (CVOW), and Vineyard Wind I ('Vineyard Wind') (Fig. 1). We did not include South Fork Wind, the fourth US wind farm under development at the time of writing, because construction began too recently for installed wind turbine generator (WTG) data to be publicly available. Block Island, completed in 2016, was the first US wind farm to be constructed and therefore offered the longest time period for changes in vessel density following construction to be measured. However, the project is only ~6.1 km (3.8 miles) offshore and is sited entirely in state waters. As a result, the project was under state management. In contrast, most future wind projects will likely occur much farther offshore (CVOW and Vineyard Wind are about 43.5 and 24.1 km [27 and 15 miles] offshore, respectively), and will therefore be fully regulated by the federal government. CVOW was built in federal waters, but consists of only 2 relatively small WTGs (Table 1). Vineyard Wind was the first offshore wind project in the USA to use full-size WTGs in federal waters, thereby providing the most representative example of effects on future regional vessel density. However, construction was not completed by the time this analysis was performed, so the full construction period was not captured in this analysis and no post-construction data were available.

2.1. Data sources

2.1.1. Wind turbine generators

The locations of each wind farm's WTGs were provided by the United States Geological Survey's (USGS) United States Wind Turbine Database (Hoen et al. 2018). The data set contained the location of WTGs in both state and federal jurisdictions and included Block Island and CVOW. However, the Vineyard Wind WTGs were still under construction at the time of this analysis and were not included in the USGS database. Instead, we obtained the location of the Vineyard Wind WTGs from the Bureau of Ocean

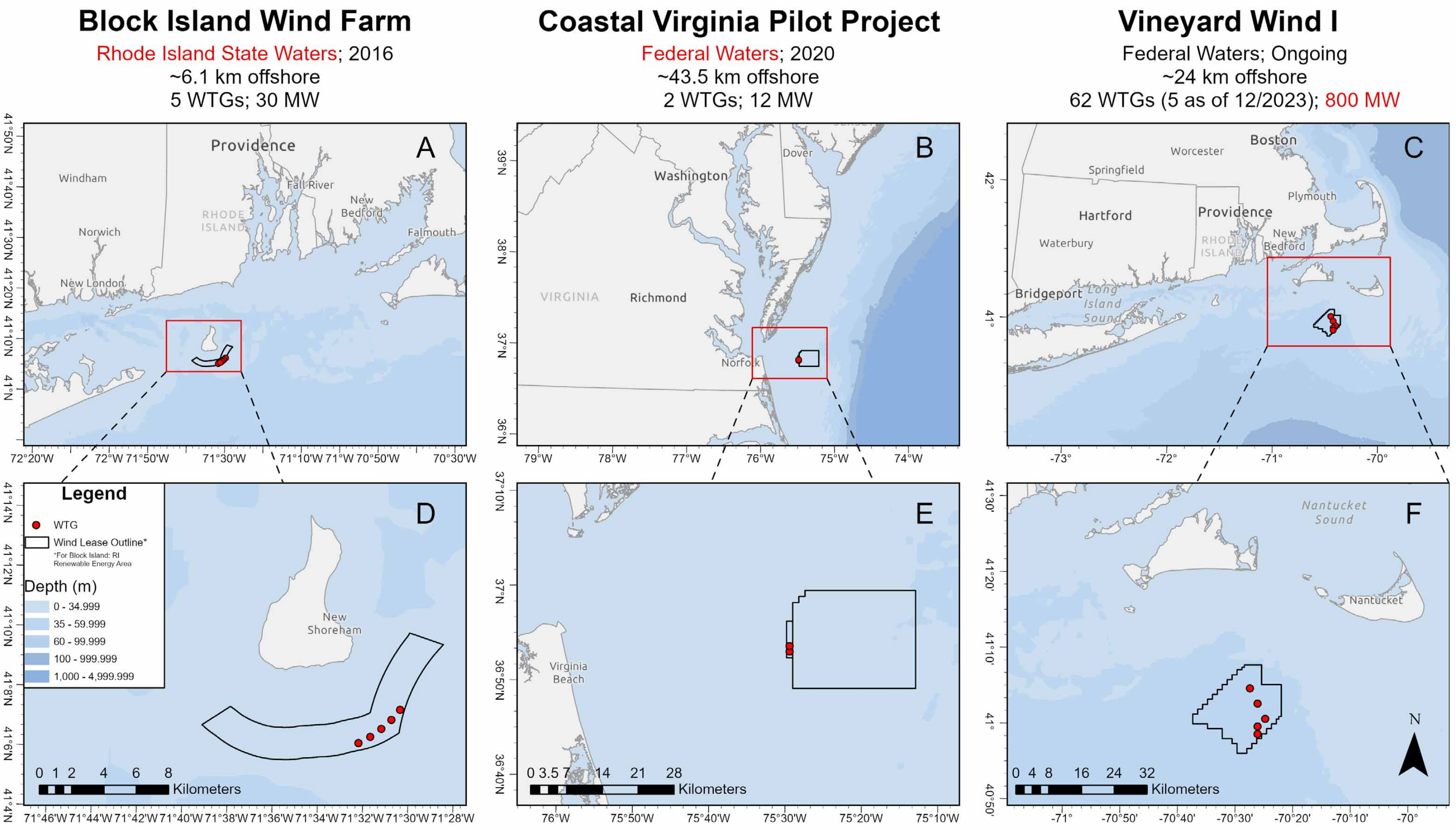

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Fig. 1. Locations of the 3 wind farms used in this analysis. Each wind farm is displayed with its respective lease site for scale (or, in the case of Block Island, the Rhode Island Renewable Energy Area). Characteristics of each wind farm that may have uniquely impacted the vessel traffic required for wind farm construction are highlighted in red. Anticipated power generation (shown in MW) reflects power aggregated across all turbines at the farm

Table 1. Installation, size, and energetic specifications of the wind turbine generators (WTGs) used in this analysis (Hoen et al. 2018, BOEM Office of Renewable Energy Programs 2023)

Project	Number of WTGs installed	Year installed	WTG maximum height (m)	WTG capacity (MW)
Block Island Wind Farm	5	2016	181	6
Coastal Virginia Pilot Project (CVOW)	2	2020	185	6
Vineyard Wind I	5 (62 planned total)	2023 (ongoing)	248	13

Energy Management's Office of Renewable Energy Programs. The data for Vineyard Wind were updated through December 2023. For more information on the WTGs used in this analysis, see Table 1.

2.1.2. Vessel density

We obtained vessel density data from the Global Maritime Traffic Density Service (GMTDS), a service developed by MapLarge that collects, cleans, and synthesizes Automated Identification System (AIS) data into monthly vessel density rasters (https://www.globalmaritimetraffic.org). AIS is a method of automatically transmitting a vessel's position and other relevant identifying information, including vessel type, course, draft, and speed, over a remote maritime communica tions system (https://globalmaritimetraffic.org/gmtds-help-resources.html#gmtdsFAQ, https://www.navcen.uscg.gov/ais-frequently-asked-questions). Each vessel's information is encoded and can be applied to a variety of research purposes. Carriage requirements vary by country; in the USA, large vessels, including commercial vessels greater than or equal to ~19.8 m (65 feet) in length and those certified to carry at least 150 passengers must carry an AIS 'Class A' device (Automatic Identification System 2024). However, a predetermined subset of vessels that have AIS carriage requirements, including fishing vessels, vessels greater than or equal to ~19.8 m (65 feet) that are certified to carry fewer than 150 passengers (with a few exceptions, including vessels that travel at speeds exceeding 14 knots; see Automatic Identification System 2024), and certain dredging vessels are permitted to carry a 'Class B' device instead. These devices have a weaker signal and lower transmission rate than Class A devices. Federal regulations do not explicitly require all offshore wind project vessels to carry Class A AIS, and it is possible that some project vessels in this analysis carried Class B instead. Both classes of AIS data were included in the GMTDS data, although Class A signals have higher priority on AIS channels, thus Class B vessels were likely underrepresented in the data set as a result (Falco et al. 2019).

To produce monthly density rasters, GMTDS aggregates raw AIS data and removes any points considered anomalous or incorrect (https://globalmaritimetraffic.org/gmtds-data.html). Indicators of abnormal data include invalid vessel identification numbers, irregular speed, course, or location information, and questionable locations, such as if the reported vessel location was over land. Vessel tracks are then calculated from the cleaned location point data. The monthly time components of each trackline are summed across grids, resulting in rasters that provide vessel density in terms of monthly h km^{-2}. For more information regarding GMTDS methodology, see the GMTDS 'Data' webpage or the EU Vessel Density Map Detailed Method, from which GMTDS 'closely modeled' their processes (Falco et al. 2019, https://globalmaritimetraffic.org/gmtds-data.html).

The vessel density data we obtained consisted of 1 raster per month for each year of the requested study period that had a resolution of 1 km^2. Density data were provided for 10 vessel categories, defined by the 'ship type' broadcasted in each vessel's AIS data: all vessels (aggregated), cargo, fishing, icebreakers, non-commercial, passenger, tankers, service ships, all vessels (other; includes wing-in-ground ships, high speed craft, etc.), and all vessels (unknown). For more information about AIS ship types, see https://globalmaritimetraffic.org/gmtds-help-resources.html#gmtdsFAQ. We conducted all analyses on every vessel category but, for the sake of simplicity, we focus here on presenting results aggregated for all vessel types only. Notably, this means that traffic not related to wind farm development was included in our analyses. Given that it was unknown whether all project-related vessels fell into the same vessel category, this approach ensured that all project-related vessels were captured in the analysis. Additionally, examining the aggregated data provided a method for analyzing general vessel traffic trends on a coarse scale and identifying changes in non-project related vessel traffic (i.e. traffic bottlenecks created by the presence of the turbines) that may have been present.

Despite our focus on all vessels aggregated, it is valuable to consider the effect that vessel density changes from wind farm development may have on specific vessel categories and industries because different vessel categories may pose different risks to marine organisms. To that end, we also present notable results from specific vessel categories. For more details regarding the changes in vessel density for each individual vessel category, see Table S1 in the Supplement at www.int-res.com/articles/suppl/esr01489_supp.pdf. We conducted all analyses in the geographic coordinate system WGS84. When linear units were required for additional data layers, we projected them in WGS 84 UTM Zone 18 or 19, depending on the wind farm location.

2.2. Vessel density analysis

2.2.1. Calculating change over time

To analyze the change in vessel density over the course of each wind farm's development, we recalculated each raster to change all cells with a value of 'No data' to a value of '0'. This was done to accurately represent cells where no vessels were detected in a given month. We subsequently divided the monthly rasters within the study period of each wind farm into 3 development phases for comparison: 'pre-construction', 'construction', and 'post-construction'.

The pre-construction period was defined as 5 yr before construction started. Data recorded earlier than 5 yr prior to construction may have included outdated vessel traffic patterns that did not represent an accurate baseline for the pre-construction period. We defined the construction period as beginning on the first day that either offshore cable laying or piledriving began, and ending when turbine construction was completed. We included operational testing and pile driving moratoriums in the construction period. This was done to ensure that all types of construction operations and the traffic patterns of their associated vessels were captured in the analysis. We excluded high-resolution geophysical surveys from the construction period because they typically require a small number of vessels, and we wanted to focus our analysis on quantifying vessel traffic added during construction. Furthermore, geophysical surveys can take place months to years before pile-driving or cable-laying begin, and excluding them from the construction phase reduced the amount of unrelated vessel traffic that would be captured in the construction period. The post-construction phase was defined as the period after turbine construction was completed, and began the month after the construction phase ended. Post-construction included every month following turbine completion until the last month for which we had data (August 2023). This allowed us to capture as much vessel traffic related to the wind farm's post-construction operation and maintenance as possible. The exact dates for the development phases of each wind farm are presented in Table 2.

We calculated changes in vessel density over time on annual and monthly scales. The annual analysis provided an overview of traffic changes throughout the development process by capturing every month of construction, thus offering insight into overall trends. We calculated annual change by taking the average of every vessel density raster that fell within each of the 3 distinct development phases, then subtracting the 3 resulting average vessel density rasters for each development phase from each other. When the subtraction was carried out, the earlier development phase was always subtracted from the later (for example post-construction minus pre-construction). This resulted in difference rasters which summarized the average change in vessel density between each development phase.

The same process and development phases were used to analyze changes in vessel density on a monthly scale. We performed a monthly analysis to examine changes in vessel density throughout development with more granularity and identify any seasonal factors that may have been driving annual trends. Additionally, the monthly analysis provided an opportu-

Table 2. Dates and number of months for each development phase per wind farm. NA: not applicable (construction ongoing at the time of writing)

	Dates	Months per phase
Block Island		
Pre-construction	January 2011 – June 2015	54
Construction	July 2015 – November 2016	17
Post-construction	December 2016 – August 2023	81
CVOW		
Pre-construction	January 2015 – April 2020	64
Construction	May 2020 – September 2020	5
Post-construction	October 2020 – August 2023	35
Vineyard Wind I		
Pre-construction	January 2017 – October 2022	70
Construction	November 2022 – August 2023	10
Post-construction	NA	NA

nity to compare development trends within specific months when right whales are typically present. If the study areas had regular fluctuations in vessel traffic on a seasonal timescale, this underlying pattern may have biased any changes observed during wind farm construction detected on an annual scale. Seasonality was an inextricable factor within the construction phase; each wind farm included in this analysis had different lengths of construction time, and each construction period was carried out over different seasons. Block Island's construction lasted 17 mo, beginning in the summer and ending in the late fall, while CVOW's construction lasted only 5 mo, and was carried out during the summer. Vineyard Wind's construction was ongoing as of August 2023, thus 10 mo of its construction, which began in the late fall of 2022, were included in this analysis.

In the monthly analysis, we aggregated data from each development phase by month and calculated the average vessel density for each month. We then found the difference in average vessel density between development phases for each month (for example, all vessel density rasters from January were aggregated and averaged by development phase, and the resulting values were subtracted. The same was done for February, then March, etc.).

Finally, we compared the average vessel density during construction and post-construction to pre-construction averages and variance at each wind farm. We did so on a monthly basis, again to examine any ongoing seasonal trends in each region. The analysis also provided insight into the magnitude of change in average vessel density over the development period by contextualizing each development period's vessel density relative to pre-construction conditions.

2.2.2. Non-WTG site analysis

The resulting difference rasters from the annual and monthly analyses described above covered large areas and included all vessel categories, regardless of their relation to wind farm development. This did not allow us to assess more localized changes at the scale of each wind farm. To examine changes in traffic at higher spatial resolution, we created localized study sites that specifically covered each wind farm by buffering every WTG by a 2 km radius, then merging the buffers into a single polygon. We chose 2 km to examine the relative contribution of local vessel traffic at the wind farm scale, without creating complex polygon boundaries within farms that have turbines spaced at the minimum distance of 1 nm (1.85 km) apart recommended by the US Coast Guard (USCG 2020). The 2 km buffer provides a good balance between highly localized information while incorporating traffic between turbine sites within a single wind farm.

We then replicated and randomly redistributed as many of these polygons as possible within a 1400 km^2 area surrounding the wind farm, creating randomized 'non-WTG sites' (Fig. 2). The length of each side of the sampling area was roughly ⅓ of a degree of latitude. We used these non-WTG sites to compare changes in vessel density detected at each wind farm to the area immediately surrounding them. By analyzing these small areas surrounding the wind farms, we were able to isolate changes in traffic associated with the farms. Furthermore, comparing the similarity between vessel traffic trends at the wind farm sites and non-WTG sites further revealed whether trends at the wind farm sites were related to project development or not. The resampling area of 1400 km^2 was selected to ensure adequate spatial coverage around the wind farm sites, enabling comparison of turbine-associated traffic with nearby background traffic patterns surrounding the wind farm, while reducing the likelihood of incorporating extraneous or unrelated movement data, or significantly different oceanographic and bathymetric conditions. We then calculated zonal statistics to extract the average change and variance in vessel density at each non-WTG site.

Construction typically includes a wide variety of vessel types that install WTGs, bury cables, and carry crew. Once completed, a smaller number of maintenance and crew transfer vessels are used to facilitate the wind farm's operation. We analyzed the variance associated with each development phase to better understand fine-scale spatial variation in vessel traffic during each phase. A high variance implies that any large changes in vessel density were highly localized within the site. In contrast, a low variance suggests that changes were more evenly distributed across the entire site area.

The 1400 km^2 resampling area allowed us to maximize the number of non-WTG site replicates in the immediate area of the wind farm. As a result, sites were selected both inshore and offshore of the wind farms but had similar oceanographic conditions due to their proximity. Due to sample site size and shape varying by wind farm, it was not possible to generate an equal number of resampling sites within each 1400 km^2 boundary. As a result, there were 14 resampling sites for Block Island and CVOW, excluding the true wind farm sites, and 10 for Vineyard Wind, whose

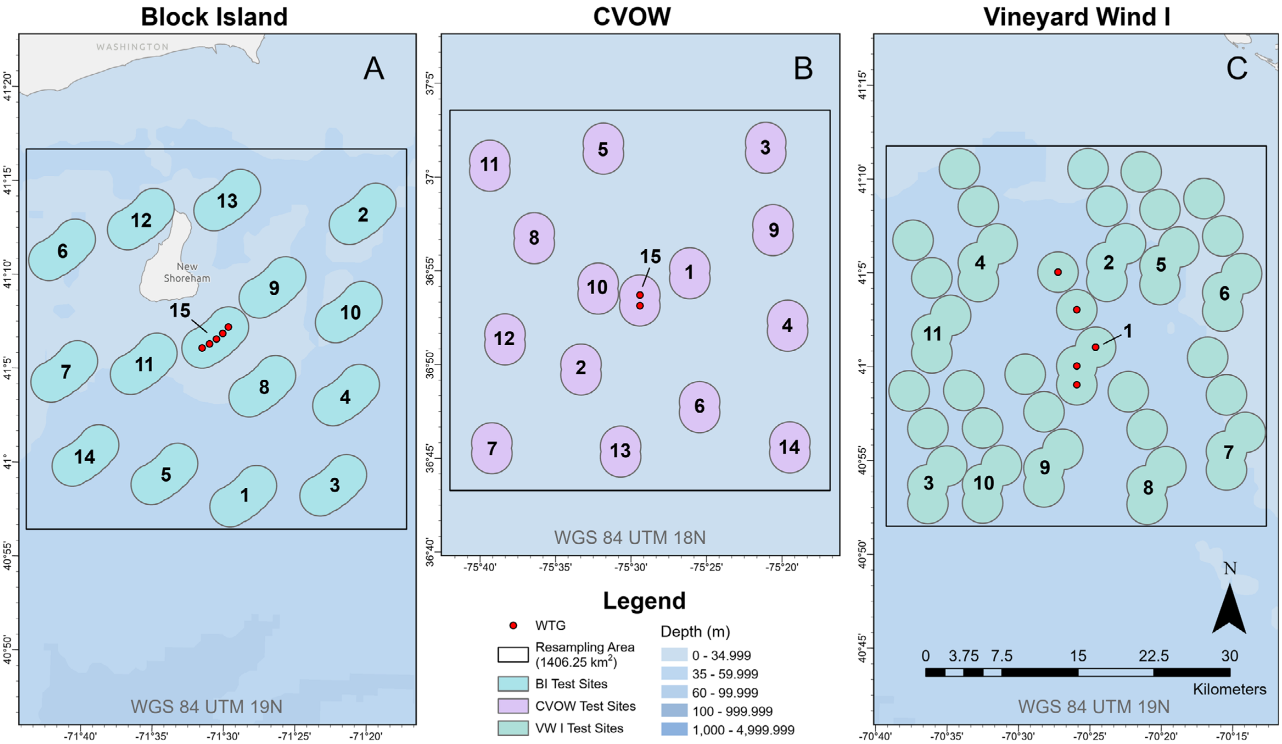

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Fig. 2. Shape, size, and distribution of each randomized non-wind turbine generator (WTG) site used in this analysis, along with the original wind farms (Block Island Wind farm [BI], the Coastal Virginia Pilot Project [CVOW], and Vineyard Wind I [VW I]) and their 2 km buffers. The non-WTG sites were exact copies of the original 2 km buffers in order to preserve their unique shape and scale

WTG extent was substantially larger. This was the largest number of non-WTG sites that could fit without overlap, although there was likely resampling of certain raster cells where sample sites were close. The non-WTG sites did not intersect land.

We conducted all raster analysis in ArcGIS Pro v3.2.0 and created all data visualizations in R v2023.12.1+402 (ESRI 2023, Posit Team 2023).

3. RESULTS

3.1. Average annual change

3.1.1. All vessels (aggregated)

We acquired 152 vessel density rasters per vessel category covering the Block Island and Vineyard Wind study areas (described together as the 'New England' rasters), and 104 rasters per vessel category covering the CVOW study area. The New England and Virginia rasters covered 135 176 and 107 476 km^2, respectively. The vessel density data set included the years 2011–2023 (n = 13) for Block Island, 2015–2023 (n = 9) for CVOW, and 2017–2023 (n = 7) for Vineyard Wind (Table 2). The average change in vessel density across all wind farms and development phase comparisons ranged from −33.89 (construction vs. post-construction) to 36.41 monthly h km^{-2} (pre-construction vs. construction) in the 2 km buffer polygon containing WTGs. In these comparisons, a negative number reflects a reduction in vessel activity, and a positive number indicates an increase in vessel activity (Fig. 3).

Overall, vessel density increased slightly between pre-construction and post-construction at both Block Island and CVOW (Figs. 3 & 4). There was an initial sharp increase in vessel density at Block Island between pre-construction and construction ($\bar{x} = 33.87$ monthly h km^{-2}), followed by an almost equally sharp decrease between construction and post-construction ($\bar{x} = -28.89$ monthly h km^{-2}), resulting in a small increase over the entire development period (pre-construction vs. postconstruction; $\bar{x} = 4.98$ monthly h km^{-2}). CVOW displayed an identical pattern to Block Island, but had a larger initial increase in vessel density, followed by a larger subsequent decrease, and a lower overall increase in vessel density than Block

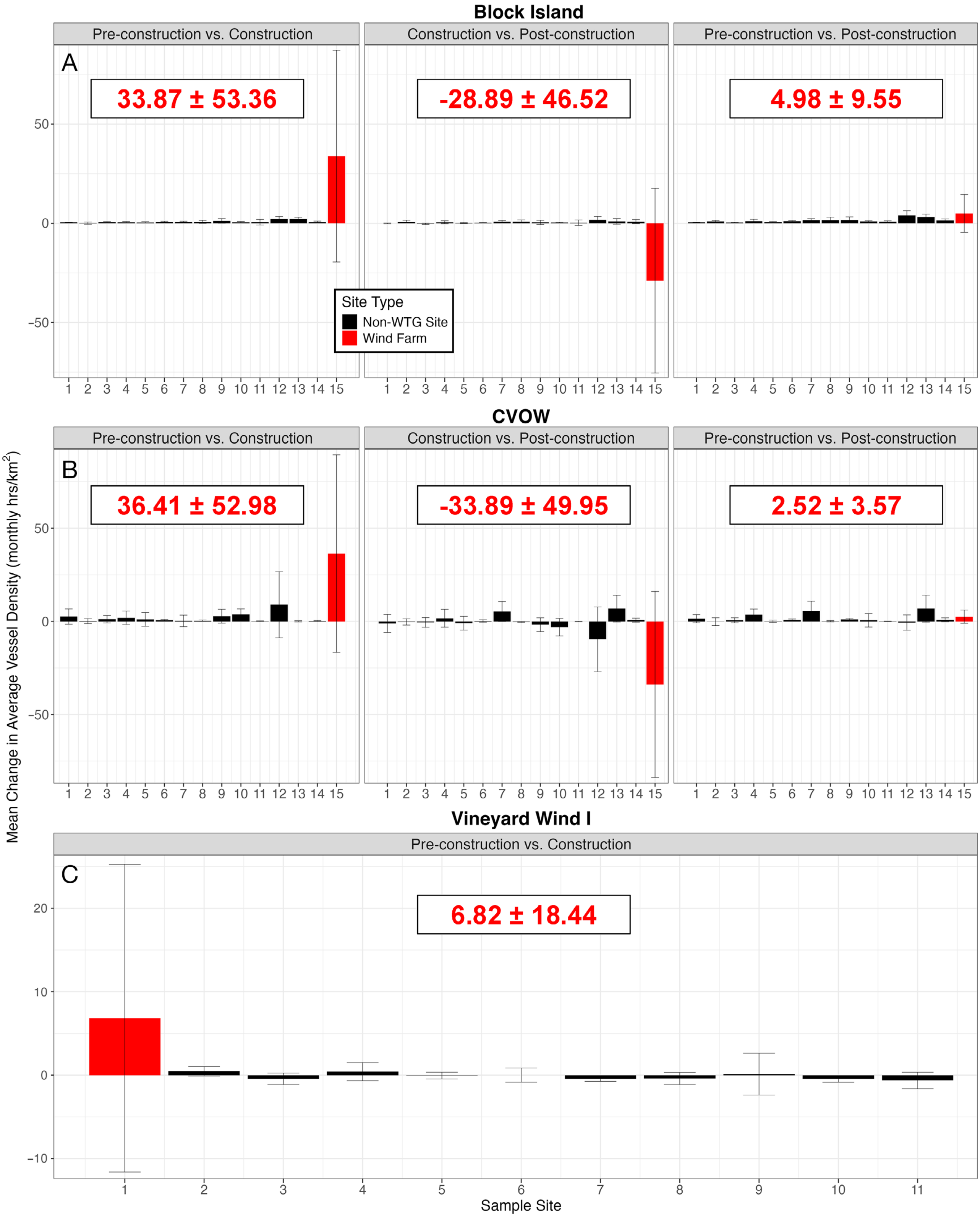

Fig. 3. Mean change and variance in vessel density at each wind farm and non-wind turbine generator (WTG) site across the 3 development phases, categorized by wind farm. The 2 km buffer polygons containing WTGs are shown in red, and the randomized non-WTG sites are shown in black. Positive (negative) numbers indicate an increase (decrease) in vessel density in the more recent period compared to the more historical period. Error bars represent SD

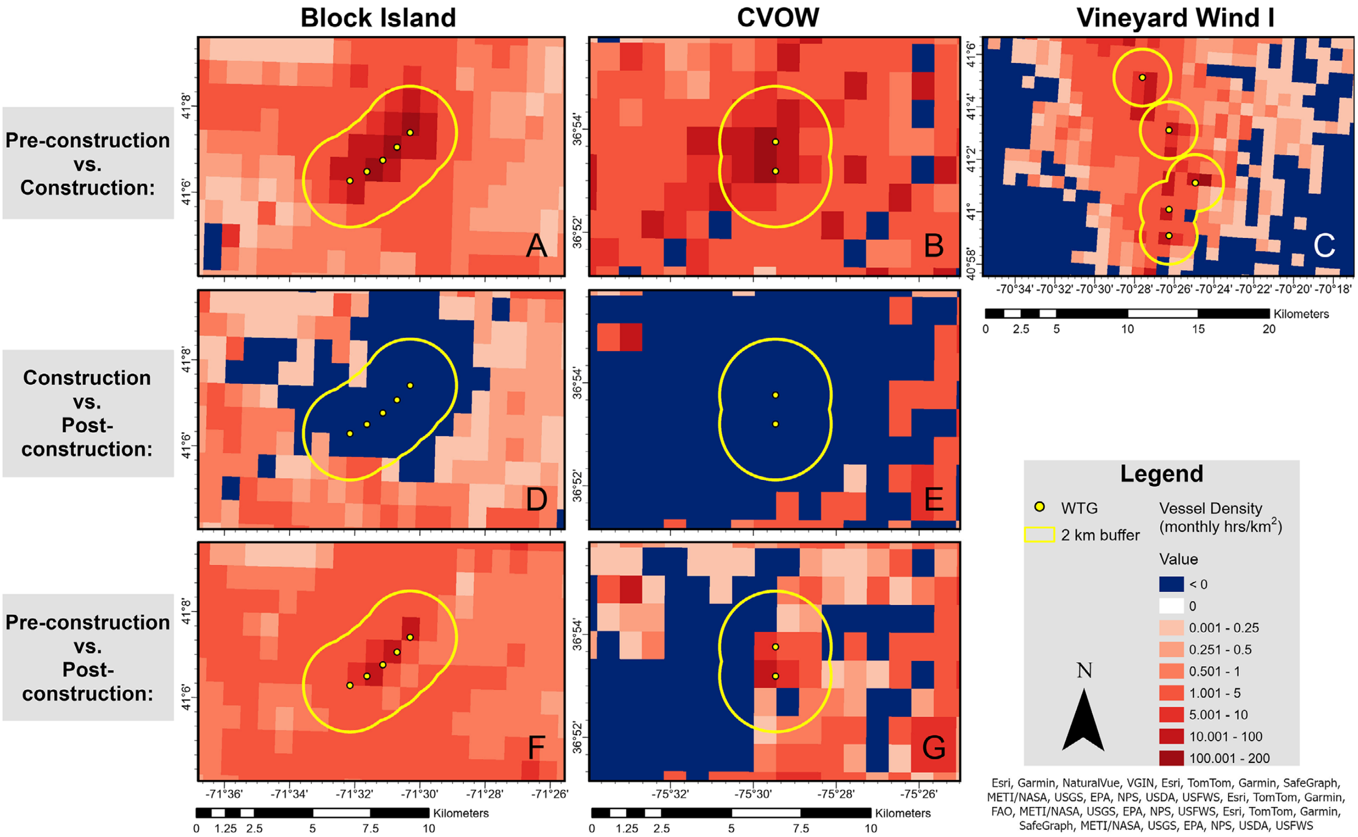

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Fig. 4. Average change in vessel density, in monthly h km^{-2}, between each wind farm's development phases. Wind turbine generators (WTGs) and 2 km buffer polygons are included as reference points. Note the legend's exponential increase in value; light pink/red coloration represents small increases in vessel density in the more recent period compared to the more historical period (0–5 monthly h km^{-2}), while the darkest reds represent more substantial increase in vessel density (100+ monthly h km^{-2})

Island ($\bar{x}$ = 36.41, −33.89, and 2.52 monthly h km^{-2}, respectively). Vineyard Wind had a smaller increase in vessel density compared to the other 2 wind farms during construction ($\bar{x}$ = 6.82 monthly h km^{-2}).

Variances were noticeably higher across all wind farms during construction, indicating that the largest changes in vessel density were highly localized (Fig. 3). The highest variance occurred between pre-construction and construction, with a range of 18.44–53.36 monthly h km^{-2}. The maximum variance within the construction vs. post-construction comparison was slightly lower, with a range of 46.52–49.95 monthly h km^{-2}. The localized change indicated by the variance of the development phase comparisons was supported by substantial increases in vessel density almost exclusively being localized to the 1 km^2 cells that directly surrounded the turbines (Fig. 4). The pre-construction vs. post-construction comparison had substantially lower variance across all wind farms, with a range of 3.57–9.55 monthly h km^{-2}. Similarly to the other development phases, the highest increases observed within the buffered turbine area were located at the cells that directly overlapped with the turbines (Fig. 4).

The degree of change in vessel density exhibited by each wind farm during construction was starkly different from that exhibited by the surrounding non-WTG sites over the same time period (Fig. 3). The largest increase in vessel density experienced by a non-WTG site near Block Island during construction was an average increase of 2.27 monthly h km^{-2}, while during the same period, the wind farm site experienced an average increase of 33.87 monthly h km^{-2}. Similarly, the greatest change that a non-WTG site near CVOW experienced was an average decrease of −9.63 monthly h km^{-2} once construction ended. Over the same comparison period, the wind farm experienced an average decrease of −33.89 monthly h km^{-2}. Notably, this trend ended once the construction phase was not included in the comparison; between pre-construction and post-construction, the difference between Block Island's total change in vessel density and that of the non-WTG site with the highest amount of change (#12) was <1 monthly h km^{-2}, while at CVOW, 3 non-WTG sites experienced larger increases in vessel density on average than the wind farm did (#4, #7, and #13; Fig. 3).

3.1.2. Other vessel categories

Of the 9 remaining vessel categories, the category 'all other' vessels experienced the largest increase in density within the wind farm sites between pre-construction and post-construction, increasing at Block Island and CVOW by 4.34 and 2.63 average monthly h km^{-2}, respectively (Table S1C). Conversely, cargo ship vessel density experienced the biggest decrease at both wind farm sites over the same time period, dropping by 0.32 and 0.21 average monthly h km^{-2}, respectively. Excluding the more general vessel categories ('all other' and 'unknown'), fishing and service vessels experienced the largest increases in vessel density after the completion of each wind farm. At Block Island, fishing vessels were the vessel category that experienced the largest increase, with their density increased by 0.27 average monthly h km^{-2}. At CVOW, the vessel category with the largest increase was service ships. Their density increased by 0.07 average monthly h km^{-2} (Table S1C).

The largest changes in vessel density experienced by any vessel category (excluding 'all vessels') across all phase comparisons, within either a wind farm or non-WTG site, were exhibited by 'all other' vessels at Block Island during the pre-construction vs. construction and construction vs. post-construction comparison periods (32.61 and −28.26 monthly h km^{-2}, respectively; Table S1A,B). 'All other' vessels frequently exhibited the largest density increase within both wind farm sites and non-WTG sites. Excluding that category, the specific vessel category that experienced the highest degree of change within a wind farm or non-WTG site were passenger ships at the CVOW wind farm site (8.06 monthly h km^{-2} between pre-construction and construction, and −8.04 monthly h km^{-2} between construction and post-construction). Indeed, of all the specific vessel categories, passenger ship traffic generally increased the most within both wind farm sites and non-WTG sites between pre-construction and construction, followed by cargo ships and non-commercial ships (Table S1A). Those industries also had the greatest, and almost perfectly inverse, decreases in vessel density between construction and post-construction. Between pre-construction and post-construction, 'all other' vessels and cargo ships experienced the highest increases in vessel density across both wind farm and non-WTG sites (Table S1C). Post-construction fishing vessel presence was relatively higher at non-WTG sites surrounding Block Island compared to CVOW.

3.2. Monthly change and variance

3.2.1. Monthly change

Similar to the results from the annual analysis, the wind farm sites experienced substantially larger changes in vessel density during wind farm construction than the surrounding non-WTG sites (Fig. 5). There was one exception at CVOW, where one of the non-WTG sites (#12) mirrored the wind farm site's sharp increase and subsequent decrease in vessel density in June. Notably, the site is located close to the CVOW export cable route (Figs. 1 & 2).

Vessel density during the construction period at Block Island remained close to pre-construction levels from December to March, consistent with the construction pause that occurred at the site. Across those months, the average increase between pre-construction and construction vessel density was 0.99 monthly h km^{-2} (Fig. 5). This was similar to the average difference within non-WTG sites across all months within the same comparison period ($\bar{x}$ = 0.7 monthly h km^{-2}). In May, however, the difference between pre-construction and construction vessel density was nearly 59 times higher ($\bar{x}$ = 57.68 monthly h km^{-2}) than it was between December and March). This elevated level was maintained through August, until vessel density began to decrease rapidly and returned to pre-construction baseline levels in December. The increase observed once construction started was nearly perfectly reflected once construction stopped; every increase in vessel density in the pre-construction vs. construction comparison phase had a corresponding decrease in vessel density in the construction vs. post-construction phase. Overall, the slight increase in post-construction vessel density at the wind farm site was similar to the average change experienced across all non-WTG sites. The largest increase in post-construction vessel density compared to pre-construction levels at the wind farm site occurred in July, with an increase of 11.74 average monthly h km^{-2}, which was within the range of post-construction vessel traffic observed across all non-WTG sites.

When construction began at CVOW, vessel density was 34 monthly h km^{-2} higher than the surrounding non-WTG sites on average (Fig. 5). Vessel density then increased to its highest peak in June, before

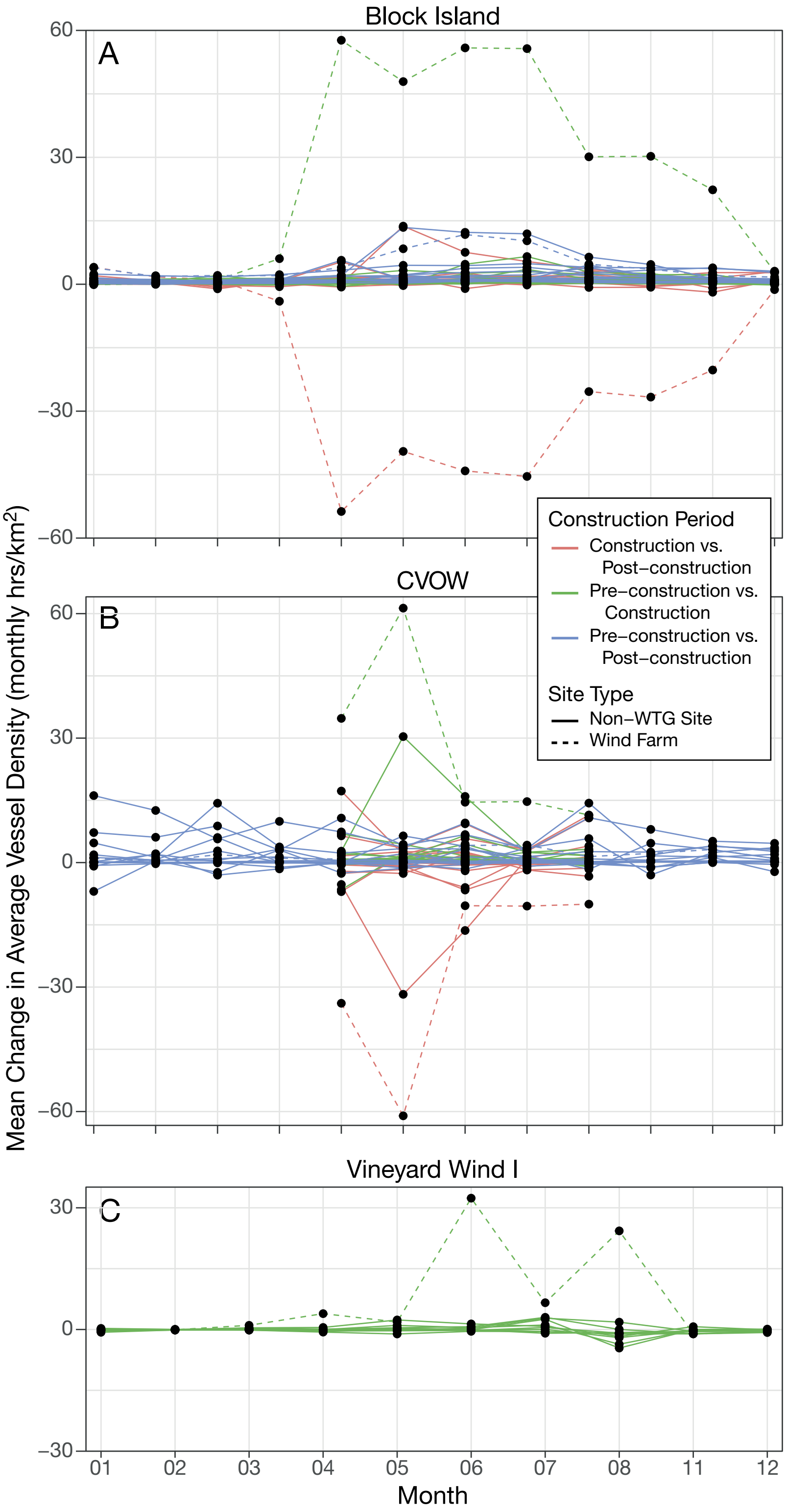


Fig. 5. Mean change in vessel density at each wind farm and non-wind turbine generator (non-WTG) site across the 3 development phases, shown on a monthly scale. The true wind farm sites are connected by dashed lines, while the randomized non-WTG sites are connected by solid lines. Positive numbers indicate an increase in vessel density in the more recent phase compared to the more historical phase in the comparison

sharply dropping to near-average values by July. Similar to Block Island, every increase in vessel density during construction reversed once construction ended. Post-construction vessel density levels were similar to pre-construction values within the wind farm across each month and did not differ from the density range across surrounding non-WTG sites. The largest increase in vessel traffic at the wind farm between pre-construction and post-construction was in August ($\bar{x}$ = 4.21 monthly h km^{-2}), although again, the increase was not substantial; this value fell well within the range of vessel density changes experienced across non-WTG sites during the same time period. Notably, there was relatively higher post-construction vessel density across non-WTG sites near CVOW between January and April, with an additional spike in September (Fig. 5).

The average difference between pre-construction and construction vessel traffic before Vineyard Wind was permitted to begin pile driving (January to April 2023) was 1.19 monthly h km^{-2}, which was similar to the non-WTG site average difference across all months sampled ($\bar{x}$ = −0.10 monthly h km^{-2}). There was no substantial increase in construction traffic in May when construction could officially commence. In June, however, the average difference between pre-construction and construction vessel traffic was nearly 27 times higher ($\bar{x}$ = 32.37 monthly h km^{-2}; Fig. 5) than the average difference between January and April. Vessel density then decreased in July, before rebounding again in August. Following the dynamic changes experienced in the summer, construction vessel density at the site dropped to below pre-construction levels in November and remained consistently low through the rest of the year. Overall, there were minimal fluctuations in vessel density across the non-WTG sites, although construction vessel density dropped to below pre-construction levels across multiple non-WTG sites in August. However, the decrease was not substantial and rose back to near zero by November.

3.2.2. Monthly variance

Post-construction vessel density was typically higher than construction vessel density across the non-WTG sites in every study area, with some exceptions (Fig. 6). At Block Island, the opposite was true at the wind farm sites, where the average construction density was substantially higher than both the pre-construction variance and post-construction average nearly every month of the year (Fig. 6A). This pattern was even more consistent at CVOW, where the average construction vessel density was higher than both the pre-construction variance and post-construction average during every month where construction occurred at the wind farm site (Fig. 6B). At Vineyard Wind, the average vessel density during construction was higher than the pre-construction variance at the wind farm site, and was higher than the construction traffic at non-WTG sites (Fig. 6C). There did not appear to be any seasonal correlation with construction or post-construction vessel density averages falling outside of the pre-construction variance other than the wind farm development across all study areas.

4. DISCUSSION

4.1. Wind farm development and vessel density

Vessel density at the 3 offshore wind sites was characterized by a sharp and temporary increase during construction that was subsequently reversed by an equally abrupt decrease once construction ended. Overall, this resulted in only a trivial increase in vessel density at each wind farm over the entire development period (4.98 more monthly h km^{-2} at Block Island, and 2.52 more monthly h km^{-2} at CVOW; see Figs. 3 & 6 for additional context). For reference, the average pre-construction vessel density range across the 3 wind farm sites was 1.02–1.39 monthly h km^{-2}. Vessel densities observed across non-WTG sites surrounding the wind farms following construction were similar to the values observed at the wind farms. Furthermore, the increases observed across the wind farm and non-WTG sites were similar in value to the average increases experienced across the entire regional study areas (Fig. 7). We conclude that the increased vessel traffic associated with offshore wind sites was restricted to the construction period and, even during construction, resulted in vessel density increases in very small areas directly surrounding the turbines (Fig. 3 & 4).

A large degree of variance was associated with the average change in vessel density between pre-construction vs. construction and construction vs. post-construction, indicating that increases in vessel traffic associated with construction were highly localized (Fig. 3). Localization was further supported in the spatial data, in which a visual analysis of the wind farm sites revealed that the largest outliers were centered around turbine locations (Fig. 4). Furthermore, the monthly analysis revealed that disproportionately large vessel traffic increases were also temporally localized. Monthly vessel density changes were occasionally twice (at Block Island and CVOW) or 5 times (at Vineyard Wind) as large as the annual average change (Figs. 3 & 5), but these occurrences were typically over short periods, ranging from 1–4 mo. The monthly analysis showed that vessel presence was not evenly distributed over the construction period; rather, vessel presence changed sporadically. Our analysis of monthly variance further underscored the inconsistency of vessel density during construction: the average vessel density during construction within some months remained close to pre-construction levels, while others were much higher (Fig. 6). However, in every month where large construction outliers occurred, post-construction average vessel density was lower than that of construction, typically returning to or close to pre-construction values. Thus, the temporal windows with the highest vessel presence associated with offshore wind development were limited, discrete, and immediately reversed following construction.

During construction, vessel density increased between 6.82 and 36.41 additional average monthly h km^{-2} across all wind farms. Interestingly, the lowest increase (6.82) was exhibited by the largest wind farm investigated, Vineyard Wind. Vineyard Wind was a much larger project than Block Island or CVOW, both in terms of the number of turbines and turbine size. Although it might seem that those parameters would result in higher vessel density to handle the installation of a larger operation, our results indicate that the opposite was true. One factor contributing to this result is that the Vineyard Wind construction period included a 6 month period where pile-driving was not yet authorized to begin (November 2022–April 2023), meaning that the average vessel density for that period may have contained more low-work months than the Block Island or CVOW construction periods. However, Block Island's construction period con-

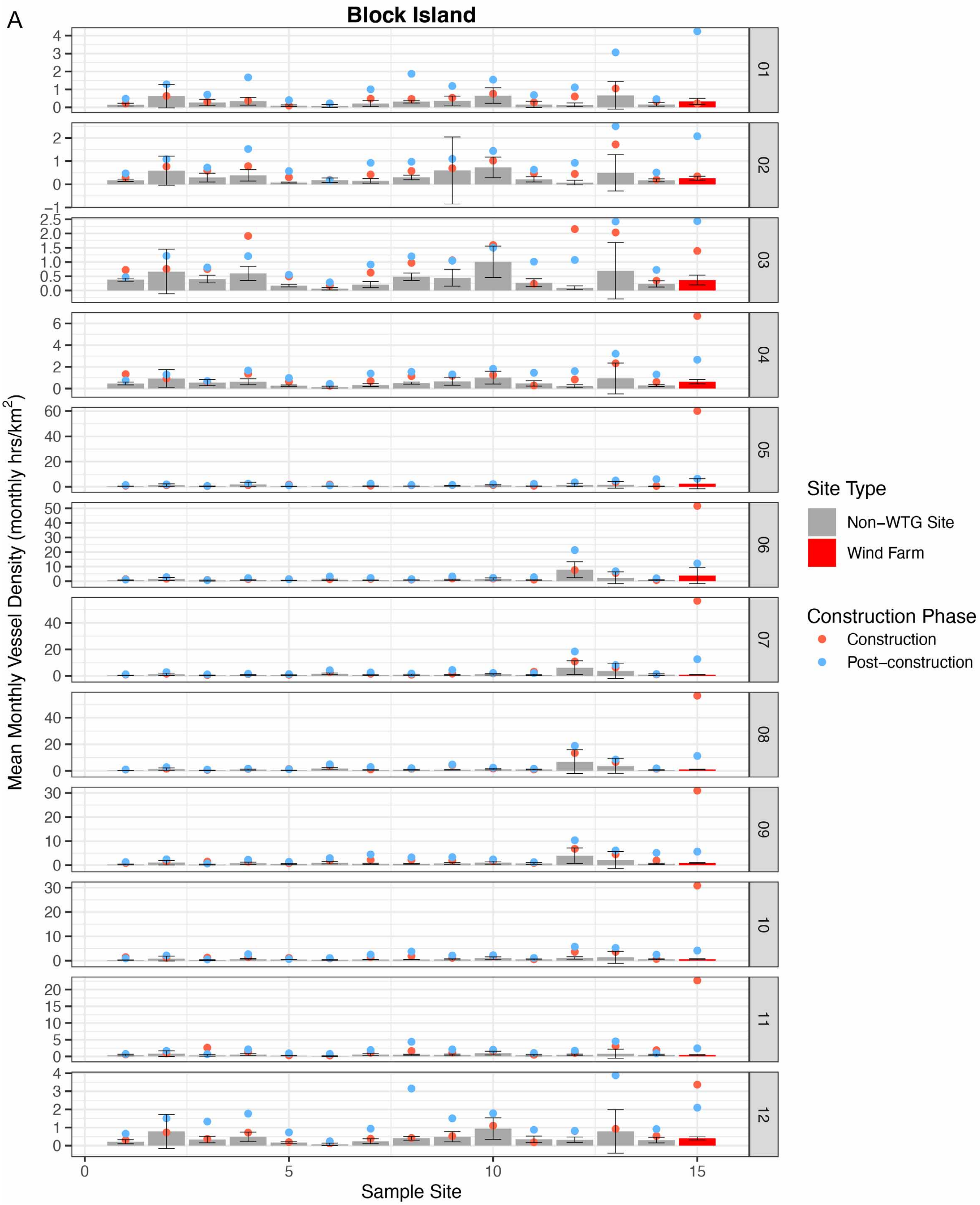


Fig. 6. (A–C) Mean vessel density and associated variance per month within the pre-construction period of each wind farm. The summary statistics from each randomized non-wind turbine generator (non-WTG) site are shown as gray bars, and wind farm sites are shown as red bars. Error bars represent SD. Vertical figure panels represent individual months, with month numbers labeled on the right side. The mean vessel densities per month are shown within the construction periods (red points) and post-construction periods (blue points). The figure visually compares whether changes in vessel density during and after the construction period (blue and red points) fit within the variance of the original pre-construction period (thin variance bars) on a monthly scale. Note the different *y*-axis scales in each panel.

Fig. 6. (*continued on next page*)

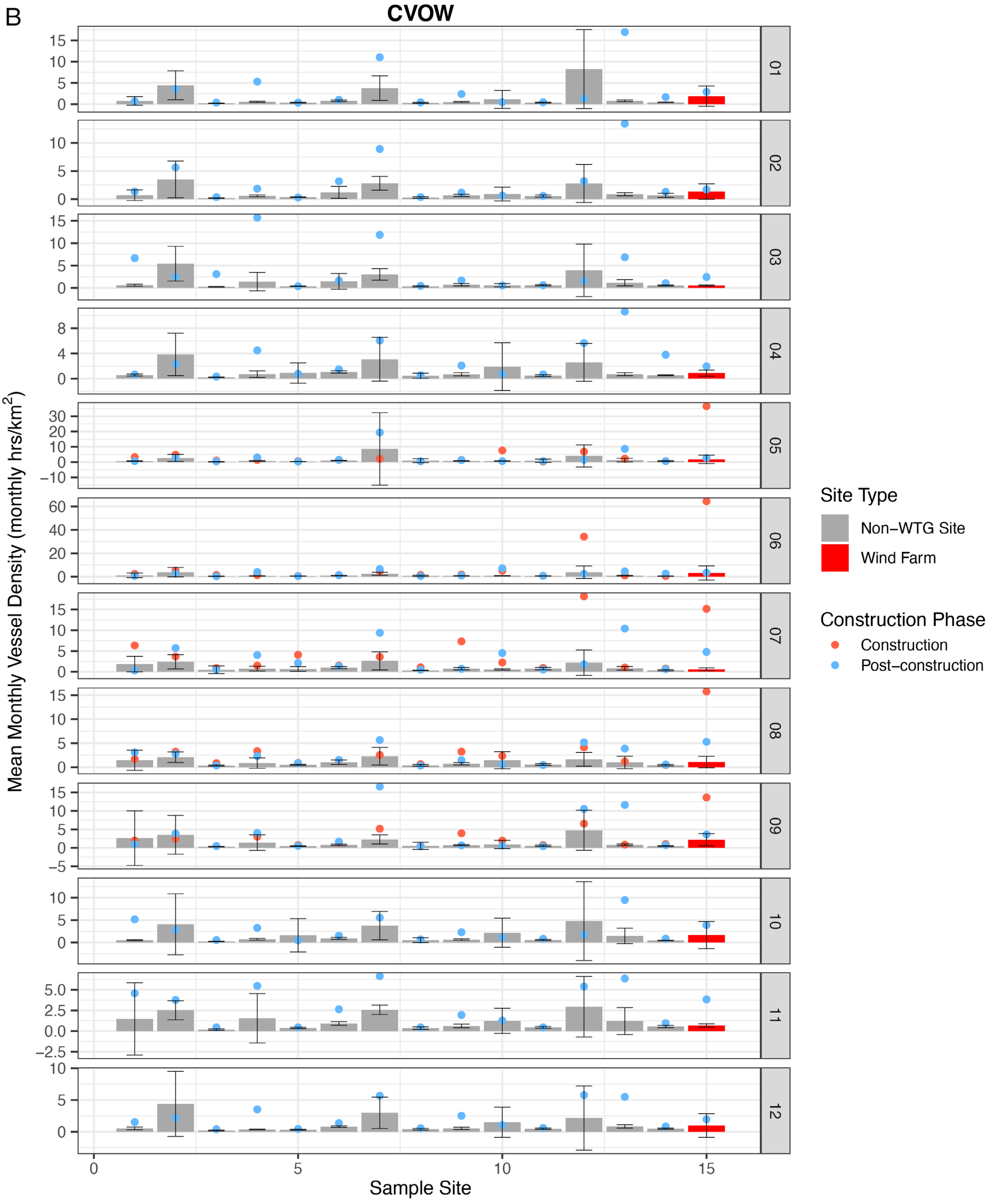


Fig. 6. (continued)

tained a multi-month pause as well, and the largest monthly increase in vessel density that occurred during the construction of Vineyard Wind was still only ~50% of the increases experienced at Block Island and CVOW (Fig. 5). An alternative explanation may be that construction practices are growing more effi-

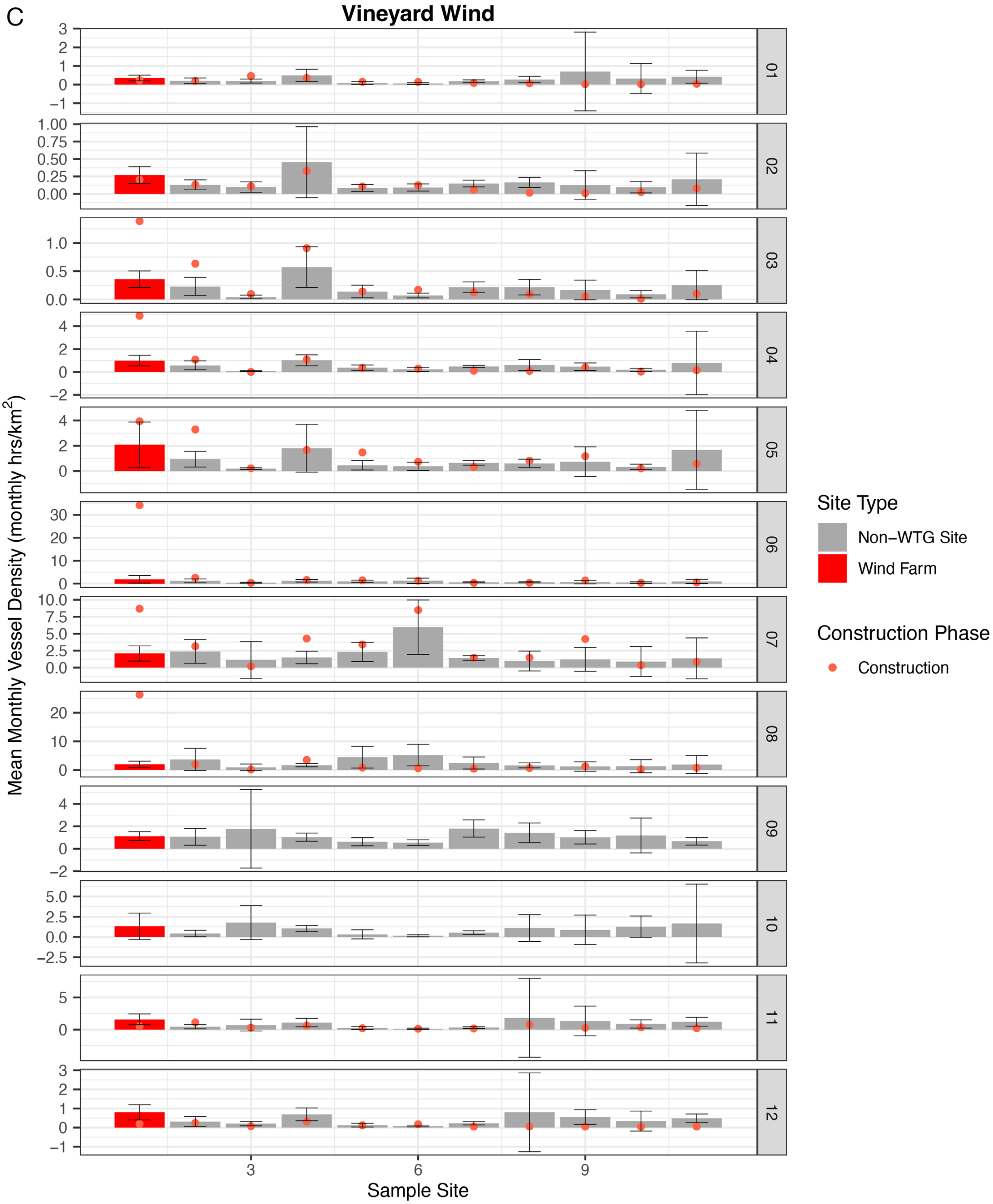
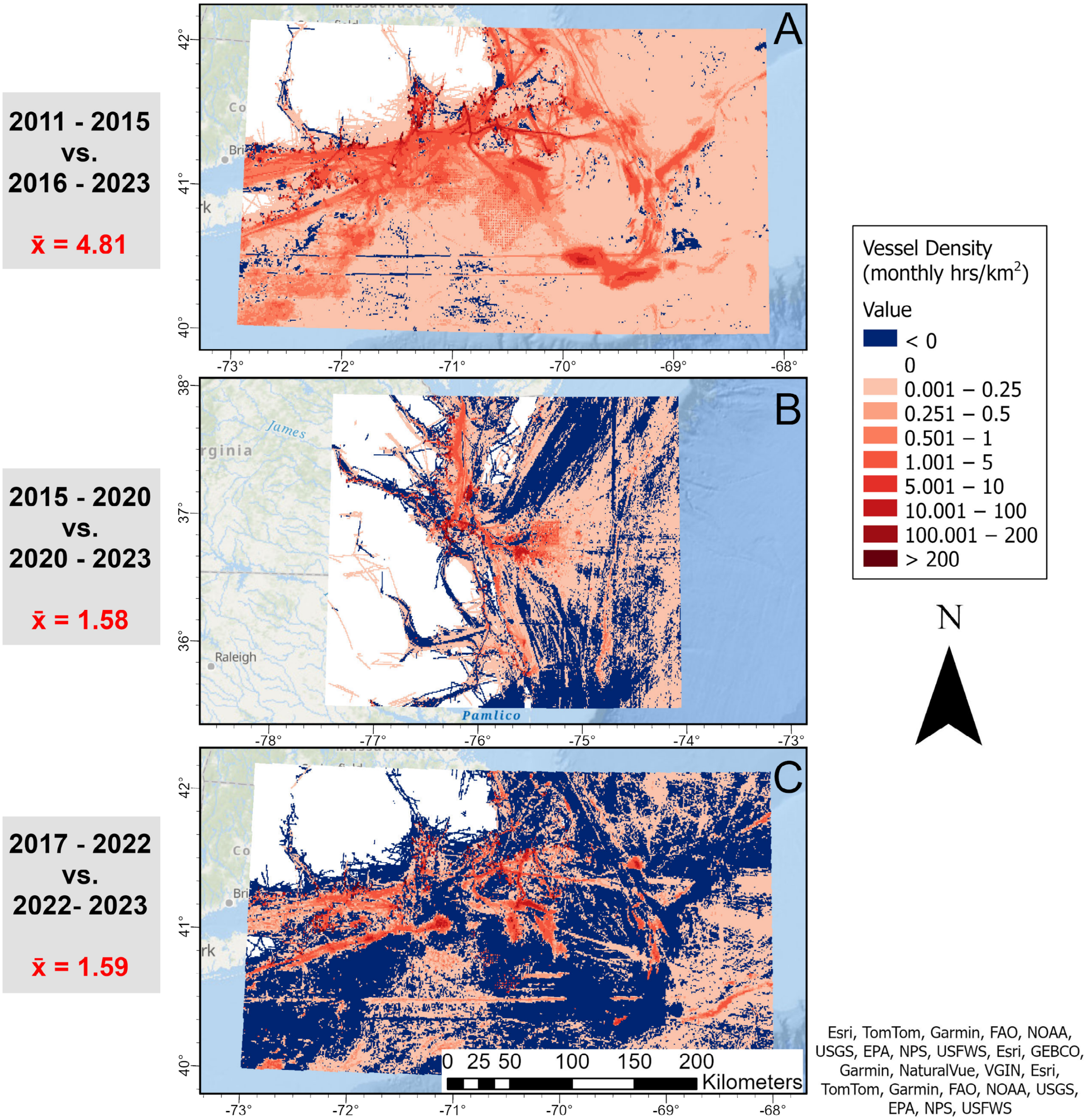


Fig. 6. (continued)

cient over time as more wind farms are developed, thereby requiring fewer vessels to accomplish the same activities. Nevertheless, given the size of the wind farm and the fact that 5 WTGs were installed during this period (the same number as Block Island), this result was surprising.



Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS, Esri, GEBCO, Garmin, NaturalVue, VGIN, Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS

Fig. 7. Average change in vessel density, in monthly h km^{-2}, between pre-construction and post-construction across the full extent of the data covering each wind farm: New England waters surrounding (A) Block Island and (C) Vineyard Wind; (B) waters off of coastal Virginia. Note the legend's exponential increase in value; light pink/red coloration represents small increases in vessel density over time (0–5 monthly h km^{-2}), while the darkest reds represent increases in vessel density that are an order of magnitude higher (100+ monthly h km^{-2})

In comparison, the maximum monthly vessel density increases during construction of Block Island and CVOW were 2 times larger than that of Vineyard Wind (57.68 and 61.32 average monthly h km^{-2}, respectively, vs. 32.34 average monthly h km^{-2}; Fig. 5). Thus, vessels were on the water for up to 61 h km^{-2} per month during construction. In context, that increase is equivalent to about 1.5 additional weeks of work for a single vessel per 1 km^2 within the 2 km-buffered wind farm sites on average, assuming a 40 h work week. However, that is likely a conservative estimate, given that pile driving was the only construction activity prohibited at night, and was only prohibited at CVOW and Vineyard Wind (NOAA 2020, 2021). These increases were heavily localized near the turbine sites, just as they were at Vineyard Wind, and vessel traffic levels decreased after the construction period was completed. This pattern was consistent across this analysis; it was observed at every wind farm, on both an annual and monthly scale, across all vessel categories. This indicates that any additional vessels present during wind farm construction were removed following construction, and post-construction maintenance vessel traffic was minimal.

The increases in vessel density we observed were mostly constrained to the period of active construction and localized to the wind farm sites, suggesting that the vessels driving this increase were most likely part of the construction fleet. We found this to be true for both the annual and monthly analysis. In addition, the 'all other' vessel category appeared to be the individual category driving the majority of the change observed within 'all vessels aggregated', indicating that the majority of the construction fleet may fall in that AIS vessel category (Table S1A,B). Furthermore, our results suggest that only a small number of additional vessels were on the water because of construction. NOAA mandates a 10 knot speed restriction for all project vessels involved in pre-construction surveys and construction when large whales are detected, which has been shown to significantly reduce mortalities caused by vessel strikes (Laist et al. 2014, NOAA 2020, 2021, Garrison et al. 2022, Redfern et al. 2024). Many offshore wind developers have voluntarily agreed to comprehensive speed restrictions to assist conservation goals, which may further reduce risks associated with increased vessel traffic (NOAA 2021). The discrete temporal windows associated with offshore wind construction and the relatively small number of vessels involved in operational maintenance should make mitigation measures imposed on project vessels straightforward to implement while simultaneously maximizing their effectiveness.

4.2. Industry-specific impacts

We did not observe any bottlenecks in industry-specific vessel traffic as a result of displacement caused by the WTGs. However, the marginal increase in fishing presence that occurred near Block Island was a notable result not mirrored in the other 2 sites, and aligns with findings from a local analysis of recreational boating activity surrounding Block Island (Carey et al. 2020). The study found higher usage of the wind farm area by fishers post-construction and identified recreational fishers as the primary users of the turbine area. Fishing vessel presence increased across the wind farm site and each non-WTG site between pre-construction and post-construction at Block Island, and fishing vessels experienced the largest increase in density post-construction overall (excluding the more general 'all others' vessel class). The sum of the vessel density increases for fishing vessels across all sample sites at Block Island post-construction was 5.54 average monthly h km^{-2}. In comparison, total fishing vessel presence decreased post-construction at CVOW and across its surrounding non-WTG sites, and also decreased once construction began at Vineyard Wind (Table S1A,C). Notably, all 3 wind farms allow fishing near their turbines. A potential explanation for this phenomenon is that Block Island's placement in state waters provides greater access for fishing vessels compared to CVOW or Vineyard Wind. Additionally, bathymetric and oceanographic dynamics in near-shore waters may stimulate fish productivity to a higher degree (Nixon et al. 1986). An alternative explanation is that the turbines serve as de facto artificial reefs: turbines may be stimulating productivity regardless of whether they are near-shore or offshore, but smaller vessels are better able to navigate between the turbines. This would explain the boost in near-shore fishing vessel density that was not shared by the wind farms constructed in federal waters, as small-scale fishers tend to stay within near-shore environments (Daw et al. 2012). Additionally, the more recent installation years of CVOW and Vineyard Wind may mean that the turbines have not been in the water long enough to increase productivity to merit the trip offshore. However, this seems unlikely given that artificial reefs are known to colonize fairly quickly at offshore wind sites (Kerckhof et al. 2019).

4.3. Implications for large whales

Right whales live in a highly developed region of the northwest Atlantic Ocean and are exposed to significant vessel strike risk through a confluence of factors including their habitat, feeding strategies, migration pattern, and behavioral ecology. This heightened risk emphasizes the need for effective mitigation during offshore wind development, particularly at sites in or near important right whale habitat areas (i.e. CVOW, which is within the species' migratory corridor, and Vineyard Wind, which is within their foraging area). To date, there has been no evidence of any correlation between offshore wind development and large whale strandings (Thorne & Wiley 2024). Our findings support that conclusion and suggest that ongoing mitigation efforts can be effective at reducing the impact of wind farm construction on large whales. The localized nature of construction-related vessel traffic increases we observed indicates that risk from increased vessel presence is mostly constrained within a 2 km buffer around each WTG. This suggests that targeted restrictions on vessel behavior, such as reduced speed, will be highly effective (Garrison et al. 2022, Findlay et al. 2023, Redfern et al. 2024). Furthermore, the immediate and abrupt decrease in vessel density that we observed once construction was completed indicates that temporal restrictions on construction have the potential to be highly effective as well. Following construction, vessel density near the wind farms dropped to near-baseline levels, indicating that pausing construction during peak whale presence is an effective means of mitigating vessel-related risks caused by wind farm development.

Our findings also suggest that allowing additional construction activities to occur at night may reduce vessel-related risk for large whales even further. Nighttime piling would result in construction vessels being removed from the scene more quickly, which has been demonstrated to be an effective tool for lowering exposure risk during development in certain contexts (Southall et al. 2023). While limited visibility at night makes visual monitoring more difficult, the benefits of concluding construction more quickly in conjunction with continued use of acoustic injury mitigations (i.e. bubble curtains) indicate that a faster construction period may still be a more effective mitigation measure, particularly for species with discreet seasonal occurrence (Southall et al. 2023).

The monthly analysis further underscored the efficacy of temporal restrictions on construction as a mitigation measure. The rapid increases and decreases in vessel density exhibited month-to-month during construction suggest that construction limitations enforced on a similar temporal scale are an effective measure for quickly taking vessels off the water. Therefore, continuing to impose construction moratoriums around seasonal whale migration patterns will significantly reduce the vessel-related risk posed to the species. Importantly, these moratoriums should be strategic and reflect the fact that different species' peak densities occur at different times; managers should exercise caution to avoid creating a construction bottleneck that disproportionately affects one species in the effort to avoid another.

Unfortunately, seasonal habitat use patterns of right whales are complex and not fully understood, and significant shifts in habitat use have occurred over the past decade (O'Brien et al. 2022, Meyer-Gutbrod et al. 2023). A study of right whale presence within Rhode Island and Massachusetts wind energy areas, which encompassed the Vineyard Wind lease site, found that right whales were absent from May through November, 2011–2015 (Leiter et al. 2017). In contrast, a later study comparing right whale presence in the same area found that right whale abundance significantly increased between 2013 and 2019, suggesting a change in distribution that was not captured in the survey period used by Leiter et al. (2017) (O'Brien et al. 2022). The subsequent study compared 2 survey periods: 2013–2015 and 2017–2019. Similar to the findings of Leiter et al. (2017), right whales were not present in the summer and fall during the first survey period. However, right whales were present for every season, and in higher abundances, during the second survey period. A similar trend was observed in a separate analysis of surveys from 2011–2015 and 2017–2019 (Quintana-Rizzo et al. 2021). These findings suggest that right whale distribution can change quickly and significantly, so it is dangerous to make assumptions about their seasonal presence. Such changes will likely continue as the species continues to adapt to a changing climate and shifting prey distributions. Adaptive management strategies, such as NOAA's Dynamic Management Area program, have been developed to mitigate human impacts amidst the species' changing distribution. Offshore wind construction protocols should adopt similar adaptive mitigation strategies in addition to mitigation measures that are defined by predetermined spatio-temporal boundaries.

Like other baleen whales, right whales feed on low trophic-level prey, which are highly responsive to changing oceanographic conditions (Stewart et al. 2025). It is therefore likely that changes in regional occurrence are not associated with right whales alone. Seasonal coordination of construction activities has the potential to mitigate vessel-strike risk associated with offshore wind development for this species, but it is critical that consistent and intensive monitoring for large whales is conducted within the region during construction to allow for effective mitigation. A variety of modalities, including passive acoustics and visual surveys, are available to achieve this objective. A simulation of survey scenarios to inform dynamic management indicated that persistent, glider-based passive acoustic monitoring may be especially effective at detecting right whales in a managed area due to higher detection ranges compared to visual surveys (Ceballos et al. 2023). In practice, glider-based passive acoustic monitoring has been used for effective management of shipping lanes and fisheries, and has recently been implemented in southern New England offshore wind lease areas to determine seasonality of right whale habitat (Indeck et al. 2025). However, there is no single survey method that is exhaustive, as each relies on different biological and environmental factors for successful detection. Complementary visual and acoustic platforms should ideally be integrated to maximize detection capability.

4.4. Limitations and future work

Overall, vessel density has increased steadily in recent decades, with global traffic increasing 4-fold between 1992 and 2012 (Tournadre 2014). As the global economy and reliance on marine trade continue to grow, this pattern will continue, with some projections estimating that vessel traffic will increase by orders of magnitude by 2050 (Sardain et al. 2019). We found that vessel density increased over time at each study area and likely contributed to the increases in vessel traffic we observed at each site (wind farms and non-WTG sites) over the study period (Fig. 7). Furthermore, in many sample sites, the post-construction average fell just above the pre-construction variance (Fig. 6). This indicates that overall vessel traffic was increasing over time. Our analysis did not account for this underlying effect, and it would be beneficial for future work to examine how this global increase may impact vessel density trends at local or regional scales. For instance, the difference in Block Island's pre-construction vs. post-construction vessel traffic was nearly 2 times greater than that of CVOW. However, the post-construction period of Block Island spanned nearly 7 yr, while that of CVOW covered almost 3 yr. It is unclear how much this phenomenon may have driven the higher post-construction difference at Block Island. Further investigation would help determine whether wind farm maintenance needs compound over time or remain relatively consistent.

We note some limitations related to the data we used and the status of offshore wind development within the USA. First, some bias was inherently included as a result of the nature of the AIS data. Small vessels are not required to use AIS and were likely underrepresented in our data set as a result (USCG 2015). Notably, offshore wind construction vessels less than ~19. 8 m (65 feet) in length were not required to use AIS at the time the projects analyzed here were constructed. However, NOAA has since begun requiring AIS by all vessels working on offshore wind projects (NOAA 2023). We did not analyze vessel speed, which is a critical component of understanding the risk posed by each vessel. Future investigation into how vessel speed relates to the density changes observed here would be useful.

Temporal differences in the development process of each wind farm led us to analyze different lengths of construction time per wind farm and include different rates of progress in each construction period. For instance, the construction period of Block Island included a pause from November 2015 to March 2016, while the construction period of Vineyard Wind included a multi-month period where pile-driving was not yet authorized to begin (NOAA 2021, Tethys 2023). Our seasonal analysis addressed some of these inconsistencies, but the unique constraints and pauses experienced by each project led to our analysis likely capturing additional unrelated traffic. Furthermore, Vineyard Wind was not completed at the time of writing, so we could not include a post-construction phase in our analysis. The construction phase of Vineyard Wind was also not completed, so the data used here did not fully capture the entire period of construction. We hope that our study will serve as a model for future work that will incorporate post-construction vessel density changes at Vineyard Wind and other wind farms constructing the new generation of large WTGs.

The vessel density data we analyzed was time-based, meaning that it captured vessels transiting over long distances as well as those that remained in one localized area for extended periods of time. This has important implications for assessing vessel-induced risk, as different risks are presented by moving vs. stationary vessels. Stationary vessels present negligible vessel strike risk, but may create other problems (Conn & Silber 2013). For instance, if a stationary vessel uses dynamic positioning to maintain its position in the water, a substantial amount of noise will be introduced into the environment (Küsel et al. 2023). It is therefore important to analyze the risk presented by various vessel states separately. Future analyses would benefit from quantifying the differences in vessel strike risk that exist based on vessel category and vessel behavior.

Given the large scale of Vineyard Wind, there may be new conclusions that could be drawn from its construction later in the process that could not be accounted for here. Our analysis concluded that the 2 federal offshore wind farms, CVOW and Vineyard Wind, had very different levels of vessel density increase during construction that could not be fully analyzed. Furthermore, Vineyard Wind was the first federal wind farm in this analysis to require a construction moratorium to mitigate impacts to North Atlantic right whales, and the direct impacts of that regulation merit subsequent analysis (NOAA 2021). Increased monitoring of vessel density during construction, both at Vineyard Wind and other sites, will be critical for understanding the impact that full-scale offshore wind projects have on local vessel density, as well as the efficacy of mitigation measures on projects of that scale.

5. CONCLUSION

We found that, to date, increases in offshore wind development vessel traffic in the northeastern USA were primarily restricted to the construction phase, with minimal increases in vessel traffic following construction. Increases in vessel traffic associated with construction were restricted to discrete periods in localized areas surrounding individual turbines. These increases almost disappeared once construction was complete, likely because vessels involved in construction departed the area. We conclude that these localized increases in vessel density during the construction phase pose a small risk to large whales compared to increases in regional vessel traffic as a whole. This limited risk is offset by the mitigation measures that each project vessel is required to follow. Our findings support the potential for targeted vessel mitigation efforts, including seasonal construction moratoriums and vessel speed restrictions to significantly reduce risk. However, the efficacy of such measures will depend on consistent monitoring and dynamic management, particularly for North Atlantic right whales. Overall, our results are a cause for optimism regarding the long-term implications of offshore wind development and its potential impact on large whales and for the North Atlantic right whale in particular. With appropriate mitigation techniques, vessel-related risk associated with the development of renewable energy in the USA need not impede the recovery of one of the country's most iconic marine mammal species.

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