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Original Article

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Acoustic presence and demographics of sperm whales (*Physeter macrocephalus*) off southern New England and near a US offshore wind energy area

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Abstract

Construction in the southern New England wind energy area (WEA), a large-scale offshore wind farm on the east coast of the United States, started in June 2023. Baseline data was collected from 2020 to 2022, with six passive acoustic recorders (SoundTraps) deployed at shallow (<60 m) sites in the vicinity of Nantucket Shoals and Cox's Ledge. Data were analysed for sperm whale presence, and demographic composition was assessed using interclick intervals. Presence varied by site, season, and year. Sperm whales were detected year-round but the majority (78%) of days with acoustic occurrences were between May and August. Three demographic classes (putative social groups, adult males, and midsize animals) were detected across multiple seasons, with social groups detected most frequently. Sound propagation tests were conducted at two sites and predicted detection ranges within 20–40 km indicate that sperm whales were likely in proximity to the WEA. These results provide a baseline that will be used to assess ongoing sperm whale presence, especially that of social groups which may be more sensitive to disturbance. This study highlights why sperm whales, classed as endangered in US waters, should be considered in mitigation plans and permitting efforts for offshore wind energy.

Keywords: acoustic monitoring; sperm whale; interclick-interval; seasonality; demographics; wind energy; detection range

Introduction

Planned development of offshore wind energy areas (WEAs) in United States (US) waters includes thousands of turbines in the Pacific, Gulf of Mexico, and on the Atlantic Outer Continental Shelf (Office of the Press Secretary 2021, 2022). In 2023, construction on the first large-scale offshore wind farm began in the Southern New England (SNE) lease area. This construction is expected to result in an increase in vessel activity and underwater noise (e.g. Ruppel et al. 2022). For cetaceans, increases in underwater noise can impact communication, foraging efficiency, and behaviour (e.g. Watkins 1986, Miller et al. 2009, Isojunno and Miller 2015, Farmer et al. 2018). The level of disturbance can vary between and within species, based on the context (e.g. critical habitat), and/or the physical and behavioural state of cetaceans (e.g. age, sex, health, previous exposure, etc.) (e.g. Southall et al. 2007, Gomez et al. 2016).

Sperm whales are protected by the Marine Mammal Protection Act and listed as 'Endangered' under the Endangered Species Act. They are a deep diving species with a global distribution (e.g. Wong and Whitehead 2014, NOAA Fisheries 2019). The continental slopes and seamount chain off SNE and Georges Bank are recognized as important seasonal habitats for sperm whales (e.g. Waring et al. 2014, Wong and Whitehead 2014, Stanistreet et al. 2018). While less well known, opportunistic sightings and scientific surveys also regularly record sperm whales on the continental shelf south and east of the SNE WEA (e.g. Scott and Sadove 1997, Palka et al. 2016, 2021). Recent studies have proposed that coastal regions were likely important sperm whale habitats prior to whaling (Whitehead et al. 2021, Letessier et al. 2023) and others have shown that as some large whale populations recover from whaling, their distribution may return to historic habitats (O'Brien et al. 2022). For sperm whales, using coastal waters off of SNE means potential exposure to the impacts of offshore wind energy development. Previously, sperm whales have exhibited avoidance and behavioural changes in response to local stressors, including seismic surveys and naval sonar (Mate 2011, Isojunno and Miller 2015, Stanistreet et al. 2022). Furthermore, certain demographic groups, such as reproductive females and calves, are expected to be more sensitive to disturbances (Farmer et al. 2018).

Passive acoustic monitoring (PAM) can be conducted year round, in remote areas (e.g. Rice et al. 2021, Van Parijs et al. 2021) and is an established method for detecting and studying sperm whales (e.g. Stanistreet et al. 2018, Solsona-Berga

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et al. 2022, Van Parijs et al. 2023). Sperm whales produce echolocation clicks, known as usual clicks, almost continuously while diving and can be detected at distances of 60 km or more depending on equipment, environmental conditions, and animal behaviour (e.g. Backus and Schevill 1966, Madsen et al. 2002, Tran et al. 2014, Stanistreet et al. 2018). During a dive, sperm whales often produce clicks at a consistent dominant rate (interclick interval, ICI) between 0.2 and 2 s, with variations in ICI occurring at the start of a dive and during foraging buzzes (e.g. Fais et al. 2016, Jiang et al. 2021). Each click is composed of multiple pulses (Backus and Schevill 1966), which are the result of reverberations within a sperm whale's head (Norris and Harvey 1972, Mohl et al. 2003a). The time between pulses (interpulse interval, IPI) is related to the size of an animal's head and thus can be used to estimate body length (Norris and Harvey 1972, Adler 1980, Mohl et al. 1981, Gordon 1991, Mohl et al. 2000, Rhinelander and Dawson 2004, Teloni et al. 2007, Growcott et al. 2011). This method often requires identification of on-axis clicks, which may be only 1% of recorded clicks, or distinguished clicks of focal animals (e.g. Antunes et al. 2010, Beslin et al. 2018). Fortunately, for odontocete species, there is also a relationship between ICI and body size (Jensen et al. 2018). Solsona-Berga et al. (2022) showed a linear relationship between IPI and ICI, and developed a method for using ICI as a proxy for body length (Posdaljian et al. 2023, preprint: not peer reviewed). Furthermore, the sexual dimorphism of sperm whales impacts an individual's click characteristics (IPI and ICI) as well as social and diving behaviour and distribution (e.g. Best 1979, Rice 1989, Gordon 1991, Growcott et al. 2011, Solsona-Berga et al. 2022, Posdaljian et al. 2023, preprint: not peer reviewed). As a result, the relationship between ICI and body length can be used to assess demographics when classes are defined based on different body lengths.

In this study, demographic composition refers to the acoustic identification of putative social groups, adult males, and midsize animals. Social groups consist of related adult females and their offspring (calves and juveniles), and inhabit tropical and temperate latitudes (Whitehead 2003). Compared to adult males, adult females are relatively small (8–11 m in length) with a more rapid ICI (~0.5 s) (e.g. Rice 1989, Jaquet 2006, McClain et al. 2015). Adult males are larger (>13 m), have a slower ICI (~1 s), and spend most of their time living alone at higher latitudes (e.g. Madsen et al. 2002, Growcott et al. 2011). Adult females, within their social group, and adult males travel to temperate latitudes to breed (Whitehead 2003). Before reaching sexual maturity, immature males will leave their mother's social group and can form loose aggregations known as bachelor groups (Best 1979). Animals in a bachelor group could range in size from <10 to 13 m (Clarke 1956, Best 1969), and thus be a similar size to and produce clicks with a similar ICI to that of adult females. Thus, acoustic detections of a midsize animal with a click rate slower than what is expected for a social group (adult females with juveniles) but faster than what is expected for a large adult male could be immature male or large adult female (Solsona-Berga et al. 2022, Posdaljian et al. 2023, preprint: not peer reviewed).

This study used passive acoustic data collected in the SNE WEA to assess the year-round acoustic presence and demographic composition of sperm whales in the region. The detection range of the sperm whales was also estimated. The results of this study are essential for understanding sperm whale habitat use in this region, especially the shelf areas undergoing offshore wind energy development, and for effectively monitoring future changes in occurrence and distribution.

Methods

Data collection

Passive acoustic data were collected in the western North Atlantic Ocean off the coast of SNE between January 2020 and November 2022 (Supplementary Table S1). Bottom-mounted acoustic recorders (SoundTrap 500 or 600; Ocean Instruments Inc.) were deployed at four sites located on Nantucket Shoals (NS) and two located on Cox's Ledge (COX), with sea floor depths ranging from 32 to 58 m (Fig. 1). Recorder locations were selected to monitor the presence of acoustically active species and characterize the soundscape before, during, and after wind farm construction (Van Parijs et al. 2023). Acoustic recordings were collected at NS01 and NS02 from January 2020 to December 2022, at COX01 and COX02 from November 2020 to October 2022, and at NS04 and NS05 for 10 months in 2022 (Supplementary Table S1). Data gaps of a few hours to 14 days occurred as a result of battery depletion and/or the turnover between instruments. Early deployments sampled at 48 kHz and in July 2021 the sampling rate was increased to 64 kHz, but this would not impact the detection of sperm whale clicks. SoundTraps have a flat frequency response (±3 dB) between 20 Hz and 60 kHz, resulting in an effective recording range of 20 Hz–32 kHz (Ocean Instruments Inc.). Acoustic recorders were attached to a fixed bottom-mounted mooring 2–3 m above the sea floor (Supplementary Fig. S1). The mooring included a subsurface float rising ~6 m vertically into the water column, a VEMCO VR2AR acoustic release receiver, and anchor weights.

Detecting sperm whale echolocation clicks

An automated multi-step detection algorithm built in MATLAB (R2016b, MathWorks Inc., Natick, MA, USA), was used to identify sperm whale usual clicks from the acoustic data (Solsona-Berga et al. 2020 appendix, 2022). Based on the sample rate of the data collected, the detection algorithm was modified to apply a bandpass filter between 5 and 23 kHz to reduce background noise. Detections were filtered at a received level threshold of 130 dB_{pp} to improve consistency in detection and validation of potential sperm whale signals. Other possible odontocete clicks (e.g. delphinid) were automatically filtered out based on the known spectral characteristics of sperm whale clicks (see settings in Solsona-Berga et al. 2022). Detections were grouped into sessions and manually validated in *DetEdit* (Solsona-Berga et al. 2020) by an experienced analyst [Annabel Westell (AW)]. False positives and any detections that occurred when a vessel was detected were manually removed as sperm whale signals are difficult to distinguish from impulsive sounds produced by vessel propellers (Solsona-Berga et al. 2022). On days when detections were brief or intermittent, the sperm whale clicks were confirmed by listening to the audio in Raven software, resulting in a high degree of confidence in the daily presence results. To assess the repeatability of validation results produced by a single analyst (AW), 10% of the 2021 sessions from the sites COX01 and NS02 were randomly selected to be reviewed by a second analyst. These sites were selected because they were spatially dispersed and data had continuous data collection in 2021.

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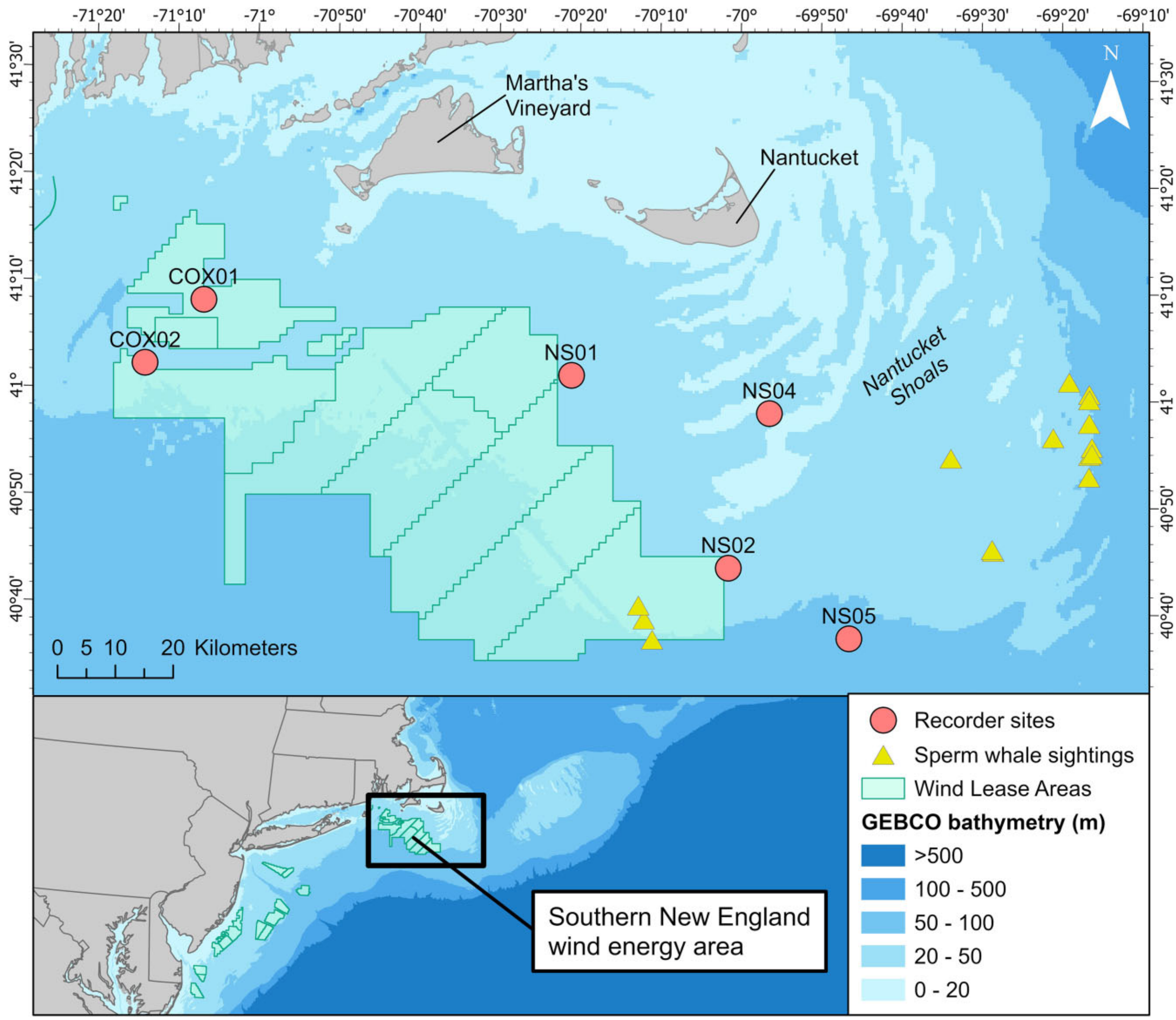

Figure 1. A map of SNE with offshore wind energy lease areas south of Martha's Vineyard, MA, USA. Passive acoustic recorders (SoundTrap 500 or 600) were deployed for various amounts of time between January 2020 and November 2022 at two sites on Cox's Ledge (COX) and four sites on Nantucket Shoals (NS). The map includes sperm whale sightings recorded between 2002 and 2021 during Northeast Fisheries Science Center (NEFSC) aerial and shipboard surveys conducted along the continental shelf and occasionally passing through/over the WEA (Palka et al. 2021). Bathymetry data was retrieved from the GEBCO Compilation Group (2022), GEBCO_2022 Grid (doi:10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c).

Agreement between the two analysts was high, for 199 out of 200 sessions (99.5%), indicating that the methods used here produce consistent results of marking sperm whale presence.

Demographic class using modal ICI

Solsona-Berga et al. (2022) differentiated three consistent sperm whale classes based on ICI using concatenated histograms (ICIgrams) that facilitate the distinction of dominant ICIs over time. Following the same method, detections were binned into 5-min encounters. ICIs were calculated and restricted to values between 0.3 and 2.0 s to reduce the inclusion of unwanted short ICIs when multiple whales were simultaneously clicking, and erroneous long ICIs when some clicks were not detected. If an encounter contained <5 clicks and was stand-alone (no adjacent encounters), it was excluded from the demographic analysis. The remaining encounters were reviewed in an ICIgram displaying ICI histograms (with a 0.1 s binwidth) over a time span of 24 h. If the pattern in ICI over time was constant across two or more encounters and was consistent with sperm whale acoustic behaviour, the analyst manually assigned one of three classes: (i) $\leq$0.6 s, (ii) 0.6–0.8 s, or (iii) $\geq$0.8 s.

These three classes were consistent throughout the data analysed and related to demographic classes representing the size of the detected sperm whale(s) (Solsona-Berga et al. 2022, Posdaljian et al. 2023, preprint: not peer reviewed). The demographic classes were (i) putative social groups (adult females, juveniles, and calves) with modal ICI $\leq$0.6 s, (ii) mid-size animals (immature males or adult females) with modal ICI between 0.6 and 0.8 s, and (iii) adult males with modal ICI $\geq$0.8 s (Solsona-Berga et al. 2022, Posdaljian et al. 2023, preprint: not peer reviewed). Two classes could be assigned to an encounter if a bimodal ICI was calculated (Fig. 2, Supplementary Fig. S2).

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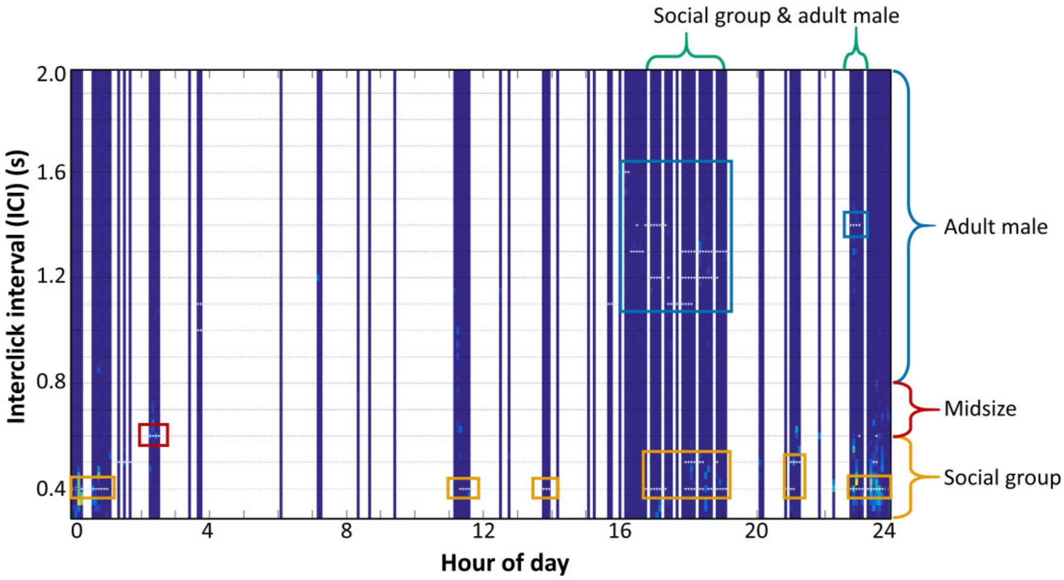

Figure 2. Example of an ICIgram displaying encounters (5-min intervals) classified as containing a social group, midsize, or adult male based on patterns in the interclick interval (ICI) over a 24-h period. The colours in the ICIgram represent the number of clicks in each 0.1 s bin, where dark blue represents any empty bin and warmer colours represent increasing counts. The modal ICI for each encounter is depicted by a white cross. The annotation of demographic classes based on consistent patterns in ICI is illustrated using coloured squares. The demographic classes were (i) social groups with modal ICI $\leq$0.6 s, (ii) midsize animals with modal ICI between 0.6 and 0.8 s, or (iii) adult males with modal ICI $\geq$0.8 s. These ICI ranges are illustrated using the brackets on the left side of the plot. Intervals when two classes were detected were summarized using combined classes, e.g. social group and adult male (green, top).

Summary statistics

Sperm whales were recorded as present for a day if there were >5 validated clicks within 1 min on that day (Van Parijs et al. 2023). Daily acoustic presence was summarized for each site across months and years. To account for variations in effort, the number of days sperm whales were detected was divided by the number of days analysed within a month and year. The annotated encounters were combined into hourly bins. If more than one demographic class was detected within an hour, these were combined and labelled (based on the combination) as social group and midsize, social group and adult male, or midsize and adult male (Supplementary Fig. S2). The total number of hours that each class was detected per site and season was calculated. Season here is defined as winter: December–February, Spring: March–May, summer: June–August, and fall: September–November. Presence of the demographic classes was summarized for each site across hours and weeks.

Estimating detection range

To better understand the spatial distribution of detected sperm whales, *in situ* sound propagation was measured and then detection ranges were estimated using multiple theoretical source levels. Sound playbacks were conducted 0.1, 1, 5, 10, and 20 km to the south of NS02 and southeast of COX01 (Supplementary Fig. S3) between 13-15 April 2023 to estimate transmission loss (TL) of sound. Based on the peak frequency of recorded sperm whale echolocation clicks, the playback sound was composed of a 6.5 kHz tone (duration 1.5 s) generated as a cosine wave with amplitude of +1 to −1. The tone was repeated 25 times, separated by 12.5 s of zero-padding, resulting in a 25-tone sequence from which repeated measures could be used to account for variability in sound propagation. The sound source was a Lubell (LL916) speaker, with a frequency response of 200 Hz–23 kHz and maximum output level of 180 dB/μPa/m @1 kHz. The speaker was connected to a Peavey PV14B 100 Watt Powered Mixer amplifier (with an output level of eight to reach the maximum output level) using an AC203E Circuit Master converter box and an iPhone as the audio player (at 100% volume).

At each of the predetermined positions, the vessel engine was turned off, the speaker was lowered into the water to a depth of 8 m, and the sound sequence was played. A handheld GPS (Garmin, GPSMAP 79sc) was used to record the vessel position at 10-s intervals during each playback as the vessel drifted. Recorded coordinates were used to determine the source range of each played tone from NS02 or COX01. After the acoustic recorders from NS02 and COX01 were retrieved, the acoustic data collected during the playback tests were extracted and analysed in MATLAB. Each tone sequence was filtered using a Butterworth (6th order) high-pass filter at 4 kHz to remove low-frequency noise. Waveforms and spectrograms of each received tone were manually inspected, and start and end indices were selected over which peak frequency and peak–peak received level (RL; dB_{pp} re 1 μPa) were calculated. If the tone was not visible above background noise or the measured peak frequency was not within 250 Hz of the source frequency (i.e. 6.5 kHz), the tone was excluded from further analysis.

To estimate TL from RL, prior knowledge of the source level (SL; dB_{pp} 1 μPa @1 m) of the playback tone was required. The peak–peak source level (SL) of the 6.5 kHz tone emitted by the speaker was evaluated in a controlled experiment off a deepwater pier with similar water temperature and chemistry by measuring the RL (peak-to-peak) at a range of 5 m and back propagating the sound level to 1 m using a spherical spreading estimation of TL [i.e. $20 \times \log_{10}(5\ \text{m}/1\ \text{m})$], thereby mitigating nearfield effects. The method described above was used to measure peak frequency

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Table 1. Number of days analysed for each of the six sites and results, including number of days sperm whales were detected, number of days a demographic class was successfully classified, and number of days each demographic class was detected.

Site	#Days analysed	#Days with sperm whales present (% of days analysed)	#Days demographic class was classified (% of days with presence)
COX01	693	3 (0.4%)	2 (66.7%)
COX02	685	9 (1.3%)	6 (66.7%)
NS01	845	81 (9.6%)	74 (91.4%)
NS02	1014	116 (11.4%)	96 (82.8%)
NS04	276	3 (1.1%)	1 (33.3%)
NS05	276	18 (6.5%)	18 (100%)
Total	3789	230 (6.1%)	197 (85.7%)

and RL of each received tone, and the SL at 1 m was then calculated as: SL = RL + TL. The standard deviation (SD) and mean SL of the 25 playback samples were calculated in the linear domain and converted to dB. Mean SL was used in further analyses of TL given measured RL as a function of range.

TL for each received tone at a known range during the NS02 and COX01 playback experiments was calculated as TL = SL–RL, where SL was the mean SL of each tone emitted by the speaker. The MATLAB Curve Fitting Toolbox was used to fit an empirical model of TL as a function of slant range (r, estimated from GPS measurements and source and receiver depths). Geometric spreading and absorption coefficients were estimated by fitting the following equation to measurements of TL vs. r at each site: $TL = b \times \log_{10}(r/1\ \text{m}) + \alpha(r)$, where b is the geometric spreading coefficient and α is the absorption coefficient. The absorption coefficient was constrained to values between 3×10^{-4} dB/m and 6×10^{-4} dB/m. These values were determined by estimating the likely range of coefficients of absorption based on the tone frequency of 6.5 kHz and *in situ* temperature, salinity, pH, and depth of the two sites (Fisher and Simmons 1977, Francois and Garrison 1982a, 1982b, Ainslie and McColm 1998).

Sperm whale detection range can vary depending on the absolute source level and orientation of the whale (Mohl et al. 2003b, Zimmer et al. 2005, Nosal and Frazer 2007, Jensen et al. 2018). To account for variability in the absolute and apparent SL, multiple theoretical values for SL were used to estimate detection range. The maximum range was estimated using a theoretical peak-to-peak (pp) source level of 235 dB_{pp} re: 1 μPa (229 dB_p re: 1 μPa; Zimmer et al. 2005). This value was assumed to be an on-axis recording of a P1 pulse. To calculate additional theoretical SL values that were inclusive of other possible off-axis angles and pulse types, 200 evenly distributed estimates of peak levels of P0 and P1 pulses at off-axis angles of 0°–180° were extracted from Zimmer et al. (2005) using PlotDigitizer software (PORBITAL 2023). The 5, 25, 50, 75, 95, and 100th percentiles of the 200 extracted levels were calculated, converted to peak-to-peak values, and used as additional theoretical SLs.

Using the range of theoretical SLs and modelled TL as a function of r, the expected RLs of sperm whale clicks were estimated at ranges up to 1000 km [$RL = SL–TL$ or $RL = SL—b \times \log_{10}(r/1\ \text{m})—\alpha(r)$] at NS02 and COX01 (Supplementary Fig. S4). The predicted model of RL vs. r at NS02 was applied to sites NS01, NS04, and NS05, while the COX01 model was extended to site COX02. For each encounter included in the demographic analysis, the source ranges of detected sperm whales were estimated by comparing the maximum RL of detections in the encounter to predictions of RL as a function of r, using the range of possible SLs (i.e. 5–100th percentile) and the appropriate site model. The range at which predicted RL matched the RL of detections was used as an estimate of source range, corresponding to range where signal excess was predicted to be zero.

Results

Acoustic presence of sperm whales and the demographics of detected animals was evaluated across six recording sites. Effort varied by site with 2 years (2021 and 2022) of continuous data analysed from the sites on COX (COX01–02) (Table 1, Fig. 3). For the sites on NS, ~2.5 and 3 years (January 2020–November 2022) of continuous data were analysed from NS01 to NS02, respectively. There were no data from NS01 during the later half of 2022 because the mooring deployed in May 2022 was lost. Nearly 1 year of continuous data were analysed from NS04 to NS05, which were new sites in 2022. The most data were collected at NS01–02 (845–1014 days, respectively), followed by COX01–02 (693–685 days, respectively), and then NS04–05 (276 days at both sites).

Sperm whale presence varied by site, season, and year

Effort corrected sperm whale detections varied by site (Fig. 3). The number of minutes excluded from analysis due to false detections and/or vessel presence ranged from 1.1 to 2% of the total minutes analysed per site. Sperm whales were detected on 0.4, 1.3, 9.6, 11.4, 1.1, and 6.5% of days analysed at COX01, COX02, NS01, NS02, NS04, and NS05, respectively. At the COX sites, sperm whales were detected in May (1 day), July (2 days), and October (9 days) of 2021, but there were no detections in 2022. On NS, sperm whales were detected more consistently and more frequently; however, there was variation between the sites. At NS02, one of the sites furthest from shore, detections occurred throughout the year while at NS04, a site on a shallower section of the shoals, detections only occurred on 2 days in July and 1 day in September of 2022.

Sperm whale presence showed clear seasonality; the majority of days with detections (78%) occurred between May and August. The highest detection percentages (~40–60% of days analysed), were recorded at NS01–02 in June and July of 2020–2021. A second peak in detections was recorded in October and November of 2021 at three sites (COX01, NS01,

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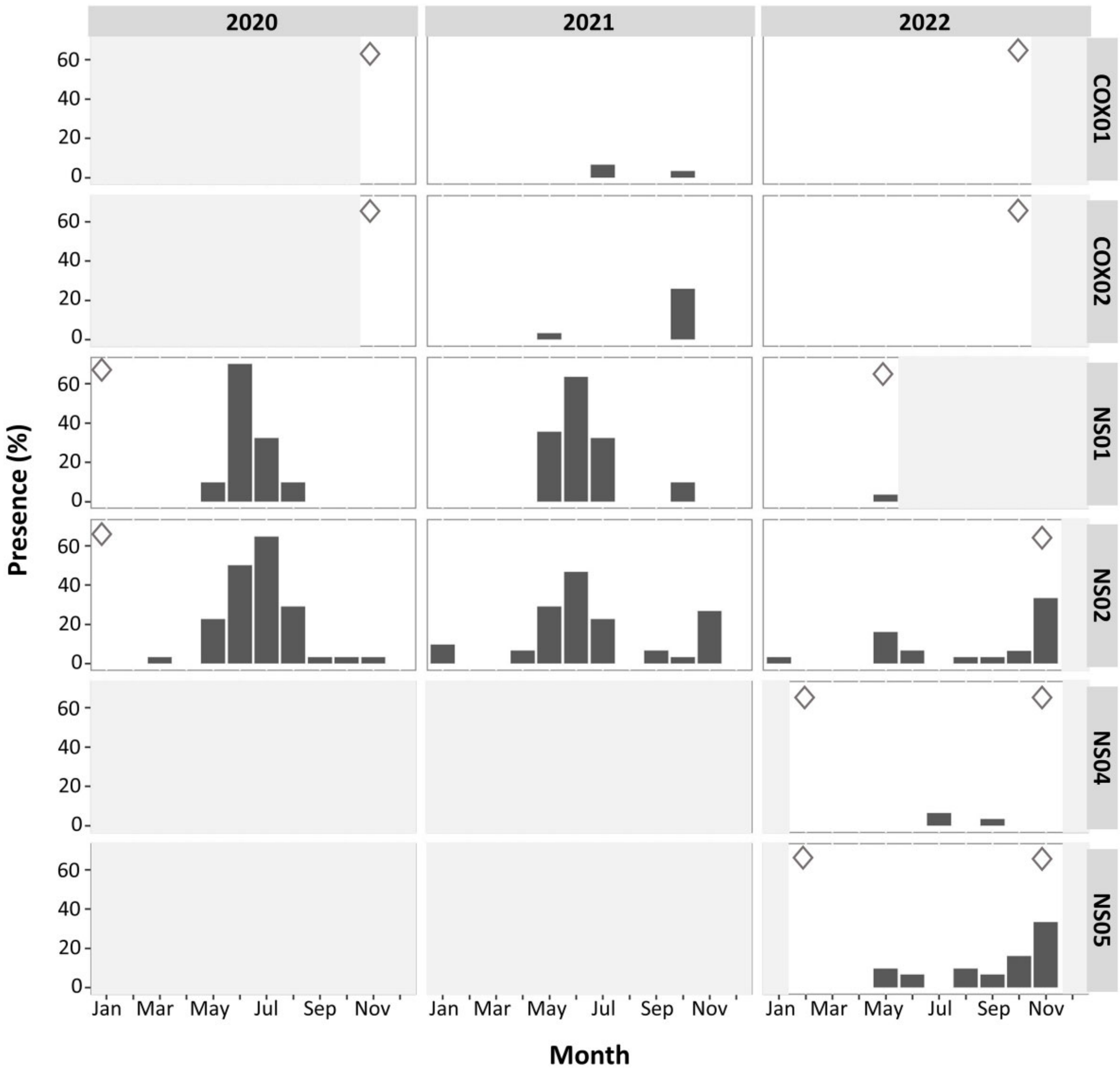

Figure 3. Effort corrected monthly presence of sperm whales at six sites in the SNE WEA between 2020 and 2022. Two sites were located on Cox's Ledge (COX) and four were located on Nantucket Shoals (NS). To account for differences in effort, presence was calculated as a percentage by dividing the number of days sperm whales were detected per month by the number of days data was recorded during that month. Grey boxes represent months when no data was collected. Diamonds indicate the month when data collection started and ended for each site, indicating partial months (Supplementary Table S1).

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and NS02) and in November of 2022 at NS02 and NS05. Between January and April, detections were scattered and infrequent.

Across all sites, the number of days with sperm whale detections decreased notably from 11.8% (of days analysed) in 2020 and 7.1% in 2021 to 2.3% in 2022. This change between years is most evident at NS02, where detections between May and September occurred on 33.9% and 20.9% of days analysed in 2020–2021, but only on 5.9% of days analysed in 2022.

Demographic class

Demographic classes were identified for the majority (~33–100% depending on the site) of days with sperm whale detections (Table 1). The amount of data available varied by site, depending on how frequently sperm whales were detected. For example, only 2 h (on 1 day) recorded at NS04 were assigned a demographic class compared to 561 h at NS02. Days were excluded if encounters had too few clicks (<5 clicks) and/or if the modal ICI was not consistent (as determined by the analyst) across two or more consecutive encounters. Across all sites, 16% of the reviewed encounters were excluded because modal ICI patterns were not consistent enough to assign a class. Three consistent patterns in modal ICI were clear across all sites and years. Most common were periods with modal ICIs of 0.4–0.6 s, matching the expected ICIs of smaller animals, likely adult females with juveniles and calves, which are often found in social groups. Consistent modal ICIs of ≥0.8 s were detected, matching the ICIs of larger animals, such as adult males. Also detected were periods with modal ICIs of 0.6–0.8 s, which were classified as midsize animals because this ICI could be linked to a large adult female or immature male. Results were evaluated at the hourly level. When more than one class was detected within an hour, these were combined into social group and midsize, social group and adult male, or midsize and adult male (Fig. 2, Supplementary Fig. S2).

Spatial overlap in social groups, midsize animals, and adults males

Social groups, midsize animals, and adult males were detected on COX in 2021, and in every year analysed (2020–2022) on NS (Table 2, Fig. 4). Across all sites and years, the majority of days (64%) and hours (73%) with sperm whale detections included a social group (Supplementary Table S2). In addition, they were the only class identified between December and February (winter). Adult males were the next most commonly identified class, detected on 39% of days with sperm whale presence, and at all sites except COX01 and NS04. Adult males were detected on their own as often as they were detected with another class. Detections of adult males with a social group or a midsize animal occurred at NS01, NS02, and NS05, predominantly between April and September. Midsize animals were detected at all sites except for NS04, and most frequently (66% of hours detected) with a social group (classified as social group and midsize, Supplementary Fig. S2). During 12% of the hours in which a social group was detected, an adult male was also detected (classified as social group and adult male).

Temporal overlap in social groups, midsize animals, and adult males

All of the sperm whale demographic classes demonstrated the same seasonality as sperm whale daily presence (Fig. 5). Social groups, midsize animals, and adult males were most frequently detected between May and September. All the classes showed similar patterns in weekly presence, the number of days per week a class was detected, which ranged from 0 to 7. At NS01–02 in 2020–2021, social groups and adult males were often detected 3–5 days per week throughout June–July. During one week in June 2021, the adult male class and the social group and midsize class occurred at NS01 every day. A second peak in sperm whale detections in the fall of 2021 (NS02) was composed of social groups, midsize animals, and adult males, all detected within a two-week period (24 October–6 November). In 2022, social groups were detected more sporadically and were never detected for >3 days in a week, and adult male detections occurred on 1 day in early June (NS01, NS02, and NS05) and with a social group (social group and male) on a few days at NS02 and NS05.

Estimated detection range

Playback experiments of 25 tones were successfully completed at ranges of 0.1, 1, 5, 10, and 20 km south of NS02 and southeast of COX01. The amplitude and peak frequency of the tones varied within a playback as the vessel drifted at each range. Within increasing range, deviation from expected peak frequency (6.5 kHz) tended to increase, resulting in the exclusion of some received tones not within 250 Hz of the played tone frequency (Supplementary Table S3). Additionally, while 18 tones were discernible at 20 km from NS02, tones played 20 km from COX01 were not visible above background noise in waveforms and spectrograms and thus were excluded from the modelling of TL as a function of range. South of NS02, RL ranged from 156 dB_{pp} at 0.1 km to 107 dB_{pp} at 20 km. Southeast of COX01, RL ranged from 165 dB_{pp} at 0.1 km to 112 dB_{pp} at 10 km. The mean SL (dB_{pp} re 1 μPa @ 1 m) of the 6.5 kHz tone played by the speaker was estimated to be 179.7 dB_{pp} ($SD = 1.7$ dB_{pp}; Range 175.3 dB_{pp}–182.1 dB_{pp}; $n = 25$), allowing for TL to be estimated for each tone received during the playback experiment (Supplementary Fig. S4). Predicted TL equations for COX01 and NS02 were generated after fitting the TL model to empirical measures of TL vs. r (Table 2). The theoretical SLs calculated based on Zimmer et al. (2005) and used to estimate detection range are reported in Table 3 and ranged from 192 to 235 dB (dB_{pp} re 1 μPa @1 m), providing multiple scenarios to account for expected variability in SL as a function of body size, pulse type, and off-axis angles.

The median peak frequency of detected sperm whale clicks was 6.7 kHz, indicating that the TL models of 6.5 kHz were appropriate for estimating source ranges of sperm whales detected at the monitoring sites. The median RL was 140 dB_{pp} at COX sites and 143 dB_{pp} at NS sites (range: 130–180 dB_{pp}). On COX, at a SL of 235 dB_{pp}, the majority of encounters were estimated to be between 30 and 50 km (range: 9–55 km, median = 42 km) from the sites (Fig. 6, Supplementary Table S4). At a SL of 210 dB_{pp}, all detections were within 25 km of the sites, and the majority of ranges were within 16 km (range: <1–23 km, median = 13 km). At the lower theoretical SLs (192–201 dB_{pp}), the maximum predicted range was 13 km. For sites on NS, a theoretical SL of 235 dB_{pp} resulted in the majority of detection ranges falling between 40 and 80 km (range: 3–88 km, median = 56 km). All estimated ranges were within 30 km of the sites using a SL of 210 dB_{pp}, with the majority of ranges between 5 and 18 km (range: <1–30 km, median = 11 km). A maximum detection range of 15 km was estimated for clicks produced at SLs at or <201 dB_{pp}.

Discussion

This study is the first to assess the year-round acoustic presence and demographic composition of sperm whales on the continental shelf off SNE, in an area where significant wind energy development is ongoing. The results represent baseline data collected for 3 years leading up to the start of offshore wind construction. Sperm whales were present mainly from May to August, with a secondary peak in October/November in 2021–2022. This seasonality was present across all 3 years, but detections decreased overall in 2022. While sperm whale demographic composition was dominated by putative social groups, all three classes (including midsize and adult males) were detected, often within the same hour. Detection range estimation indicates that at least some of the detected whales, especially those in social groups producing clicks at lower source levels, were in close proximity (<20 km) to the recording sites and SNE WEA.

Detection range

The estimated detection range confirms that sperm whales can and do use the shallow continental shelf waters around and possibly within the SNE WEA. For all sites, a sperm whale at a range of 40–100 km would be on the shelf, up to the 500 m depth contour (Fig. 6b). A range within 20 or 40 km indicated a whale was in shallow (<100 m) water and proximity to, and possibly within, the WEA. Using a theoretical SL of 235 dB_{pp}, representing an on-axis click, the predicted detection range spanned 3–88 km, with 22% of ranges falling within 40 km (Fig. 6, Supplementary Table S4). At a SL of 210 dB_{pp} or lower, the majority (84%) of predicted ranges were within 20 km of the sites. The presence of sperm whales in the shallow waters near the recording sites is corroborated by

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Table 2. Predicted TL equations based on TL model fit to empirical data collected at COX01 and NS02.

TL model	TL equation
COX01	$15.0 \times \log_{10}(r/1\text{ m}) + 6 \times 10^{-4}(r)$
NS02	$15.8 \times \log_{10}(r/1\text{ m}) + 3 \times 10^{-4}(r)$

The model was fit with the equation $b \times \log_{10}(r/1\text{ m})—\alpha(r)$, where b is the spreading coefficient, α is the absorption coefficient, and r is range. The absorption coefficient was constrained to values between 3×10^{-4} dB/m and 6×10^{-4} dB/m based on in-situ environmental conditions.

sightings in the same area, on the continental shelf, between 2002 and 2021, including a sighting <20 km from NS02 in 2016 (Fig. 1; Palka et al. 2016, 2021).

The detection range of sperm whales can vary depending on (i) signal SL and the relative position of the whale; (ii) TL as function of environmental covariates; and (iii) estimation methods (e.g. sound propagation model) and recorder type and position (i.e. depths and ranges). These factors are discussed below.

(i) The amplitude (absolute SL) of sperm whale clicks can vary based on body size (Weilgart and Whitehead 1988, Jensen et al. 2018) and within a sequence of clicks; Nosal and Frazer (2007) reported a 10–15 dB decrease in source level over time within a click sequence. In addition, the apparent SL of sperm whale clicks will vary due to directionality (e.g. Mohl et al. 2000, 2003a, Zimmer et al. 2005). To account for this, multiple theoretical source levels (192, 194, 196, 201, 210, and 235 dB_{pp}) were used to produce a distribution of possible ranges, and as expected, the effect of SL on detection range was notable. For a click detected at NS02 with a received level of 180 dB_{pp} re 1 μPa, varying the theoretical SL between 192, 210, and 235 dB_{pp} resulted in range estimates of 5, 79, or 2709 m, respectively (Table 3, Supplementary Table S4).

It is important to note that the values reported by Zimmer et al. (2005) do not account for differences in body size, and the maximum SL is likely underestimated. Assuming one apparent SL for all demographic classes could result in an underestimate of range for an on-axis click from a large adult male and an overestimate of range for adult females and calves. Mohl et al. (2003a) recorded large adult males and reported a SL of 245 dB_{pp} re 1 μPa (235 dB_{rms} re 1 μPa), assumed to be the P1 component of an on-axis click. At this SL, the maximum detection range reported in this study would be underestimated by ~20–30%. Data on the SL of clicks produced by smaller animals, such as adult females and calves, is not yet available. However, Zimmer et al. (2005) recorded a midsize (12 m) animal, suggesting the values used in this analysis could correspond to an adult female or immature male. Furthermore, the use of a lower theoretical SLs (<235 dB_{pp}) may be appropriate for smaller animals, such as immature females and calves. Importantly, as more information on the SLs and habitat use of demographic classes becomes known, the results provided in this study may allow for further interpretation and improved estimation of detection ranges of different classes.

(ii) TL was evaluated by completing *in-situ* sound propagation tests, which revealed that the recorders at NS02 and COX01 would pick up signals from a sound source at least 10–20 km away, based on a mean SL of 179.7 dB_{pp} of the Lubell speaker and environmental conditions in April 2023. A caveat for the results is that the TL models do not account for vari-

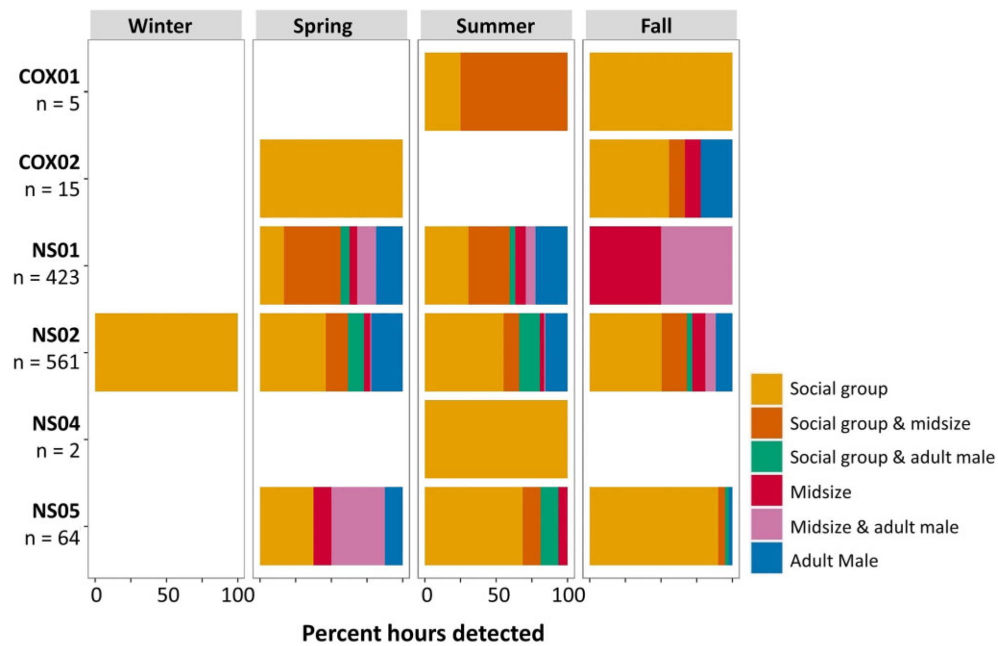

Figure 4. For each of six sites in the SNE WEA, the % of hours each demographic class was classified is shown by season. The *n* represents the total number of hours during which demographics could be classified for that site. The % hours detected was calculated by dividing the number of hours a class was detected per season by the total number of hours included in the demographic analysis for that season. Seasons were defined as winter: December–February, spring: March–May, summer: June–August, and fall: September–November.

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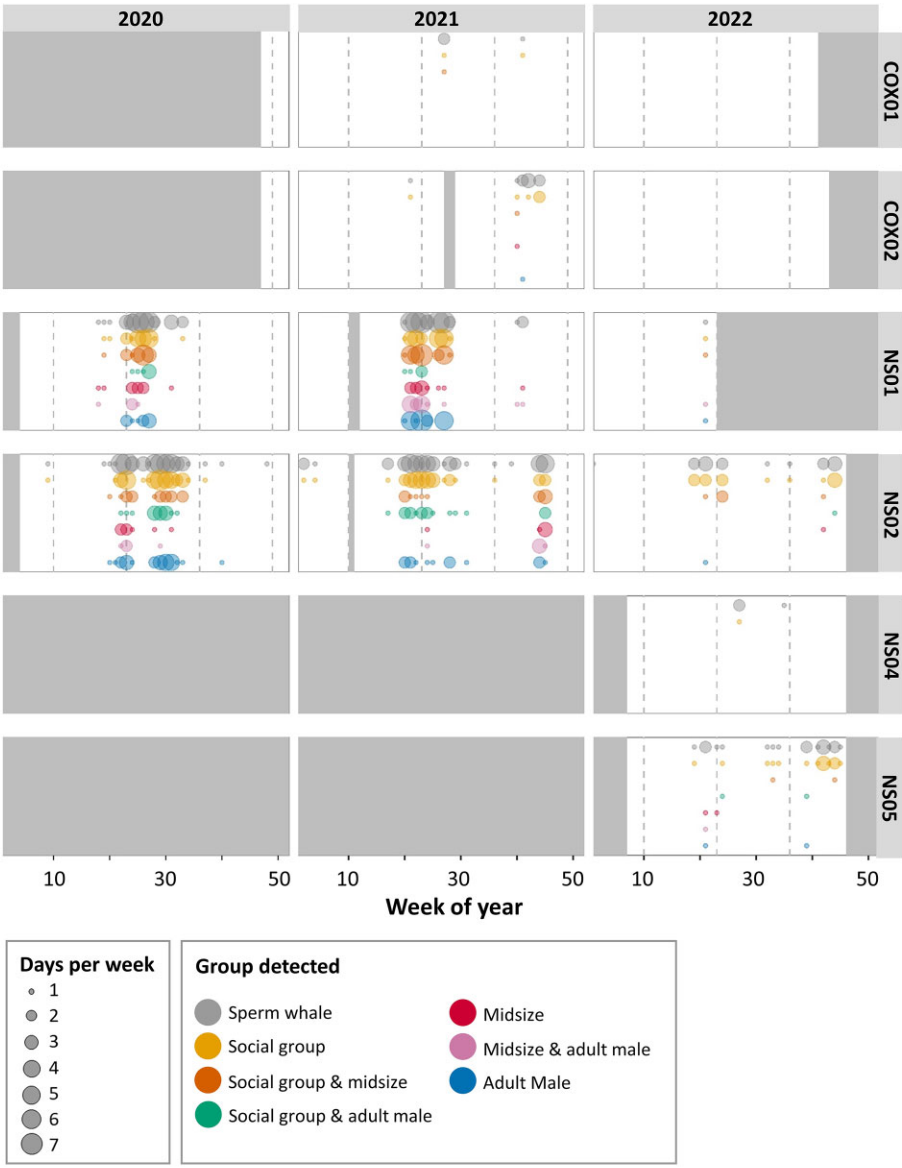

Figure 5. Weekly presence of sperm whales and the three demographic classes plus three combined groups at the six sites in the SNE WEA across 3 years (2020–2022). The number of days per week a class was detected is represented by the size of the bubble. If sperm whales were not detected no bubble appears on the figure. Grey boxes represented weeks when data was not collected or not available. Dashed vertical lines mark transitions between seasons (December–February, March–May, June–August, and September–November).

Table 3. Theoretical sperm whale source levels (dB_{pp} re: 1 μPa) used to determine expected ranges of clicks up to 1000 km from acoustic recorder locations.

Percentile	Peak level (dB_{pp} re 1 μPa)
100	235
95	210
75	201
50	196
25	194
5	192

SLs correspond to the 5, 25, 50, 75, 95, and 100th percentiles of peak levels estimated by Zimmer et al. (2005) at off-axis angles of 0°–180°; levels were converted from zero-peak to peak–peak.

ations in environmental conditions (e.g. season, sea state, etc.); however, as additional *in-situ* measurements are made, condition-specific models may reduce uncertainty.

(iii) The predicted ranges of sperm whales were realistic when compared to the results from previous studies; however, it is difficult to compare given the different environments, methods, and positions of source and receiver. Mathias et al. (2013) measured detection range using a vertical array system (at 300 m depth) and predicted a maximum detection range of 35 km in high wind conditions and 90 km in calm sea conditions. Shabangu and Andrew (2020) reported a modelled maximum detection range of 83 km for clicks produced at 1100 m depth, and based on SL of 190 dB re 1 μPa at 2 kHz and 200 dB re 1 μPa at 4 kHz. In the Gulf of Maine (just north of the SNE study area), a towed array receiver and beamforming methods resulted in expected detection ranges >60 km (Tran et al. 2014). Thus, the predicted source ranges reported in this study are consistent with those reported in the literature.

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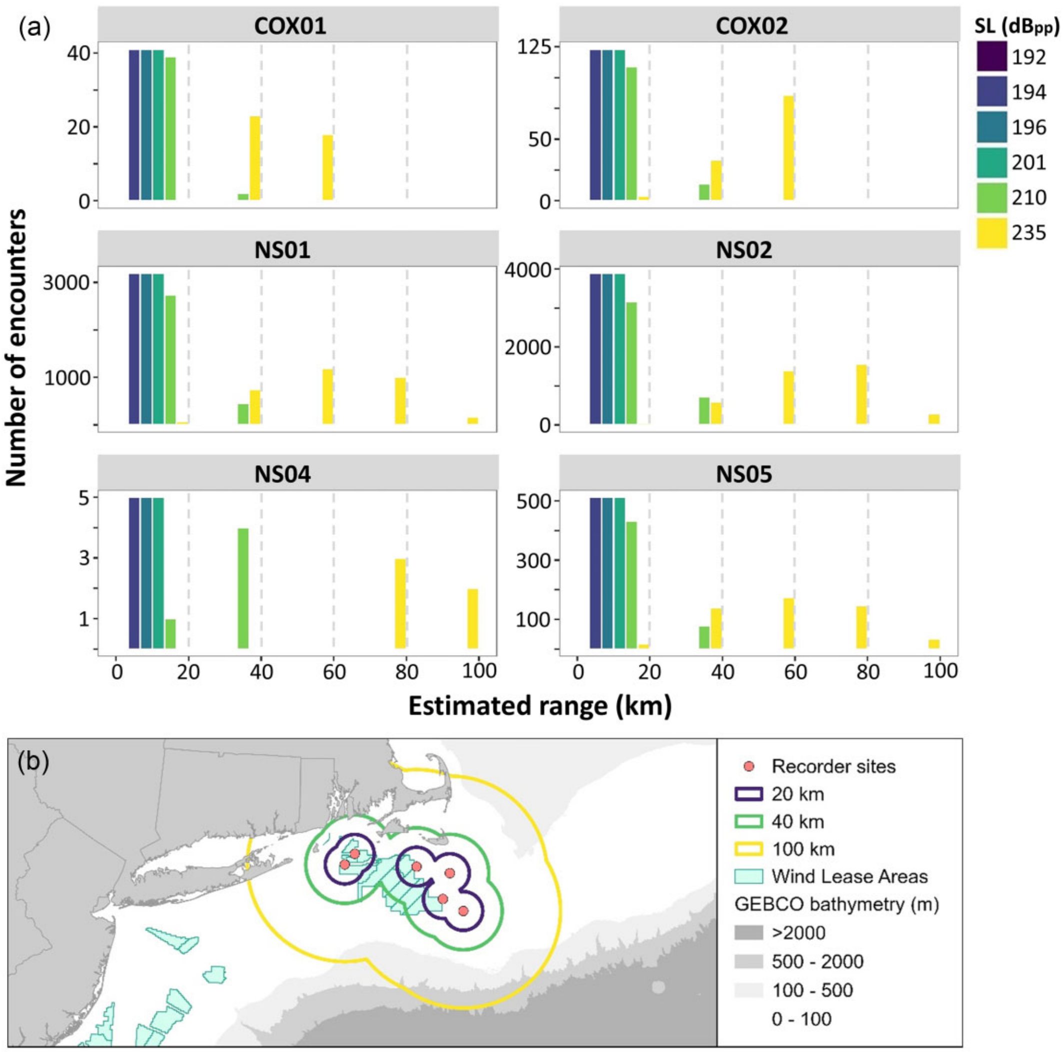

Figure 6. (a) Histogram of estimated range (km) of sperm whale encounters (maximum received level within a 5-min interval) detected at two sites on Cox's Ledge (COX) and four on Nantucket Shoals (NS) and using six theoretical source levels (SL) of 192, 194, 195, 200, 210, and 235 dB_{pp}. Bins are right-aligned and bin size is 20 km, marked by vertical dashed vertical lines. At a SL of 210 dB_{pp} or less, all estimated ranges are within 30 km of the sites. At a SL of 235 dB_{pp}, the maximum estimated range is 88 km. Note that the scale of the *y* axis varies by site. (b) Map of six sites of passive acoustic recorders on Cox's Ledge and Nantucket Shoals and the SNE WEA. Buffer lines mark areas 20, 40, and 100 km around each site. Detection ranges within 40 km indicate a whale was within or in proximity to the WEA, and in shallow water (<100 m). Ranges of 40–100 km indicate a whale could be on the shelf or near the 500 m contour. Bathymetry data were retrieved from the GEBCO Compilation Group (2022) GEBCO_2022 Grid (doi:10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c).

Detections

Sperm whale acoustic presence varied by month, year, and site and was likely driven by both foraging and social opportunities (Jaquet et al. 1996). The relationship between sperm whales, prey distribution, and oceanographic conditions is complex, varies over spatial and temporal scales, and can change quickly (e.g. Griffin 1999). The reason for the decrease in detections in 2022 is unknown, but may be related to changes in the distribution and/or abundance of squid prey (e.g. CETAP 1982, Scott and Sadove 1997, Salois et al. 2023). Offshore, sperm whales are often associated with oceanographic features (e.g. canyons), which may be areas of prey aggregation (Waring et al. 1993, Wong and Whitehead 2014). On the continental shelf, near the recording sites, sperm whales observed in these shallow waters are thought to be following migrating squid (CETAP 1982, Scott and Sadove 1997, Palka et al. 2016). The seasonality of acoustic occurrence reported here is consistent with previous offshore studies, which have identified Georges Bank as an important spring and summer habitat for sperm whales (Perry et al. 1999, Waring et al. 2014, Stanistreet et al. 2018). Furthermore, seasonal peaks in detection coincide with increased squid presence in the shallow shelf waters off SNE, further substantiating the theory that sperm whales are moving into this area to forage.

Detections on COX were infrequent, which was expected given these sites are farthest (>100 km) from the shelf break, but were also predicted to be produced relatively close by (maximum: 10–55 km), indicating that at least some of the detected sperm whales were in proximity to the WEA. Detections at NS04 were also infrequent and produced by whales up to 63–83 km away (SL = 235 dB_{pp}, Supplementary Table S5), which is consistent with visual sightings of sperm whales to the east of this site (Fig. 1). NS04 is located on a shallower

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section of the shoals, and based on the results, it seems probable that the detected sperm whales were travelling by this area instead of using it to forage. At the other sites on NS, detections were more frequent, and using a SL of 235 dB_{pp}, 22% of detected sperm whales were predicted to be within 40 km. Using a SL of 210 dB_{pp}, 47% of predicted ranges were within 10 km. At NS01–02, the relatively high detection rate and estimated range of the whales suggest that the area around these sites is suitable habitat for prey and an important foraging habitat for sperm whales.

Demographic composition

The method used in this study to evaluate demographic composition using modal ICI distributions was first developed and validated for sperm whales in the Gulf of Mexico (Solsona-Berga et al. 2022), where the adult females are reported to be smaller than the global mean size (Jaquet 2006; Jochens et al. 2008). However, this method was also successfully applied to sperm whales in the Gulf of Alaska, where sperm whale sizes are more similar to those expected in the North Atlantic (Adler 1980, McClain et al. 2015, Posdaljian et al. 2023, preprint: not peer reviewed). Posdaljian et al. (2023, preprint: not peer reviewed) demonstrated that this method works across different regions, encapsulating different life history stages (e.g. breeding grounds vs. feeding grounds). Although this method cannot be used to estimate an individual's size, it is efficient for assessing demographic composition as it can be applied to large-scale acoustic data without a lot of data being excluded. In this analysis, demographic classes were recorded on the majority (86%) of days on which sperm whales were detected. As Solsona-Berga et al. (2022) and Posdaljian et al. (2023, preprint: not peer reviewed) examined IPI and validated the use of ICI distribution to analyse size class and demographic composition, this analysis uses only ICI.

The three patterns in modal ICI distributions (≤0.6, 0.6–0.8, and ≥0.8 s) were linked to three demographic classes: small animals assumed to be putative social groups (adult females with juveniles and calves), midsize animals (adult females or immature males), and large animals assumed to be adult males (Fig. 2, Supplementary Fig. S2). Solsona-Berga et al. (2022) identified the same classes and reported ICI ranges of 0.44–0.64 s for small animals (likely part of social groups), 0.64–0.83 s for midsize animals, and 0.72–1 s for adult males. Social groups and adult males were easily distinguished by the difference in dominant ICI distributions (0.4–0.6 s vs. 0.8–1.2 s). The third demographic class identified was that of midsize individuals, hypothesized to be adult females or bachelor groups by Solsona-Berga et al. (2022). Given the possible detection range as well as social behaviour of sperm whales, it was expected that animals from different demographic classes would be detected simultaneously. When this occurred, demographic classes were combined (e.g. social group and adult male) to summarize spatial and temporal overlap. When detected within the same encounter or hour as a social group, a midsize animal was likely an adult female within that social group; at the hourly scale, this would be classified as 'social group and midsize' (Supplementary Fig. S2). When detected independently of a social group, a midsize animal could be an adult female or an immature male (Posdaljian et al. 2023, preprint: not peer reviewed), travelling alone or in a bachelor group (Best 1979).

Although the social behaviour of sperm whales in the western North Atlantic Ocean is not well documented, breeding is expected to take place between spring and fall and when adult females and males overlap spatially at temperate latitudes (Best 1979, Perry et al. 1999). Sperm whale acoustic occurrences around the WEA often meant the presence of social groups. Adult males were detected less frequently, but peaks in detections regularly occurred within the same week and/or month as those of putative social groups. This indicates that the region around the SNE WEA is used consistently and simultaneously by both demographic classes, possibly for breeding as well as foraging. The pattern of two peaks in acoustic presence might indicate migration in summer (e.g. May—July) and in late fall (e.g. November). Ongoing data collection at these sites and additional sites will enable future exploration of patterns in presence and how they might relate to migratory movements.

Conclusion

The construction phase of the SNE WEA began in June 2023 and will cause a temporary but significant increase in underwater noise due to pile driving and vessel activity (e.g. Ruppel et al. 2022). This is occurring at what was, in 2020–2021, the peak time for sperm whale presence in and around this area. In addition, ongoing development and operations will increase vessel activity, which will lead to an increase in underwater noise as well as a risk of vessel strike (Vanderlaan and Taggart 2009, Van Der Hoop et al. 2012). The long-term impact on sperm whale presence and demographic composition is unknown. This study provides a baseline for sperm whale presence and demographic composition around the WEA, which can be used to assess future changes, especially in the detection of social groups, which may be more sensitive to disturbance (Farmer et al. 2018). Currently, sperm whales are often discounted from monitoring in this region as they are thought to not occur in high densities on the continental shelf. However, contemporary visual sightings (e.g. Scott and Sadove 1997, Palka et al. 2021) and the results of this passive acoustic study prove that sperm whales can and do use inshore shallow waters off of SNE regularly and inter-annually, and should be considered in monitoring, management, and/or mitigation plans.

Animal ethics and welfare

There are no animal ethics and welfare concerns.

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Supplementary material

The following Supplementary data is available at *ICES Journal of Marine Science* online. This includes four supplementary figures and five tables to support information provided in the methods and results sections.

Author contributions

S.M.V.P. was responsible for the study design. A.I.D. was responsible for conceptual development and advised on data analysis. A.S.B. and N.P. were responsible for developing the sperm whale detector and demographic analysis methods and advised on data analysis. T.R. was responsible for developing the sound playback experiments and detection range analysis and advised on data analysis. Annabel Westell was responsible for developing data analysis methods, completing the data analysis, and writing of the manuscript. All co-authors reviewed and provided feedback on the manuscript.

Conflict of interest: The authors have no conflicts of interest to declare.

Data availability

As these data were collected with federal funding and are publically available upon request. We are working to integrate them into the publicly available Passive Acoustic Cetacean Map (PACM) at https://apps-nefsc.fisheries.noaa.gov/pacm/#/

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