ICES Journal of Marine Science, 2023, Vol. 0, Issue 0, 1–15
https://doi.org/10.1093/icesjms/fsad174
Received: 4 April 2023; **revised:** 26 July 2023; **accepted:** 21 September 2023
Original Article

ICES
CIEM
International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

Upcalling behaviour and patterns in North Atlantic right whales, implications for monitoring protocols during wind energy development

G. E. Davis[1,*], **S. C. Tennant**[2], **S. M. Van Parijs**[1]

[1]Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 166 Water Street, Woods Hole, MA 02543, USA
[2]Under Contract to the Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 166 Water Street, Woods Hole, MA 02543, USA

[*] *Corresponding author: +1 508 495 2325; e-mail: genevieve.davis@noaa.gov.*

Abstract

Offshore wind energy is rapidly developing in US waters, with construction underway off Southern New England (SNE), an important region for many species, including the critically endangered North Atlantic right whale (NARW). A data-driven understanding of NARW upcalling behaviour is presented here to help establish proper monitoring protocols for mitigating impacts. Analyses of individual upcalls from 2 years of acoustic recordings showed that NARWs were detected at least 1 day every week throughout both years, with highest NARW presence from October to April. Weeks with more days of acoustic presence typically had more hours with calling activity, but the number of upcalls within a day or hour was variable, reflective of the social function of the upcall. Within SNE, on average, 95% of the time NARWs persisted for 10 days, and reoccurred again within 11 days. An evaluation of the time period over which it is most effective to monitor prior to commencing pile driving activities showed that with 1 h of pre-construction monitoring there was only 4% likelihood of hearing a NARW, compared to 74% at 18 h. Therefore, monitoring for at least 24 h prior to activity will increase the likelihood of detecting an up-calling NARW.

Keywords: acoustic behaviour; North Atlantic right whale; offshore wind energy area; passive acoustic monitoring; Southern New England; upcall

Introduction

The increasing demand for alternative energy sources has turned to solar and wind energy solutions, with plans for offshore wind energy development expanding rapidly in the United States (US; Office of the Press Secretary, 2021; Office of the Press Secretary, 2022). There are currently over 27 offshore wind energy lease areas (WEAs) planned in the Atlantic Ocean along the US east coast, from the Gulf of Maine to waters off South Carolina, with additional lease areas opening up regularly (https://www.boem.gov/renewable-energy/renewable-energy-program-overview; https://www.northeastoceandata.org/data-explorer/?energy-infrastructure).

Offshore WEAs have been operational in other countries, particularly Europe, for decades producing a wide range of studies that assess the effects on marine life, including underwater noise, species displacement, and cumulative stressors (e.g. Bailey *et al*., 2010; Lindeboom *et al*., 2011; van Deurs *et al*., 2012; Popper *et al*., 2022). Although these studies provide a great background for the extensive WEA development facing the US waters, the western North Atlantic is home to a greater number of marine species, making the problem of potential impacts much more complex. In particular, four of the six baleen whale species inhabiting US east coast waters, including the NARW, in addition to sperm whales (*Physeter macrocephalus*), are considered endangered under the Endangered Species Act (est. 1973) and Marine Mammal Protection Act (est. 1972). One of the first potential WEA threats facing marine mammals is from pile driving during the construction phase: a process that emits intense, impulsive noise that radiates into the surrounding environment as turbines are hammered into the sea floor (Amaral *et al*., 2020). Various effects on marine life have been observed from pile driving, ranging from avoidance to behavioural changes in harbour porpoises (Brandt *et al*., 2011) to displacement and physical injuries in fish (Popper *et al*., 2006). It is not yet known how pile driving will affect each species that has not yet been exposed to it.

The first major offshore WEA development began in the spring of 2023 in the Southern New England (SNE) area, which consists of nine separate WEAs that cover both state and federal waters (https://www.boem.gov/renewable-energy/state-activities). This area spans waters to the west of Nantucket Shoals, an important region for marine species, particularly for endangered large whale species such as the North Atlantic right whale (NARW), *Eubalaena glacialis*, who utilize the area for feeding, socializing, and as part of the migratory route (Leiter *et al*., 2017; Stone *et al*., 2017; O'Brien *et al*., 2022). NARWs commonly occur in on-shelf waters in the western North Atlantic, ranging from winter calving grounds off the southeast US coast, to northern summer feeding grounds up through the Gulf of St. Lawrence, Canada. While some individuals undergo clear seasonal migrations, NARWs occur along the entire US east coast during winter months, and are found in some regions throughout the year (Davis *et al*., 2017). Since 2010, shifts in habitat use have been seen, including increased use of SNE, Cape Cod Bay,

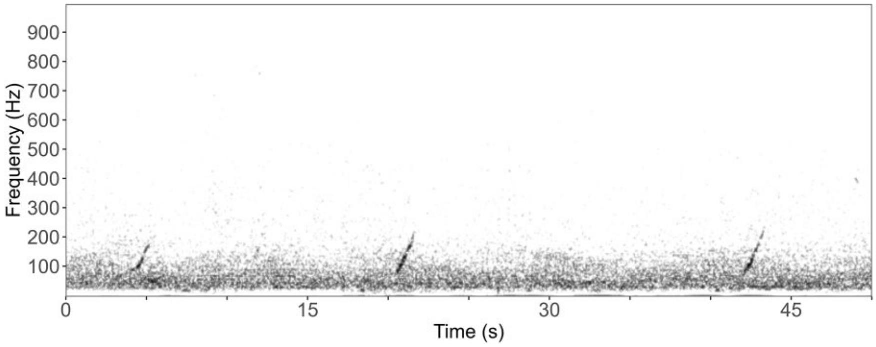

Figure 1. Spectrogram example of three North Atlantic right whale upcalls recorded on 15 January 2022, at site NS02. Spectrogram parameters: FFT: 512 samples, 75% overlap, Hann window.

and Gulf of St. Lawrence, and decreased use of Gulf of Maine and Scotian Shelf waters for summer feeding grounds (Meyer-Gutbrod *et al.*, 2021, 2022). The remaining population of <340 individual NARWs face lethal threats of entanglement in fishing gear and ship strike: it is unclear what effects offshore WEA may introduce to the species, but limiting cumulative stressors is essential if this species is to have a chance at survival (Pirotta *et al.*, 2022, 2023; Moore, 2023; Pettis *et al.*, 2023). With such a small population, and where breeding females make up less than half the population, any individuals impacted by increased vessel traffic, noise from construction and operation, or displacement of prey species, could have detrimental effects to NARW recovery (Pace *et al.*, 2017; Christiansen *et al.*, 2020; Reed *et al.*, 2022).

State and federal government agencies, non-government organizations (NGOs), and scientific groups have all put forward a range of requirements and recommendations aimed at minimizing the effects of wind energy development (e.g. Bailey *et al.*, 2014; Kraus *et al.*, 2019; Van Parijs *et al.*, 2021). Amongst others, these include: limiting certain construction activities to times when NARWs are not expected in high densities; having observers survey to ensure animals are not present in the project area prior to and during construction; and long-term monitoring to assess potential effects of offshore wind development (e.g. https://rwsc.org/science-plan/; https://www.nrdc.org/bio/francine-kershaw/monitoring-priorities-offshore-wind; https://www.boem.gov/rodeo). Historically, visual monitoring has been the primary tool used to monitor prior to, during, and after construction activities. As a result, clear standards and training programmes have been developed for visual monitoring (Baker *et al.*, 2013).

Over the last two decades, passive acoustic monitoring (PAM) has emerged as a widespread technology effective for monitoring species distribution and occurrence, as well as behaviour, and for mitigating anthropogenic impacts (Rountree *et al.*, 2006; Van Parijs *et al.*, 2009; Gibb *et al.*, 2019; Davis *et al.*, 2020; Van Parijs *et al.*, 2021). Archival bottom-mounted PAM has been used extensively to understand NARW distribution, occupancy, and effects of anthropogenic noise on their communication space (Parks *et al.*, 2007, 2010; Hatch *et al.*, 2012; Cholewiak *et al.*, 2018) over both large spatial scales (Davis *et al.*, 2017; Simard *et al.*, 2019; Durette-Morin *et al.*, 2022; Kowarski *et al.*, 2022) and within smaller regions (e.g. Muirhead *et al.*, 2018; Charif *et al.*, 2019; Estabrook *et al.*, 2022; Murray *et al.*, 2022). These PAM systems are stationary (remain anchored to the sea floor), and require the retrieval of the instrument to access the recordings. In addition, real-time PAM technologies have also come to the forefront as both a monitoring and mitigation tool allowing for vocalizing species to be acoustically detected in near real time, providing close to instant information on species presence in an area when calling (Bröker *et al.*, 2015; Baumgartner *et al.*, 2019, 2020; Aerts *et al.*, 2022). While PAM is highly effective at documenting calling animals, silent animals, or animals outside of the detection range of the recorders, will be missed.

Unlike visual observer protocols, PAM for certain mitigation purposes is still relatively new, although PAM has been used for some time for seismic survey mitigation (Nowacek *et al.*, 2013). The manner in which different species use sounds for foraging, navigation, social behaviour, and reproduction varies and is often species-specific. For example, odontocetes echolocate frequently and therefore have a higher probability of being acoustically heard compared to baleen whales who are variable callers with temporally clustered vocal activity (Thomisch *et al.*, 2015). As a result, not only are clear standards, protocols, and training of observers still being developed for PAM, they also need to be tailored to each of the primary species of concern. Baleen whale species acoustic behaviour varies from species to species, where identifying a target call (the call used to determine species presence), in addition to observing the context of the call, is just as important (Clark and Gagnon, 2022; Franklin *et al.*, 2022). Certain call types, like the NARW upcall, can be identical to vocalizations made by humpback whales (*Megaptera novaeangliae*), and thus require experience and training to be able to properly distinguish between species to correctly and confidently identify which species is present (Mussoline *et al.*, 2012; Simard *et al.*, 2019). NARWs produce a variety of vocalizations; however, the upcall, spanning on average 100–400 Hz and lasting 1–2 s, functions as a contact call and is produced by all ages, sexes, and throughout their range (Figure 1; Clark *et al.*, 2010; Parks *et al.*, 2011). The upcall is used extensively in PAM studies as an indicator of NARW acoustic presence (Matthews and Parks, 2021). However, information is still needed in order to improve understanding of NARW upcall rates and behaviour, as calling rates are highly variable and may vary by age, sex, behaviour, region, and season (Parks *et al.*, 2011, 2014; McCordic *et al.*, 2016; Durette-Morin *et al.*, 2019; Franklin *et al.*, 2022; Parks, 2022).

In order to fulfil US government permitting requirements, wind energy companies are required to submit for approval marine mammal monitoring and mitigation plans, which may include the use of PAM and/or visual monitoring methods for protected species before, during, and after certain construction activities (e.g. NMFS, 2021). If a sighting or detection of a protected species occurs within a specified WEA-related zone, mitigation actions may need to be taken. The "PAM Plan" portion of the monitoring and mitigation plans cover all of the details to meet the acoustic monitoring and mitigation requirements set forth in permits (Van Parijs *et al.*, 2021). In the SNE area, construction and pile driving activities are currently not allowed during the time-of-year restriction from January to April (e.g. NMFS, 2022), based on historical data demonstrating high densities of NARWs in and around the area (e.g. Estabrook *et al.*, 2022; O'Brien *et al.*, 2022).

To ensure mitigation measures based on information from PAM provide adequate protections for NARWs in the SNE region, more detailed information—specific to upcall calling (hereafter referred to as "upcalling") behaviour in this area—in recent years—is necessary. In particular, information is needed on the upcalling rates, upcalling bout duration, and persistence in the area to inform the length of monitoring via PAM prior to construction to ensure monitoring protocols are designed to effectively detect upcalling NARWs and thus provide guidance for mitigation actions. In this study, we address a number of these needs, specific to upcalls, and provide data-driven results for managers to use for further decision making.

Methods

Bottom-mounted acoustic recorders (SoundTrap500s and SoundTrap600s; Ocean Instruments Inc.) were deployed across six sites in the Southern New England (SNE), USA region, located in the western North Atlantic Ocean, spanning Cox's Ledge (COX) to Nantucket Shoals (NS) (Figure 2). Recording sites occurred within, or nearby, the nine SNE wind energy lease areas (WEA), with NS sites purposefully covering a known North Atlantic right whale (NARW) hotspot area and COX01 representing the western extent of the WEAs. NS sites ranged 22–26 km apart, with COX01 spaced 65 km from NS01. Sites varied by deployment date and duration as additional sites were added to the recording region (Table 1). Three sites (COX01, NS01, and NS02) were deployed from February 2021 to November 2022, and three sites (NS03, NS04, and NS05) were deployed from February 2022 to November 2022. A total of 617 days of acoustic data were collected across the six sites. Each SoundTrap, moored 1–3 m above the ocean floor, recorded continuously with a sample rate of 48 (for SoundTraps deployed before July 2021) or 64 kHz (for SoundTraps deployed after July 2021) (Table 1).

Data were processed and analysed for NARW upcalls using similar methods as described in Davis *et al.* (2017). All acoustic data were low-pass filtered and decimated to 2 kHz, then processed using the Low Frequency Detection Classification System (LFDCS; Baumgartner and Mussoline, 2011). The LFDCS programme creates conditioned spectrograms using a short-time Fourier transform, with a data frame of 512 samples and 75% overlap, resulting in a time step of 64 ms and a frequency resolution of 3.9 Hz. It then traces "pitch tracks" of tonal sounds above a relative amplitude threshold, and uses a multivariate discriminant function to classify these pitch tracks according to a user-defined call library (see Davis *et al.* 2020; Supplementary Table S1 for specifics on the call library used). Each pitch track, or automatic detection, is then assigned a Mahalanobis distance (MD) to quantify the deviation between a given pitch track and its assigned call type, with a lower MD indicating a better match. For most species, setting an MD threshold of 3.0 or less minimizes the probabilities of both false detections and missed detections (Baumgartner *et al.*, 2013).

Following Davis *et al.* (2017), all automatic NARW upcall detections with a maximum MD of 3.0 were reviewed by trained acousticians (researchers with 6 months or more of NARW-specific acoustic analysis experience) to assess daily acoustic presence. A day (24-h period, standardized to UTC-5) was considered detected for NARWs if it had at least three pitch-tracked and manually confirmed automatic upcall detections at that site. This criterion was used to be consistent with daily presence protocols from previous studies (Davis *et al.*, 2017) and in order to be conservative and confident in stating NARW presence, while accounting for the possibility of a few incorrectly classified calls. Days that could not meet this criteria, but contained one or two confirmed NARW upcall detections, were deemed "possibly detected" for additional analysis beyond the daily presence review. Davis *et al.* (2017) found the LFDCS had a missed detection rate of 33%; this study did not further evaluate the missed detection rate specific to this dataset; therefore, the resulting analysis covers minimum NARW upcall presence and likely excludes some days that had NARW upcalls missed by the LFDCS.

All days that were marked as detected (contained three or more confirmed automatic upcall detections), or possibly detected (contained one or two confirmed automatic upcall detections) were manually annotated and every NARW upcall was logged for each of those days, regardless of whether it was automatically detected, using a customized Interactive Data Language (IDL) script within the LFDCS programme. Only days with one or more confirmed automatic upcall detections were then manually annotated. The number of hours with detections and the number of upcalls per hour were then averaged across each deployment to assess seasonal and diel trends. Here, we define diel as trends over a 24-h period, regardless of day or night.

For the above analyses all available data were used, including sites that did not have a full year of recordings. To avoid any potential seasonal bias, only sites that had at least one full year of data (COX01, NS01, and NS02; hereafter referred to as "full year sites"), were used for the following analyses, which averaged values across a calendar year.

To understand how far apart upcalls are spaced, and for how long upcalling activity occurs once an upcall is heard, inter-call intervals (ICIs) were measured between every logged upcall, calculated as the difference between the start time of one upcall and the start time of the next. No distinction was made between whether the upcalls measured came from one or more individuals. To define an upcall bout, we took the weighted mean of the 95th percentile of all ICIs for full-year sites (COX01, NS01, and NS02), using R Statistical Programming Language (R Core Team, 2022). Any upcalls with ICIs less than the weighted mean were considered to occur within a single upcalling bout, and any upcalls with ICIs greater than this amount were considered the start of a separate event and new upcalling bout. Bout lengths and number of upcalls within a bout were then measured across each of the three full-year sites (COX01, NS01, and NS02).

Daily presence results were used to calculate the number of days with consecutive acoustic presence (hereby defined as

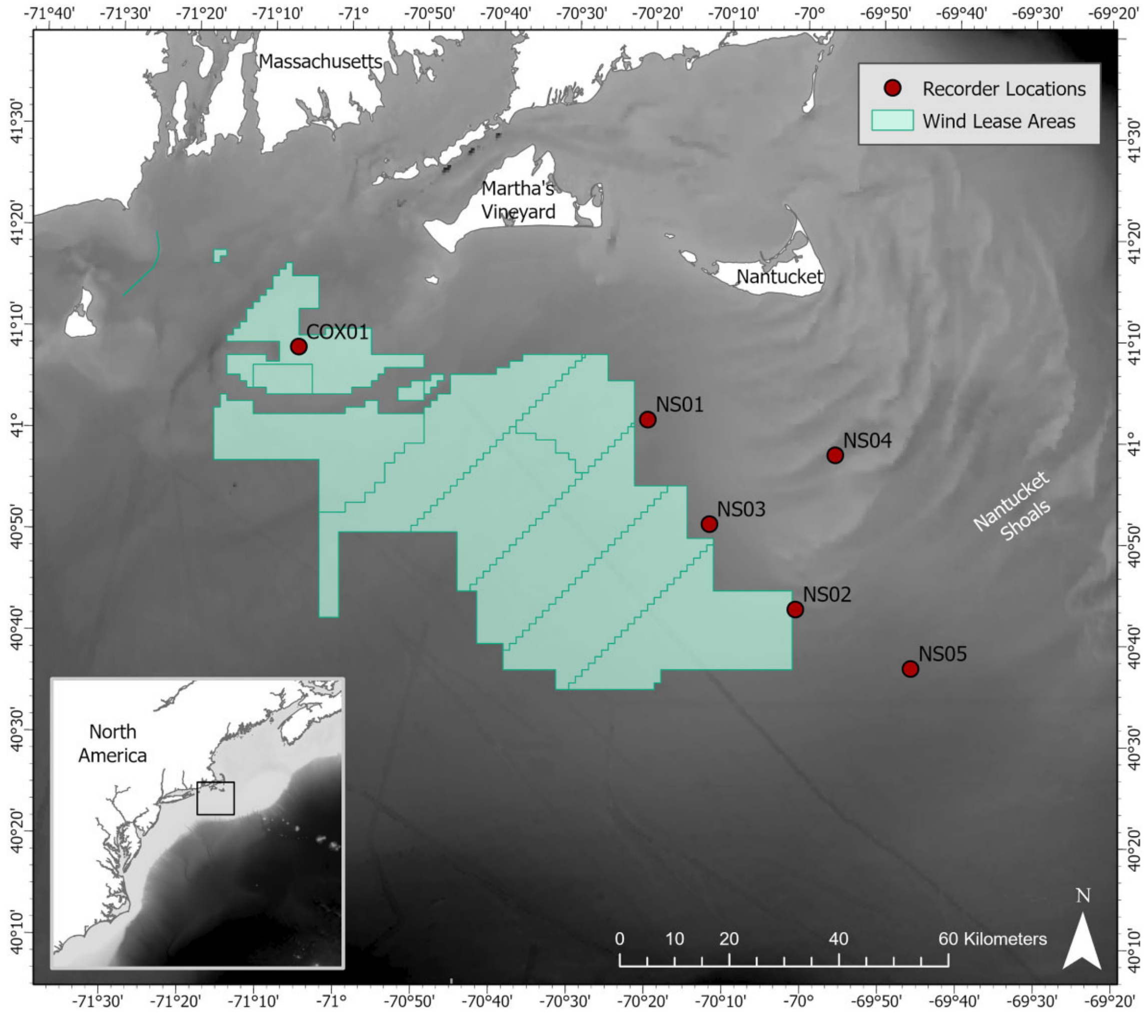

Figure 2. Map of bottom-mounted acoustic recorder locations (red points) in the Southern New England (SNE), USA offshore wind energy area, with recording site names labelled. Green shapes indicate SNE wind energy lease areas. Bathymetry layer provided by GEBCO Compilation Group (2022); GEBCO (2022); Grid (doi:10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c).

Table 1. Summary of bottom-mounted acoustic recorder locations, configurations, and deployment durations.

Site name	Latitude	Longitude	Water depth (m)	Start date (DD/MM/YY)	End date (DD/MM/YY)	Sampling rate (kHz)	Data gaps
COX01∗	41.14128	– 71.10312	32	26/02/21	16/07/21	48	N/A
				15/07/21	08/10/22	64	19/05/22 09:15–19/05/22 09:57
NS01∗	41.03343	– 70.34125	38	17/03/21	21/07/21	48	N/A
				21/07/21	29/05/22	64	N/A
NS02∗	40.73645	– 70.01428	32	10/03/21	21/07/21	48	N/A
				21/07/21	09/11/22	64	30/05/22 08:14–30/05/22 08:49
NS03	40.86260	– 70.20480	38	07/02/22	29/05/22	64	N/A
NS04	40.97809	– 69.93346	32	07/02/22	09/11/22	64	30/05/22 12:18–30/05/22 13:35
NS05	40.62812	– 69.76597	58	07/02/22	09/11/22	64	30/05/22 06:24–30/05/22 06:30

Sites with varied sampling rates, the site, sample rate, and corresponding dates are listed separately. Data gaps indicate periods where no recordings were available due to recording failure or unrecoverable instruments. Asterisks (∗) indicate sites that had at least one full year of recordings.

NARW acoustic persistence) or silence, where silence refers to days with no confirmed automatic detections from LFDCS. NARW reoccurrence, or the number of days following a confirmed automatic upcall detection in which NARWs are most likely to be detected again, was calculated from days with one or more automatic NARW upcall detections. Using full-year sites (COX01, NS01, and NS02), the probability of detecting a NARW again for each day following a confirmed automatic upcall detection was estimated over a 4-week period. The weighted mean of the 95th percentile across each of the three sites was used to determine the average number of days over which NARWs are likely to continue to be detected or remain acoustically detected, following an initial detection: hereby defined as NARW acoustic reoccurrence.

Lastly, we evaluated the likelihood of detecting NARW upcalls when they are acoustically present, prior to the start of anthropogenic activity (i.e. pile driving; wind farm construction). The manually logged NARW upcalls were summarized into hourly presence over the full-year sites (COX01, NS01, and NS02). For days with one or more automatic NARW upcall detections, 12 theoretical "start times" (each daylight hour when pile driving is currently permitted, from 07:00 to 18:00 UTC-5) were used to back-calculate and determine if NARW upcalls were detected 1–24 h before the start time of construction. For each possible start time (07:00, 08:00, 09:00…to 18:00 UTC-5), every hour from 1 to up to 24 cumulative hours prior to the start time was examined to determine if manually logged NARW upcalls were acoustically detected in any sum number of those hours. A cumulative proportion of NARW detection over time, given a known presence within that 24 h, was determined by dividing the cumulative hours with presence by the total number of evaluated NARW hours, for each start time and site. Days without a full 24 h prior to any start time were excluded from this portion of the analysis.

Results

Seasonal occurrence

A total of 2337 recording days were analysed for NARW upcall presence across the six sites using the LFDCS. Despite varying recording effort (ranging from 112 recording days at NS03 to 619 recording days at NS02), all sites had automatic NARW upcall detections. A total of 29% (667 days) of the total recording days had at least one confirmed automatic NARW upcall detection; a total of 22% (513 days) of the total recording days were classified as detected for NARW acoustic presence, having three or more true upcall detections in a 24-h period; and a total of 7% (154 days) were classified as possibly detected, having only 1–2 confirmed upcall detections in a day. NS03 had the highest percentage of days with definite NARW detections (45%), despite having the lowest number of days (112 days) for recording effort (Table 2). COX02 and NS05 had varying recording effort (604 recording days and 277 recording days, respectively), but both had the lowest percentage of days (12%) with NARWs detected.

NARWs were acoustically present for at least 1 day every month on all six sites when data were available, except for September at NS01, where no days were considered detected (Figure 3). NARW acoustic occurrence was highest from November to April. While detections were lowest, but not absent, from May to October, NARWs were consistently detected at all sites, when data were available. During May–October, acoustic occurrence peaked in August–October at NS02, and from July to October at NS04. From June to November, NARWs were detected consistently at the easternmost sites on or near Nantucket Shoals (NS02, NS04, and NS05).

Days that had at least one confirmed automatic NARW upcall detection were further reviewed to analyse and count every upcall. NARWs upcalled throughout the day and night at varying degrees based on season and site location (Figure 4). In general, where NARWs were acoustically present for consecutive days, upcalling activity persisted throughout the day at each site. During periods where they occurred less frequently throughout the week, daily activity varied: days ranged from a few to many upcalls detected throughout the day (Figure 4).

Hourly presence

The average number of hours per day with detected upcalls, or vocal hours, showed similar trends to the average number of days per week with NARW acoustic occurrence, with NARWs typically detected for six or more hours on days they were acoustically present (Figures 3 and 5). In general, months and sites with more days per week with NARW acoustic presence had more hours with upcall detections per day. For all sites, October–April had days with a higher percentage of hours with detections, compared to other months. Days with 6 h or less of upcalls (25% or less of a day with detections) typically occurred between April and October; however, some sites had more hours with upcall detections each day (i.e. NS04 from July to October), and some days had fewer hours with upcall detections, despite high daily presence periods (i.e. NS05 in March).

The total number of upcalls per day was averaged in weekly bins for each site (Figure 6). Across all sites, where data were available, January–April had the highest average number of upcalls per day [min = 1, max = 1549, mean = 176, and standard deviation (*SD*) = 238 upcalls]. There was little variation in the number of upcalls per day from May to December, despite the peaks in NARW daily acoustic presence (Figure 3) and number of hours with upcalls (Figure 5), suggesting that when NARWs are upcalling, there could be the same number of upcalls produced in 1 h, or spread over 24 h. At NS02, there was an additional peak in the number of upcalls per day from November to December (min = 4, max = 1046, mean = 340, and *SD* = 255 upcalls), compared to the other sites (for COX01: min = 1, max = 39, mean = 9.1, and *SD* = 10.6; for NS01: min = 3, max = 173, mean = 67.3, and *SD* = 74.4), reflecting an increase both in the number of upcalls and the number of hours NARWs were detected during those months. Overall, upcalling activity and the number of upcalls per day throughout the dataset varied and were often low, even in periods of high daily and hourly presence.

The average number of upcalls per hour across each full-year site was averaged to examine diel (24-h) trends (Figure 7). In general, there is minimal variation in the number of upcalls detected across all hours of a day, especially at COX01. A peak in upcall detections were seen at 18:00 UTC-5 at NS01, and at 16:00 and 17:00 UTC-5 at NS02.

ICI and bout length

A total of 79032 ICIs were measured between all upcalls for full-year sites (COX01, NS01, and NS02). The weighted average of 95% of all evaluated upcalls across all three sites was 17.5 min between upcalls (Table 3). NS01 had the lowest overall time between upcalls: 95% of all upcalls at this site occurred within 13.9 min of another upcall. COX01 had the longest ICI with 33.6 min occurring between 95% of the upcalls. The average 95% of all ICIs across sites, 17.5 min, was used to define NARW upcall bouts: any upcalls

Table 2. Number of days of recording effort, number of days with definite NARW daily presence (3 or more confirmed automatic upcall detections), and number of days defined as possibly detected (1–2 confirmed automatic upcall detections) for NARWs, for each site.

Site	#Recording days	"Detected days" (3 or more true detections)	"Possibly detected days" (1–2 true detections)
COX01	604	70 (12%)	23 (04%)
NS01	448	88 (20%)	26 (06%)
NS02	619	173 (28%)	52 (08%)
NS03	112	50 (45%)	2 (02%)
NS04	277	100 (36%)	28 (10%)
NS05	277	32 (12%)	23 (08%)

The percentage of days from the dataset for each detected or possibly detected category are in parentheses for each site.

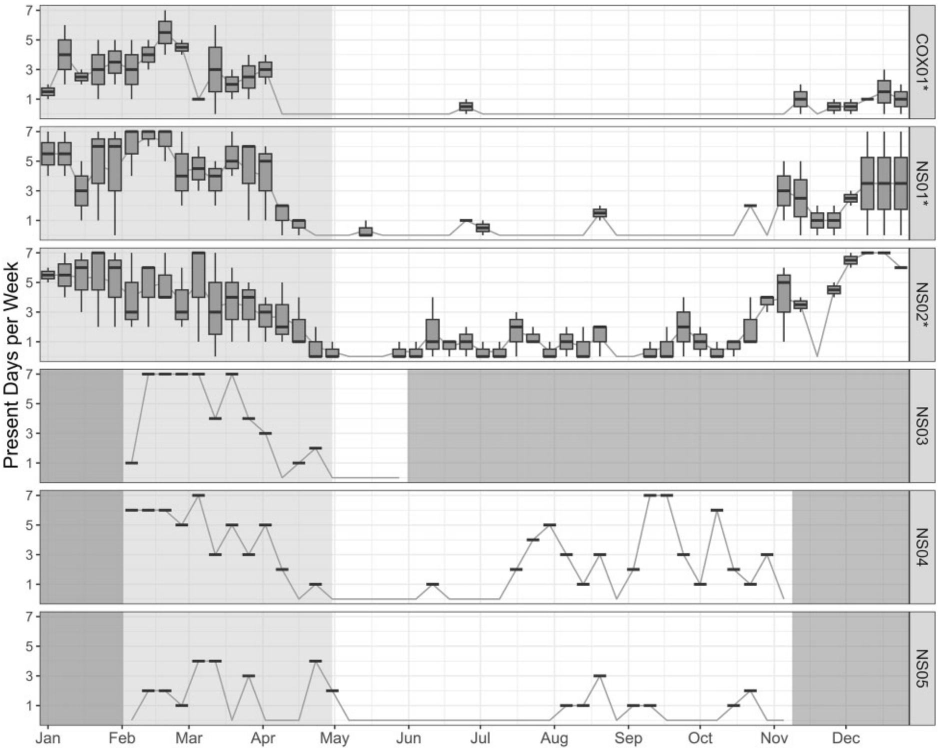

Figure 3. Weekly presence summary: boxplot representing the average number of days per calendar week with confirmed daily acoustic presence for NARW upcalls, for each recording site across all years of the study. Horizontal lines within the boxes indicate the median; box boundaries indicate the 25th (lower boundary) and 75th (upper boundary) percentiles; and vertical lines indicate the largest (upper whisker) and smallest (lower whisker) values no further than 1.5 times the interquartile range. Dark grey blocks indicate weeks where no data were available for that site. Light grey blocks overlap time-of-year restrictions in which pile driving is not allowed for that region (January–April). Asterisks (∗) indicate sites with at least one full year of data.

that had an ICI >17.5 min was determined to be a new upcalling bout. There were 808 NARW upcall bouts observed at COX01, 1239 bouts at NS01, and 1800 bouts at NS02. On average, upcall bouts lasted 20.7 min at COX01, 33.3 min at NS01, and 33.5 min at NS02. At each of the three sites, 95% of upcall bouts lasted <87.2, 145, and 149 min, with maximum bout lengths of 581, 1300, and 954 min, respectively. Using a weighted average, 95% of upcall bouts at all three sites were equal to or shorter than 135 min in duration.

Persistence/Reoccurrence

For each full-year site (COX01, NS01, and NS02), days with at least one confirmed NARW upcall detection were evaluated to measure the number of consecutive days of NARW acoustic presence, or "acoustic persistence", at that site (Table 4, Figure 8). On average, NARW upcalls were detected 3 days in a row across seasons and sites in SNE. A total of 95% of the time, NARW upcalls were detected from 7 (at COX01) to 12 days (at NS02) in a row or less, with a weighted average of 10 days of consecutive upcall persistence across the three sites. Consecutive days with no automatic NARW upcall detections varied more considerably between the three sites (an average of 13 days for COX01, 9 days for NS01, and 5 days for NS02), with 95% of consecutive days with no upcall detections lasting 31 days or fewer.

The proportion of days detecting a NARW upcall again after a first day with confirmed automatic detections (reoccurrence) was analysed for each full-year site. Reoccurrence varied across sites, where 95% of the time a NARW upcall was detected again within 9 (at NS02) to 31 (at COX01)

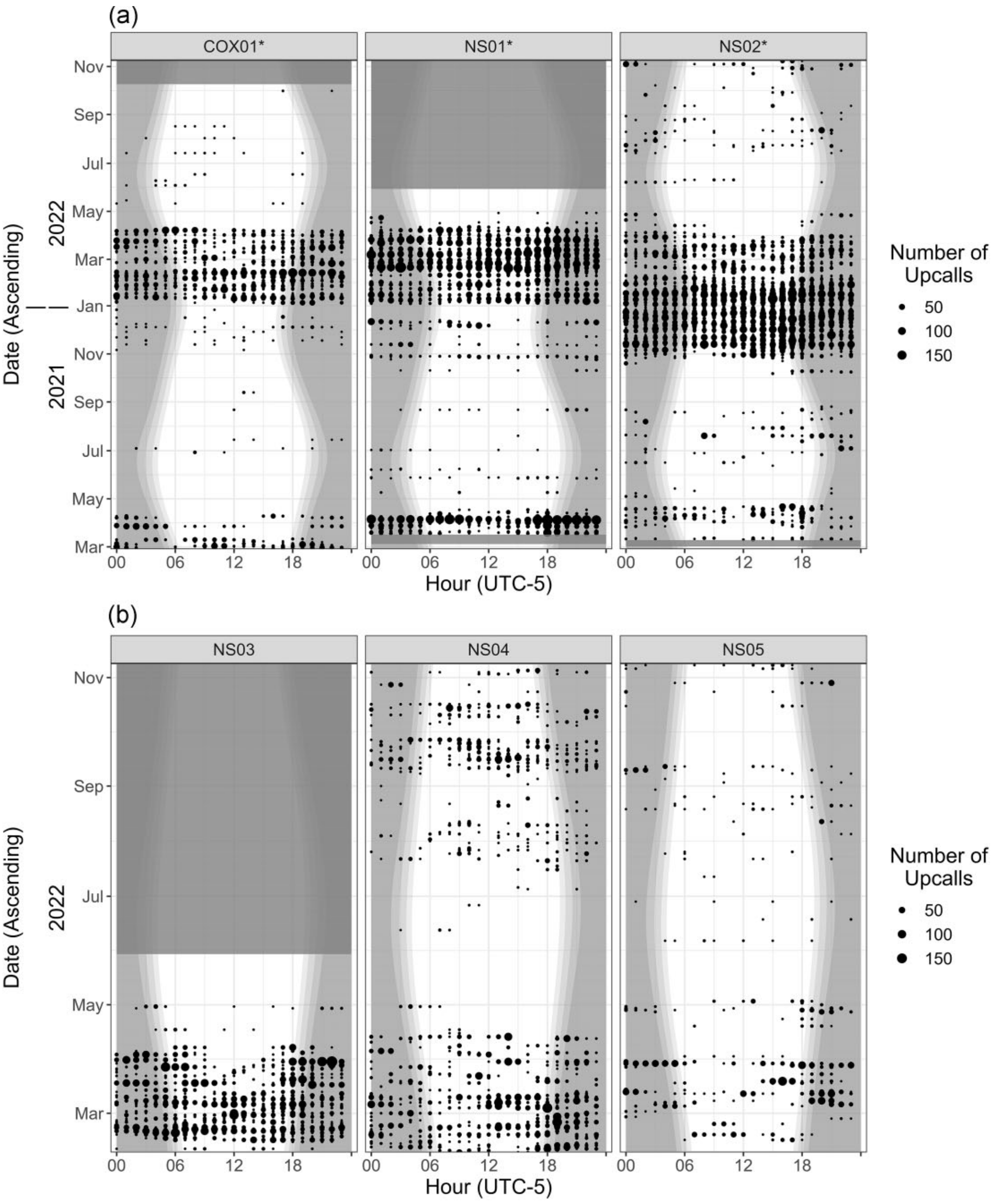

Figure 4. Seasonal and diel distribution of NARW upcalls at each recording site. Each black circle represents the number of upcalls manually annotated during that hour for days that were found to have at least one NARW automatic detection by the LFDCS. Circle size indicates the number of upcalls per hour. The *y*-axis shows date (ascending from bottom to top); sites in panel A (COX01, NS01, and NS01) span >1 year of data from 26 February 2021 (bottom) to 09 November 2022 (top); sites in panel B (NS03, NS04, and NS05) span <1 year, from 07 February 2022 (bottom) to 09 November 2022 (top). The *x*-axis represents time of day in US Eastern Standard Time (UTC-5). Grey shading illustrates times between sunset and sunrise, with lighter shading indicating dusk and dawn. Dark grey blocks indicate periods of missing data. Asterisks (∗) indicate sites with at least one full year of data.

days after the first day of detection (Table 4, Figure 9). Across the three sites, the weighted average for 95% of days with NARW acoustic presence occurred within 11 days of another confirmed acoustic presence day. Therefore, most of the time in the SNE region, when NARWs are detected, there will likely be another upcall detection in the area within 11 days.

Pre-construction-activity monitoring

To assess the likelihood of detecting an acoustically present NARW prior to an initial start time, 144 (at COX01) to 279 (at NS02) days were evaluated at each full-year site (Figure 10). All of the sites and start times showed the same increasing trend with slight variation. Here, 6-h intervals—with a minimum of 1 h and a maximum of 24 h—were used as realistic time requirements to monitor for NARWs prior to construction. Overall, the more time monitored (in this case, up to 24 h) prior to a start time, the more often a NARW was detected, as there were more cumulative hours with an upcall detection (Figure 11). When averaged across the three sites and modelled start times, an upcalling NARW would only be detected in 74.4% of the hours if monitoring 18 h

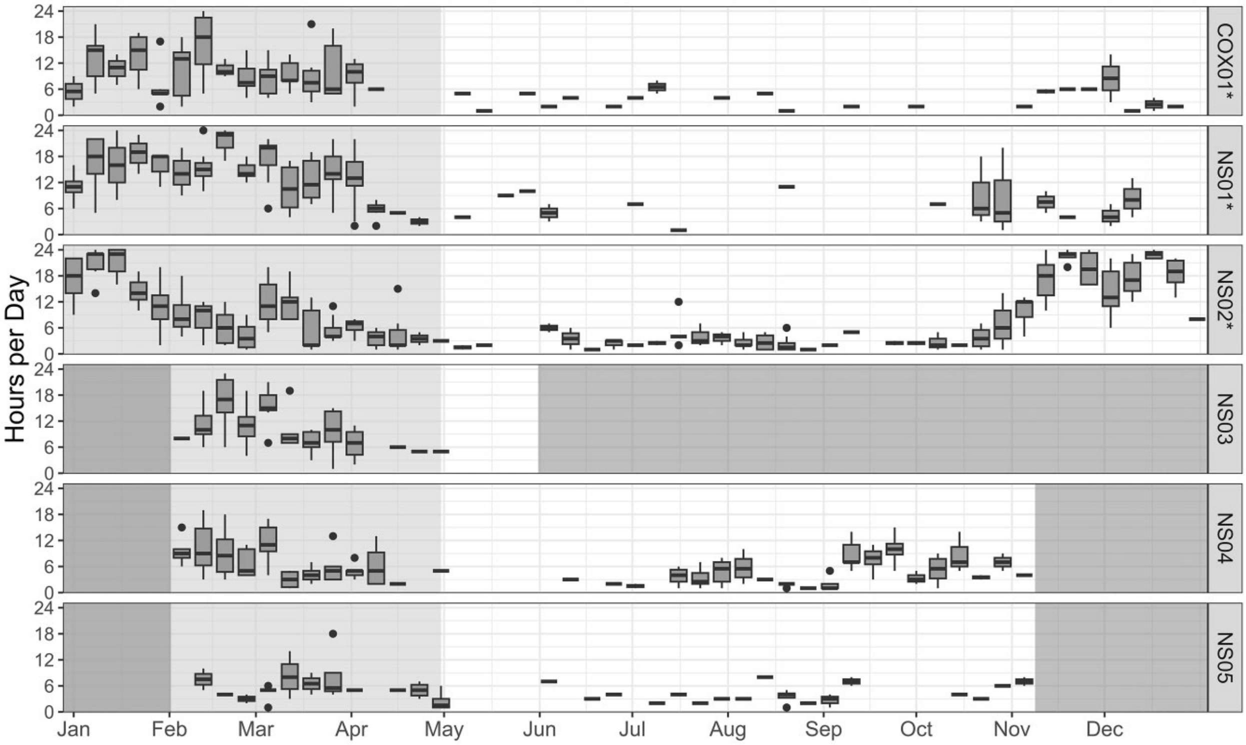

Figure 5. Number of vocal hours: boxplot representing the average number of hours with NARW upcalls per calendar week, for each recording site across all years of the study. Horizontal lines within the boxes indicate the median; box boundaries indicate the 25th (lower boundary) and 75th (upper boundary) percentiles; vertical lines indicate the largest (upper whisker) and smallest (lower whisker) values no further than 1.5 times the interquartile range; and black dots represent outliers. Dark grey blocks indicate weeks where no data were available for that site. Light grey blocks overlap time-of-year restrictions in which pile driving is not allowed for that region (January–April). Asterisks (*) indicate sites with at least one full year of data.

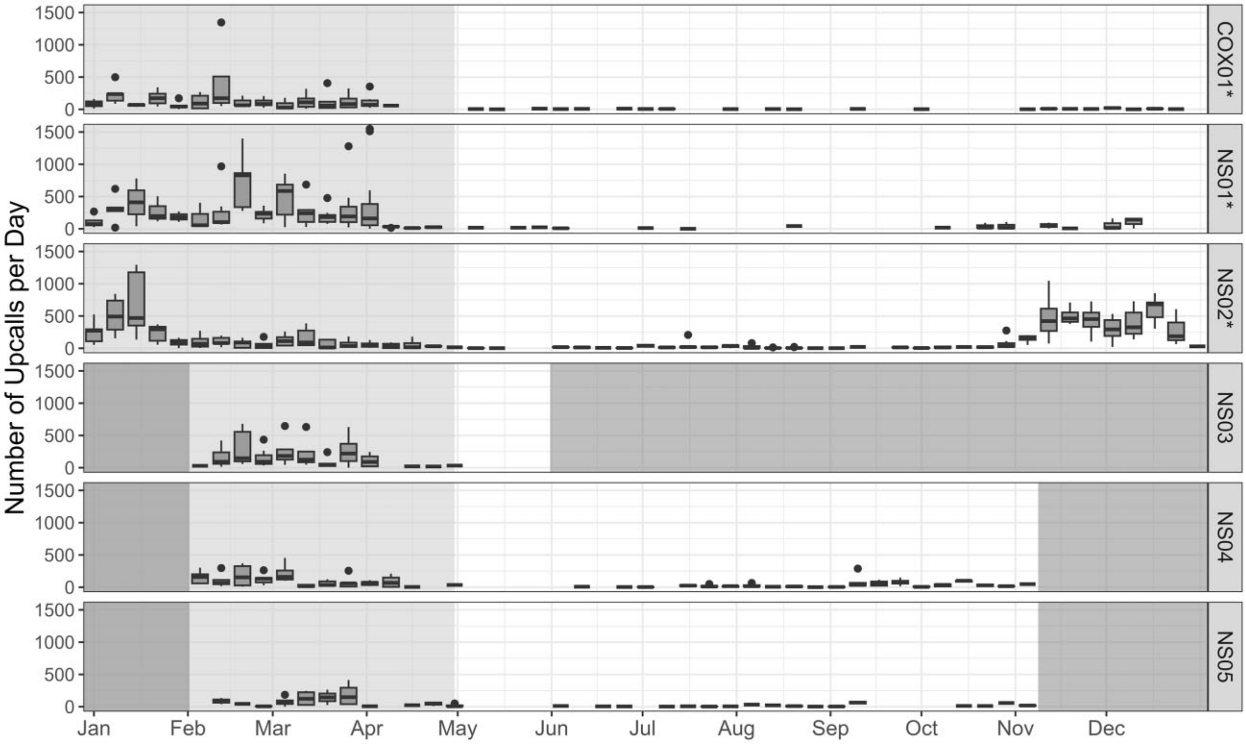

Figure 6. Number of upcalls per day: boxplot representing the average number of NARW upcalls per day for each calendar week, for each recording site across all years of the study. Horizontal lines within the boxes indicate the median; box boundaries indicate the 25th (lower boundary) and 75th (upper boundary) percentiles; vertical lines indicate the largest (upper whisker) and smallest (lower whisker) values no further than 1.5 times the interquartile range; and black dots represent outliers. Dark grey blocks indicate weeks where no data were available for that site. Light grey blocks overlap time-of-year restrictions in which pile driving is not allowed for that region (January–April). Asterisks (*) indicate sites with at least one full year of data.

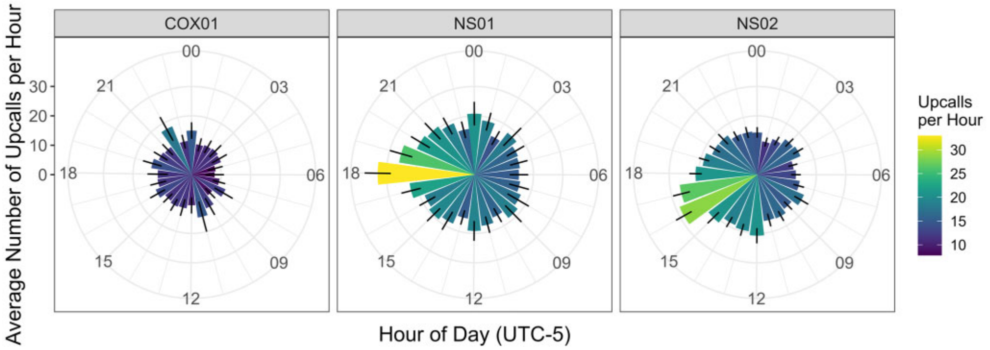

Figure 7. The average number of upcalls per hour across the entire deployment, for each of the recording sites. Polar axis shows the hour of day (UTC-5), with hour 00 at the top and travelling clockwise. The R-axis and bar colour show the average number of upcalls per hour. Averages were totalled only from hours with upcalls; no hours with 0 upcalls were included. Only sites with at least one full year of data were used (COX01, NS01, and NS02).

Table 3. The number of upcalls used to measure inter-call intervals (ICIs), number of upcall bouts, and upcall bout lengths, for each site with >1 year of data.

Site	Number of confirmed NARW upcalls	95% ICI (inter-call interval; min)	Number of upcall bouts	Average bout length (min)	95% bout length (min)
COX01	10421	33.6	808	20.7	87.2
NS01	29658	13.9	1239	33.3	145.0
NS02	38953	15.9	1800	33.5	149.0
Totals/Averages across sites	79032	17.5	3847	30.7	134.8

Last row contains total numbers (for confirmed upcalls and number of upcall bouts) or weighted averages (for 95% ICIs, average upcall bout length, and 95% bout length) across all three sites.

Table 4. The average (and 95th percentile) number of days for consecutive presence ("persistence"—number of consecutive days in a row with NARW upcall presence) and consecutive silence (number of days in a row with no NARW upcall detections); and the 95% of days for NARW acoustic reoccurrence (the proportion of days that detected a NARW upcall again after the first day with confirmed upcall detections).

Site	Average consecutive presence-persistence (days)	95% consecutive presence-persistence (days)	Average consecutive silence (days)	95% consecutive silence (days)	95% reoccurrence (days)
COX01	2.33	7.10	12.8	56.4	31.4
NS01	3.14	7.90	9.14	34.8	19.0
NS02	2.93	11.5	5.03	16.8	9.00
Across sites	2.82	9.52	7.99	31.2	10.7

Last row has the weighted averages across all three sites for each measurement.

prior to activity. The proportion of hours with detections for an acoustically present NARW dropped dramatically for less monitoring time: 47.3% for 12 h of monitoring, 22.9% for 6 h, and 3.9% for 1 h. For all full-year sites, we looked at time periods during the time-of-year restriction (when pile driving is not permitted in the region, January–April) and allowed construction periods (May–December) separately, but differences were negligible compared to results across the year as a whole.

Discussion

This study provides a detailed overview of NARW upcall acoustic occurrence in the SNE region, using data collected >2 years prior to the start of WEA construction. With NARWs acoustically present every month across all recording sites, the SNE continues to be an important area, as documented in visual and acoustic surveys since 2011 (e.g. Leiter *et al.*, 2017; Quintana-Rizzo *et al.*, 2021; Estabrook *et al.*, 2022; O'Brien *et al.*, 2022). The National Oceanic and Atmospheric Administration (NOAA) and Bureau of Ocean Energy Management (BOEM) regulations currently restrict pile driving from occurring during the months of January–April, when NARWs occur in high numbers in the area; however, NARWs were detected in equally high amounts throughout the area during the months of October–December, months during which further protections should be considered. NS02, NS03, and NS04 were the sites with the highest number of NARW upcalls, showing high densities both on Nantucket Shoals and along the edge of the Shoals (Figure 2). NARW acoustic presence peaked within the time-of-year restriction (during February–April) at NS02, NS03, and NS04, where there was recording effort. At NS04, the recording site located on Nantucket Shoals, acoustic presence also peaked in July and September. This data reinforces previous visual and acoustic data, which showed high variability across years with occasional presence in July and August (Quintana-Rizzo *et al.*, 2021; Estabrook *et al.*, 2022).

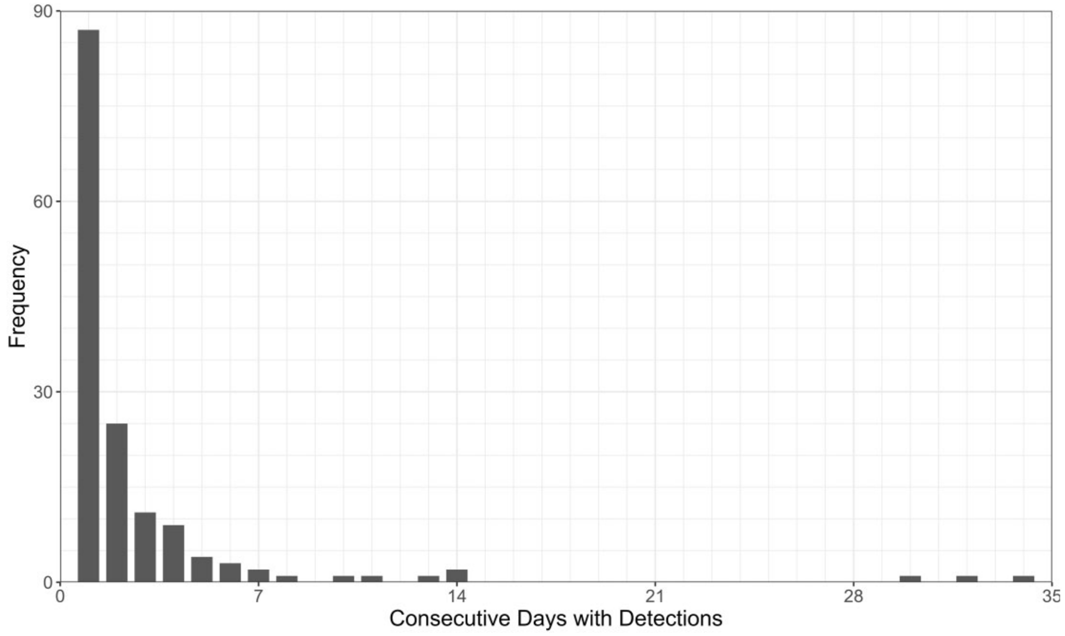

Figure 8. Histogram showing the frequency in which the number of consecutive presence days occurs across the dataset. The *x*-axis represents the number of consecutive days with NARW daily presence (three or more automatic upcall detections occurred within 24 h), and the *y*-axis indicates the number of times NARWs were detected × number of days in a row. Only sites with at least one full year of data were used (COX01, NS01, and NS02).

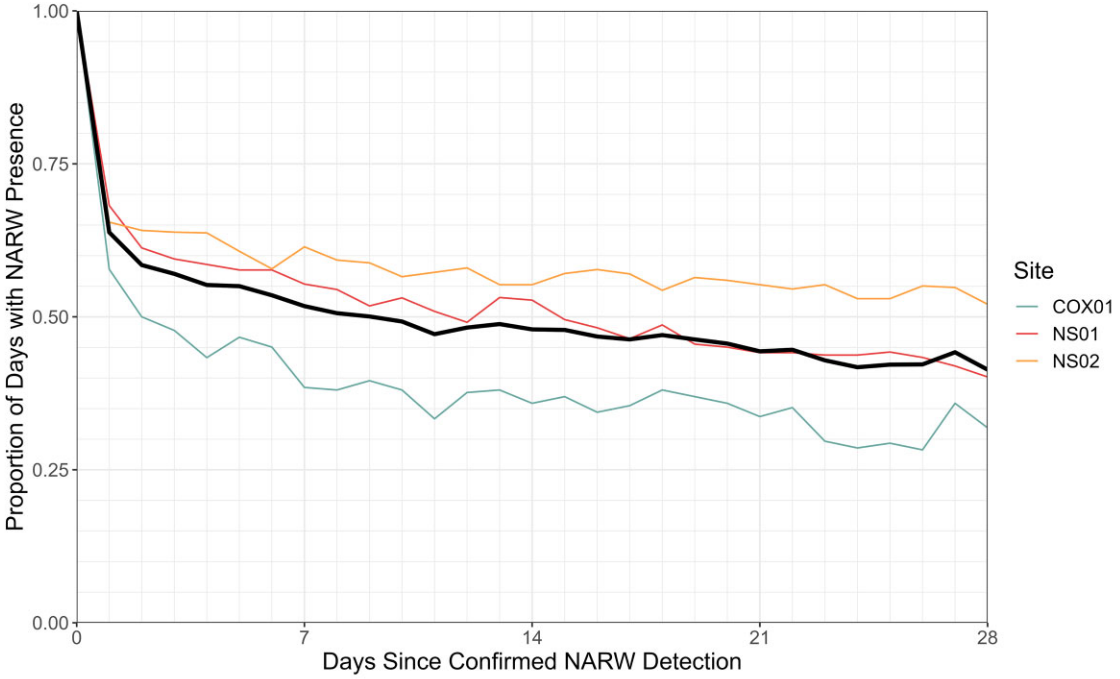

Figure 9. The proportion of days with NARW upcall detections after the first day of detection. The *x*-axis represents the number of days since a detected NARW upcall, and the *y*-axis indicates proportion of days that detected another NARW 24 h or more after the first detection. Only sites with at least one full year of data were used (COX01, NS01, and NS02). Coloured lines show proportions at each specified site; black line is the average proportion across all sites.

For some species, such as in odontocetes, it is possible to estimate the number of animals present, given the number of acoustic cues recorded (e.g. Buckland *et al.*, 2001; Marques *et al.*, 2019). In contrast, NARWs are social communicators and tend to show high variability in their calling rates regardless of group size (e.g. Clark, 1990; Parks *et al.*, 2011; Root-Gutteridge *et al.*, 2018). Variability of calling rates has been seen across age groups and in other regions (Parks *et al.*, 2011, 2019b; Durette-Morin *et al.*, 2019) as well as changes in vocalizations in mom and calf pairs (Parks *et al.*, 2019a), making it challenging to estimate the number of animals present from acoustic detections alone. Our results reflected this variability as weeks with a high daily presence could have the same number of upcalls as weeks with fewer presence days. Like-

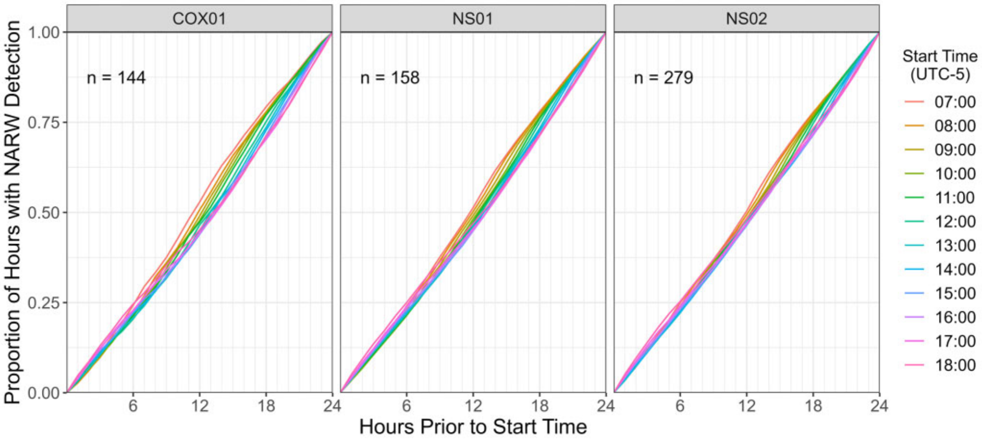

Figure 10. The proportion of hours with NARW upcalls for each cumulative hour prior to theoretical start times for wind energy construction. Each panel represents a recording site for all available data at that site. Coloured lines correspond to the modelled start time in UTC-5, for each hour from 07:00 to 18:00. The number of days with confirmed NARW upcall detections that went into this analysis, for each site, is identified by the *n* value in each site panel. The *y*-axis represents the proportion of hours with NARW upcall detections, and the *x*-axis represents the number of hours prior to the start time. Only sites with at least one full year of data were used (COX01, NS01, and NS02).

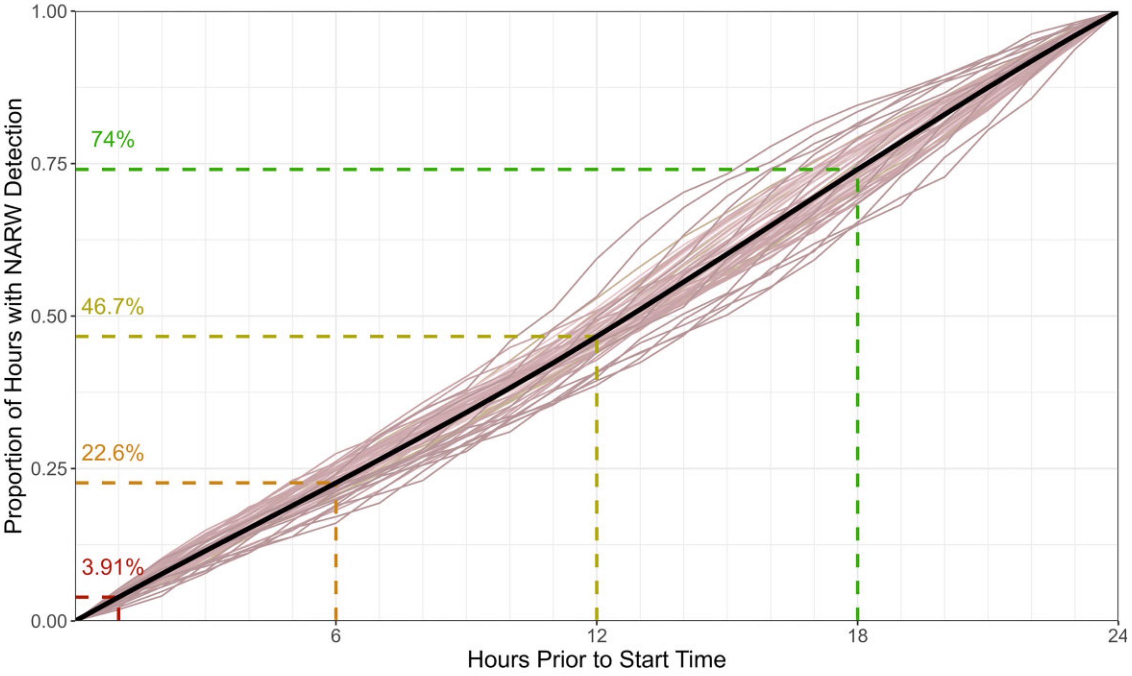

Figure 11. The proportion of hours with NARW upcalls for each cumulative hour prior to theoretical start times for wind energy construction, summarized across all full-year sites (COX01, NS01, and NS02) and start times. All pink lines represent one of the start time hours (for each hour from 07:00 to 18:00 UTC-5), for one site. The black line represents the average across all start times and sites. The *y*-axis represents the proportion of hours with NARW upcall detections, and the *x*-axis represents the number of hours prior to the start time. Dotted lines highlight the percentage of hours with detections captured if monitoring for 1, 6, 12, or 18 h prior to activity.

wise, some days with acoustic presence had the same number of upcalls over 24 h as were detected within 1 h elsewhere. One animal could be present and consistently calling, or many animals could be passing through, calling infrequently, if at all. With this in mind, NARW upcalls are useful for detecting their presence given that one individual alone can trigger a management action; however, it is not as yet possible to extrapolate to abundance for this species using PAM.

Previous studies have evaluated upcall occurrence for seasonal and diel trends in the Gulf of Maine (Bort *et al.*, 2015), Massachusetts Bay (Clark *et al.*, 2010; Morano *et al.*, 2012; Mussoline *et al.*, 2012), New York Bight (NYB; Murray *et al.*, 2022), and the SNE region (Estabrook *et al.*, 2022), revealing an increase in upcalling activity in evening hours (16:00–20:00 UTC-5) in some regions (NYB, SNE), and in both twilight periods (dawn and dusk) further north in Massachusetts Bay and Gulf of Maine. When comparing NARW acoustic activity over time, Charif *et al.* (2019) found changes in when and how often NARWs are detected in Massachusetts Bay, showing an earlier, and greater peak of acoustic occurrence (more hours of the day with detections) after 2010 compared to before 2010. This study found minimal diel patterns across the dataset, suggesting that NARWs may have changed their behaviour in the region. Sites that showed the highest diel trend for evening hours, NS01 and NS02, were in similar locations as Estabrook *et al.* (2022), and had year-round recordings. No discernible diel patterns were found on COX01, which could indicate that NARWs exhibit different diel patterns in locations further northwest. Overall, these results demonstrate that monitoring only during certain selective hours of the day does not guarantee that NARWs are detected and longer monitoring time periods are needed to ensure that their presence is captured.

NARW acoustic persistence and reoccurrence are important contexts to evaluate since they can determine both how long NARWs may stay in a given area as well as how long you need to listen for NARWs to ensure that you will detect an acoustically active animal(s) in an area. This study showed that when NARWs were detected in the SNE, they were likely to persist, or reoccur, within the area for an average of 10 and 11 days, respectively. This supports current slow zone rules, where slow zones are in place or "persist" for 15 days after sighting or detecting a NARW (https://www.fisheries.noaa.gov/feature-story/help-endangered-whales-slow-down-slow-zones). An extension of 15 days is issued whenever a NARW is heard or sighted within the last 7 days of the 15-day period. Given the range of persistence (8–12 days) and reoccurrence (9–31 days) found in SNE, applying these methods to data in other regions would provide a better understanding of persistence in other habitats, which will help to inform the proposed changes to the NARW vessel speed rule to further reduce the likelihood of mortalities and serious injuries to endangered NARWs from vessel collision, currently under consideration (https://www.fisheries.noaa.gov/national/endangered-species-conservation/reducing-vessel-strikes-north-atlantic-right-whales).

Within management discussions, there is considerable emphasis on attempting to localize calling animals to determine if they are within or outside of a given WEA. However, the reoccurrence results demonstrate that whales either remain in an area, or move to and fro between a given area so that once detected, NARWs are likely to be detected again within 11 days or fewer at that same site within the SNE region. If whales are heard by a PAM system monitoring in a WEA, even if they are out of the construction zone at the time of detection, it is not unlikely that they will repeatedly move into, near, or through the area. Johnson *et al.* (2020) showed that from simulated results, in <24 h after an initial detection, there was a <10% probability of a whale remaining within 5 km of reported position, but a >71% chance that the whale remained within 25 km. The SNE is a known feeding and socializing (Quintana-Rizzo *et al.*, 2021) ground for NARWs, and animals will persist or call differently here than in other areas. Using a similar analysis approach in other areas, where different behaviours may occur, is necessary before applying these conclusions across other WEA regions.

When determining the length of time for which monitoring should occur in order to have a higher likelihood of detecting an acoustically active NARW(s) in an area, for the SNE, it was clear that, for example, monitoring for 24 h would give a 100% likelihood of detecting an upcalling NARW; 18 h would give a 74% likelihood of the species being heard, as opposed to monitoring for 1 h would provide only a 4% likelihood of hearing NARWs. Current monitoring requirements prior to pile driving require 1 h of monitoring prior to pile driving operations commencing (e.g. NMFS, 2022). A longer monitoring period is clearly needed to provide "situational awareness" in order to support a more robust mitigation approach. The data for the SNE WEA shows that the longer you listen, the higher the likelihood of detecting an acoustically active NARW. An additional element to consider is the variable and more sparse calling behaviour of NARWs during time periods where their occurrence is lower and when pile driving is permitted (May–December). During this time period, monitoring for at least 24 h prior to activity is critical to increase the likelihood of detecting an NARW if they are in the area and upcalling.

Passive acoustic monitoring is a highly effective tool for mitigation purposes; however, it is important to understand its applications, how and where it should and shouldn't be used. Ceballos *et al.* (2022) showed that PAM was 20 times more reliable than a visual survey at detecting a single animal. Here, we present results on NARW upcall presence, and provide guidance on how to use PAM for monitoring and mitigation of WEA impacts on NARWs. It is important to remember that animals can be present but silent, be producing vocalizations different from the target call (in this case, the upcall), or be calling outside of the detection range of the recorders. NARWs produce a variety of vocalizations beyond the upcall, but they can be harder to identify reliably and their use across different regions has not yet been examined, thus are not used for monitoring and mitigation to the same extent as upcalls (Van Parijs *et al.*, 2009; Franklin *et al.*, 2022). Additionally, detection ranges of calls vary with oceanographic conditions, including bathymetry, bottom type, temperature, salinity, and ambient noise conditions. On average, throughout their range, NARWs can be detected from 10 km away (e.g. Laurinolli *et al.*, 2003; Clark *et al.*, 2010; Van Parijs *et al.*, 2021). Estabrook *et al.* (2022) estimated detection ranges in the SNE region to be 8–22 km on bottom-mounted recorders, and Johnson *et al.* (2022) estimated detection ranges from 6 to 27 km on real-time platforms. In all cases, detection ranges were affected by ambient noise levels, and will be heavily impacted by the proximity and amount of pile driving, vessel traffic, and other WEA activity (Van Parijs *et al.*, 2023). Thus, combining visual and acoustic methods when monitoring to ensure an area is "clear" during WEA construction is important, especially during times of increased ambient noise (i.e. pile driving), when NARW acoustic detection may be challenging. However, mitigation measures such as bubble curtains are known to reduce pile driving sound levels and may therefore still allow for effective acoustic detection (Dähne *et al.*, 2017).

Therefore, understanding the target species' calling behaviour is essential when designing effective monitoring and mitigation strategies aimed at reducing the impact of anthropogenic activities. In this study, we present data on NARW upcalling behaviour for the SNE WEA with the understanding that other WEA regions will require similar analyses and evaluations to assess how widely the trends from this region can be applied across areas or not, and if these SNE trends change in future years. Similarly, in regions where other acoustically active species are of primary concern, comparable assessments should be done to evaluate that species calling behaviour as well.

Acknowledgements

We thank Molly Martin for analysis help and Mark Baumgartner for his invaluable input for methods. Thanks to Nick

Sisson, Jaclyn Daly, and Carter Esch for their regulatory expertise. Thank you to Kate Choate and Catherine Dodge for all the QA/QC work on these data. Thanks to all the crew and field teams that helped collect this data, especially Tim Rowell, Tyler Aldrich, Jessica McCordic, Amanda Holdman, Annabel Westell, and Rochelle Gordon.

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

Data availability

All these data were collected with federal funding and are publicly available upon request. We are working to integrate the detection data into the publicly available Passive Acoustic Cetacean Map at https://apps-nefsc.fisheries.noaa.gov/pacm.

Author contributions

GED was responsible for the study design, figure creation, conceptual development, and writing of the manuscript; SCT was responsible for data analysis, figure creation, and reviewing the manuscript; and SMVP was responsible for the study design, conceptual development, and writing of the manuscript.

Funding

Funding was provided by BOEM Award #M19PG00015 and the Northeast Fisheries Science Center's Wind Energy Program.

Animal ethics and welfare

There are no animal ethics and welfare concerns.

References

Aerts L., Jenkerson M. R., Nechayuk V. E., Gailey G., Racca R., Blanchard A. L., Schwarz L. K *et al.* 2022. Seismic surveys near gray whale feeding areas off Sakhalin Island, Russia: assessing impact and mitigation effectiveness. *Environmental Monitoring and Assessment*, **194**: 746.

Amaral J. L., Miller J. H., Potty G. R., Vigness-Raposa K. J., Frankel A. S., Lin Y.-T., Newhall A. E *et al.* 2020. Characterization of impact pile driving signals during installation of offshore wind turbine foundations. *The Journal of the Acoustical Society of America*, **147**: 2323.

Bailey H., Brookes K. L., Thompson P. M. 2014. Assessing environmental impacts of offshore wind farms: lessons learned and recommendations for the future. *Aquatic Biosystems*, **10**: 13–13.

Bailey H., Senior B., Simmons D., Rusin J., Picken G., Thompson P. M. 2010. Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. *Marine Pollution Bulletin*, **60**: 888–897.

Baker K., Epperson D. M., Gitschlag G. R., Goldstein H. H., Lewandowski J., Skrupky K., Smith B. K *et al.* 2013. National standards for a Protected Species Observer and Data Management Program : a model using geological and geophysical surveys. https://repository.library.noaa.gov/view/noaa/15851 (last accessed 26 October 2023).

Baumgartner M. F., Bonnell J., Corkeron P. J., Van Parijs S. M., Hotchkin C., Hodges B. A., Bort Thornton J *et al.* 2020. Slocum gliders provide accurate near real-time estimates of baleen whale presence from human-reviewed passive acoustic detection information. *Frontiers in Marine Science*, **7**: 100.

Baumgartner M. F., Bonnell J., Van Parijs S. M., Corkeron P. J., Hotchkin C., Ball K., Pelletier L. P *et al.* 2019. Persistent near real-time passive acoustic monitoring for baleen whales from a moored buoy: system description and evaluation. *Methods in Ecology and Evolution*, **10**: 1476–1489.

Baumgartner M. F., Fratantoni D. M., Hurst T. P., Brown M. W., Cole T. V. N., Van Parijs S. M., Johnson M. 2013. Real-time reporting of baleen whale passive acoustic detections from ocean gliders. *Journal of the Acoustical Society of America*, **134**: 1814–1823.

Baumgartner M. F., Mussoline S. E. 2011. A generalized baleen whale call detection and classification system. *Journal of the Acoustical Society of America*, **129**: 2889–2902.

Bort J., Van Parijs S. M., Stevick P. T., Summers E., Todd S. 2015. North Atlantic right whale *Eubalaena glacialis* vocalization patterns in the central Gulf of Maine from October 2009 through October 2010. *Endangered Species Research*, **26**: 271–280.

Brandt M. J., Diederichs A., Betke K., Nehls G. 2011. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. *Marine Ecology Progress Series*, **421**: 205–216.

Bröker K., Gailey G., Muir J., Racca R. 2015. Monitoring and impact mitigation during a 4D seismic survey near a population of gray whales off Sakhalin Island. *Russia. Endangered Species Research*, **28**: 187–208.

Buckland S. T., Anderson D. R., Burnham K. P., Laake J. L., Borchers D. L., Thomas L. 2001. *Introduction to Distance Sampling—Estimating Abundances of Biological Populations*. Oxford University Press, Oxford.

Ceballos V., Taggart C., Johnson H. 2022. Comparison of visual and acoustic surveys for the detection and dynamic management of North Atlantic right whales (*Eubalaena glacialis*) in Canada. *Conservation Science and Practice*, **5**: e12866.

Charif R. A., Shiu Y., Muirhead C. A., Clark C. W., Parks S. E., Rice A. N. 2019. Phenological changes in North Atlantic right whale habitat use in Massachusetts Bay. *Global Change Biology*, **26**: 734–745.

Cholewiak D., Clark C. W., Ponirakis D., Frankel A., Hatch L. T., Risch D., Stanistreet J. E *et al.* 2018. Communicating amidst the noise: modeling the aggregate influence of ambient and vessel noise on baleen whale communication space in a National Marine Sanctuary. *Endangered Species Research*, **36**: 59–75.

Christiansen F., Dawson S. M., Durban J. W., Fearnbach H., Miller C. A., Bejder L., Uhart M *et al.* 2020. Population comparison of right whale body condition reveals poor state of the North Atlantic right whale. *Marine Ecology Progress Series*, **640**: 1–16.

Clark C. W. 1990. Acoustic behavior of mysticete whales. *Sensory Abilities of Cetaceans: Laboratory and Field Evidence*, **196**: 571–583.

Clark C. W., Brown M. W., Corkeron P. 2010. Visual and acoustic surveys for North Atlantic right whales, *Eubalaena glacialis*, in Cape Cod Bay, Massachusetts, 2001–2005: management implications. *Marine Mammal Science*, **26**: 837–854.

Clark C. W., Gagnon G. J. 2022. Baleen whale acoustic ethology. *In Ethology and Behavioral Ecology of Mysticetes*, pp. 11–43. Ed. by Clark C. W.and Garland E. C.. Springer International Publishing, Cham.

Dähne M., Tougaard J., Carstensen J., Rose A., Nabe-Nielsen J. 2017. Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbour porpoises. *Marine Ecology Progress Series*, **580**: 221–237.

Davis G. E., Baumgartner M. F., Bonnell J. M., Bell J., Berchok C., Bort Thornton J., Brault S *et al.* 2017. Long-term passive acoustic recordings track the changing distribution of North Atlantic right whales (*Eubalaena glacialis*) from 2004 to 2014. *Scientific Reports*, **7**: 13460.

Davis G. E., Baumgartner M. F., Corkeron P. J., Bell J., Berchok C., Bonnell J. M., Bort Thornton J *et al.* 2020. Exploring movement patterns and changing distributions of baleen whales in the western North Atlantic using a decade of passive acoustic data. *Global Change Biology*, **26**: 29.

Durette-Morin D., Davies K. T. A., Johnson H. D., Brown M. W., Moors-Murphy H., Martin B., Taggart C. T. 2019. Passive acoustic monitoring predicts daily variation in North Atlantic right whale presence and relative abundance in Roseway Basin, Canada. *Marine Mammal Science*, **35**: 1280–1303.

Durette-Morin D., Evers C., Johnson H. D., Kowarski K., Delarue J., Moors-Murphy H., Maxner E *et al.* 2022. The distribution of North Atlantic right whales in Canadian waters from 2015–2017 revealed by passive acoustic monitoring. *Frontiers in Marine Science*, **9**: 976044.

Estabrook B., Tielens J., Rahaman A., Ponirakis D., Clark C., Rice A. 2022. Dynamic spatiotemporal acoustic occurrence of North Atlantic right whales in the offshore Rhode Island and Massachusetts Wind Energy Areas. *Endangered Species Research*, **49**: 115–133.

Franklin K., Cole T., Cholewiak D., Duley P., Crowe L., Hamilton P., Knowlton A *et al.* 2022. Using sonobuoys and visual surveys to characterize North Atlantic right whale (*Eubalaena glacialis*) calling behavior in the Gulf of St. Lawrence. *Endangered Species Research*, **49**: 159–174.

GEBCO Compilation Group 2022. GEBCO 2022 Grid. https://doi.org/10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c

Gibb R., Browning E., Glover-Kapfer P., Jones K. E., Börger L. 2019. Emerging opportunities and challenges for passive acoustics in ecological assessment and monitoring. *Methods in Ecology and Evolution*, **10**: 169–185.

Hatch L. T., Clark C. W., Van Parijs S. M., Frankel A. S., Ponirakis D. W. 2012. Quantifying loss of acoustic communication space for right whales in and around a U.S. National Marine Sanctuary. *Conservation Biology*, **26**: 983–994.

Johnson H. D., Baumgartner M. F., Taggart C. T. 2020. Estimating North Atlantic right whale (*Eubalaena glacialis*) location uncertainty following visual or acoustic detection to inform dynamic management. *Conservation Science and Practice*, **2**: e267.

Johnson H. D., Taggart C. T., Newhall A. E., Lin Y.-T., Baumgartner M. F. 2022. Acoustic detection range of right whale upcalls identified in near-real time from a moored buoy and a Slocum glider. *The Journal of the Acoustical Society of America*, **151**: 2558–2575.

Kowarski K. A., Martin S. B., Maxner E. E., Lawrence C. B., Delarue J. J. Y., Miksis-Olds J. L. 2022. Cetacean acoustic occurrence on the US Atlantic outer continental shelf from 2017 to 2020. *Marine Mammal Science*, **39**: 175–199.

Kraus S. D., Kenney R. D., Thomas L. 2019. A Framework for Studying the Effects of Offshore Wind Development on Marine Mammals and Turtles. Report prepared for the Massachusetts Clean Energy Center, Boston MA 02110, and the Bureau of Ocean Energy Management. https://www.boem.gov/sites/default/files/environmental-stewardship/Environmental-Studies/Renewable-Energy/A-Framework-for-Studying-the-Effects.pdf (last accessed 26 October 2023).

Laurinolli M. H., Hay A. E., Desharnais F., Taggart C. T. 2003. Localization of North Atlantic right whale sounds in the Bay of Fundy using a sonobuoy array. *Marine Mammal Science*, **19**: 708–723.

Leiter S. M., Stone K. M., Thompson J. L., Accardo C. M., Wikgren B. C., Zani M. A., Cole T. V. N *et al.* 2017. North Atlantic right whale *Eubalaena glacialis* occurrence in offshore wind energy areas near Massachusetts and Rhode Island, USA. *Endangered Species Research*, **34**: 45–59.

Lindeboom H. J., Kouwenhoven H. J., Bergman M. J. N., Bouma S., Brasseur S., Daan R., Fijn R. C *et al.* 2011. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environmental Research Letters*, **6**: 1–13.

Marques T. A., Jorge P. A., Mouriño H., Thomas L., Moretti D. J., Dolan K., Claridge D *et al.* 2019. Estimating group size from acoustic footprint to improve Blainville's beaked whale abundance estimation. *Applied Acoustics*, **156**: 434–439.

Matthews L. P., Parks S. E. 2021. An overview of North Atlantic right whale acoustic behavior, hearing capabilities, and responses to sound. *Marine Pollution Bulletin*, **173**: 113043.

McCordic J. A., Root-Gutteridge H., Cusano D. A., Denes S. L., Parks S. E. 2016. Calls of North Atlantic right whales *Eubalaena glacialis* contain information on individual identity and age class. *Endangered Species Research*, **30**: 157–169.

Meyer-Gutbrod E. L., Davies K. T. A., Johnson C. L., Plourde S., Sorochan K. A., Kenney R. D., Ramp C *et al.* 2022. Redefining North Atlantic right whale habitat-use patterns under climate change. *Limnology and Oceanography*, **68**: S71–S86.

Meyer-Gutbrod E. L., Greene C. H., Davies K. T. A., Johns D. G. 2021. Ocean regime shift is driving collapse of the North Atlantic right whale population. *Oceanography*, **34**: 22–31.

Moore M. 2023. Policy enabling North Atlantic right whale reproductive health could save the species. *ICES Journal of Marine Science*, **80**: fsac239.

Morano J. L., Rice A. N., Tielens J. T., Estabrook B. J., Murray A., Roberts B. L., Clark C. W. 2012. Acoustically detected year-round presence of right whales in an urbanized migration corridor. *Conservation Biology*, **26**: 698–707.

Muirhead C. A., Warde A. M., Biedron I. S., Nicole Mihnovets A., Clark C. W., Rice A. N. 2018. Seasonal acoustic occurrence of blue, fin, and North Atlantic right whales in the New York Bight. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **28**: 744–753.

Murray A., Rekdahl M. L., Baumgartner M. F., Rosenbaum H. C. 2022. Acoustic presence and vocal activity of North Atlantic right whales in the New York Bight: implications for protecting a critically endangered species in a human-dominated environment. *Conservation Science and Practice*, **4**: e12798.

Mussoline S. E., Risch D., Hatch L. T., Weinrich M. T., Wiley D. N., Thompson M. A., Corkeron P. J *et al.* 2012. Seasonal and diel variation in North Atlantic right whale up-calls: implications for management and conservation in the northwestern Atlantic Ocean. *Endangered Species Research*, **17**: 17–26.

NMFS 2021. National Marine Fisheries Service Endangered Species Act Section 7 Biological Opinion Construction, Operation, Maintenance, and Decommissioning of the Vineyard Wind 1 Offshore Wind Energy Project (Lease OCS-A 0501)—Reinitiation. https://repository.library.noaa.gov/view/noaa/37556 (last accessed 26 October 2023).

NMFS. 2022. Takes of marine mammals incidental to specified activities; taking marine mammals incidental to construction of the vineyard wind offshore wind project. *ICES Document FR Document*, **84**: 18346–18381.

Nowacek D. P., Bröker K., Donovan G., Gailey G., Racca R., Reeves R. R., Vedenev A. I *et al.* 2013. Responsible practices for minimizing and monitoring environmental impacts of marine seismic surveys with an emphasis on marine mammals. *Aquatic Mammals*, **39**: 356–377.

O'Brien O., Pendleton D. E., Ganley L. C., Mckenna K. R., Kenney R. D., Quintana-Rizzo E., Mayo C. A *et al.* 2022. Repatriation of a historical North Atlantic right whale habitat during an era of rapid climate change. *Scientific Reports*, **12**: 12407.

Office of the Press Secretary. 2021. *FACT SHEET: Biden Administration Jumpstarts Offshore Wind Energy Projects to Create Jobs*. The White House, Washington, DC.

Office of the Press Secretary. 2022. *FACT SHEET: Biden-Harris Administration Announces New Actions to Expand U.S. Offshore Wind Energy*. The White House, Washington, DC.

Pace R. M., Corkeron P. J., Kraus S. D. 2017. State-space mark–recapture estimates reveal a recent decline in abundance of North Atlantic right whales. *Ecology and Evolution*, **7**: 8730–8741.

Parks S. E. 2022. Right Whales from north to south: similarities and differences in acoustic communication. *In Ethology and Behavioral Ecology of Mysticetes*, pp. 297–327. Ed. by Clark C. W.and Garland E. C.. Springer International Publishing, Cham.

Parks S. E., Clark C. W., Tyack P. L. 2007. Short- and long-term changes in right whale calling behavior: the potential effects of noise on acoustic communication. *The Journal of the Acoustical Society of America*, **122**: 3725–3731.

Parks S. E., Cusano D. A., Van Parijs S. M., Nowacek D. P. 2019a. Acoustic crypsis in communication by North Atlantic right whale mother-calf pairs on the calving grounds. *Biology Letters*, **15**: 20190485.

Parks S. E., Cusano D. A., Van Parijs S. M., Nowacek D. P. 2019b. North Atlantic right whale (*Eubalaena glacialis*) acoustic behavior on the calving grounds. *The Journal of the Acoustical Society of America*, **146**: EL15–EL21.

Parks S. E., Johnson M., Nowacek D., Tyack P. L. 2010. Individual right whales call louder in increased environmental noise. *Biology Letters*, **7**: 33–35.

Parks S. E., Searby A., Célérier A., Johnson M. P., Nowacek D. P., Tyack P. L. 2011. Sound production behavior of individual North Atlantic right whales: implications for passive acoustic monitoring. *Endangered Species Research*, **15**: 63–76.

Parks S., Conger L., Cusano D., Van Parijs S. 2014. Variation in the acoustic behavior of right whale mother-calf pairs. *Journal of the Acoustical Society of America*, **135**: 2240.

Pettis H. M., Pace III R. M., Hamilton P. K. 2023. North Atlantic right whale consortium 2022 annual report card. *Report to the North Atlantic Right Whale Consortium, November 2022*. https://www.narwc.org/uploads/1/1/6/6/116623219/2022reportcardfinal.pdf

Pirotta E., Schick R. S., Hamilton P. K., Harris C. M., Hewitt J., Knowlton A. R., Kraus S. D *et al.* 2023. Estimating the effects of stressors on the health, survival and reproduction of a critically endangered, long-lived species. *Oikos*, **2023**: e09801.

Pirotta E., Thomas L., Costa D. P., Hall A. J., Harris C. M., Harwood J., Kraus S. D *et al.* 2022. Understanding the combined effects of multiple stressors: a new perspective on a longstanding challenge. *Science of the Total Environment*, **821**: 153322.

Popper A. N., Carlson T. J., Hawkins A. D., Southall B. L., Gentry R. L. 2006. *Interim Criteria for Injury of Fish Exposed to Pile Driving Operations: A White Paper. Report to the Fisheries Hydroacoustic Working Group*. California Department of Transportation, Sacramento, CA. 15pp.

Popper A. N., Hice-Dunton L., Jenkins E., Higgs D. M., Krebs J., Mooney A., Rice A *et al.* 2022. Offshore wind energy development: research priorities for sound and vibration effects on fishes and aquatic invertebrates. *The Journal of the Acoustical Society of America*, **151**: 205–215.

Quintana-Rizzo E., Leiter S., Cole T., Hagbloom M., Knowlton A., Nagelkirk P., O'Brien O *et al.* 2021. Residency, demographics, and movement patterns of North Atlantic right whales *Eubalaena glacialis* in an offshore wind energy development area in southern New England, USA. *Endangered Species Research*, **45**: 251–268.

R Core Team 2022. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna.

Reed J., New L., Corkeron P., Harcourt R. 2022. Multi-event modeling of true reproductive states of individual female right whales provides new insights into their decline. *Frontiers in Marine Science*, **9**: 994481.

Root-Gutteridge H., Cusano D. A., Shiu Y., Nowacek D. P., Van Parijs S. M., Parks S. E. 2018. A lifetime of changing calls: North Atlantic right whales, *Eubalaena glacialis*, refine call production as they age. *Animal Behaviour*, **137**: 21–34.

Rountree R. A., Gilmore R. G., Goudey C. A., Hawkins A. D., Luczkovich J. J., Mann D. A. 2006. Listening to fish: applications of passive acoustics to fisheries science. *Fisheries*, **31**: 433–446.

Simard Y., Roy N., Giard S., Aulanier F. 2019. North Atlantic right whale shift to the Gulf of St. Lawrence in 2015, revealed by long-term passive acoustics. *Endangered Species Research*, **40**: 271–284.

Stone K. M., Leiter S. M., Kenney R. D., Wikgren B. C., Thompson J. L., Taylor J. K. D., Kraus S. D. 2017. Distribution and abundance of cetaceans in a wind energy development area offshore of Massachusetts and Rhode Island. *Journal of Coastal Conservation*, **21**: 527–543.

Thomisch K., Boebel O., Zitterbart D. P., Samaran F., Van Parijs S., Van Opzeeland I. 2015. Effects of subsampling of passive acoustic recordings on acoustic metrics. *Journal of the Acoustical Society of America*, **138**: 267–278.

Van Deurs M., Grome T. M., Kaspersen M., Jensen H., Stenberg C., Sørensen T. K., Støttrup J *et al.* 2012. Short- and long-term effects of an offshore wind farm on three species of sandeel and their sand habitat. *Marine Ecology Progress Series*, **458**: 169–180.

Van Parijs S. M., Baker K., Carduner J., Daly J., Davis G. E., Esch C., Guan S *et al.* 2021. NOAA and BOEM recommendations for use of passive acoustic listening systems in offshore wind energy development monitoring and mitigation programs. *Frontiers in Marine Science*, **8**: 760840.

Van Parijs S. M., Clark C. W., Sousa-lima R. S., Parks S. E., Rankin S., Risch D., Van Opzeeland I. C. 2009. Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales. *Marine Ecology Progress Series*, **395**: 21–36.

Van Parijs S. M., DeAngelis A. I., Aldrich T., Gordon R., Holdman A., McCordic J. A., Mouy X *et al.* 2023. Establishing baselines for predicting change in ambient sound metrics, marine mammal and vessel occurrence within an US offshore wind energy area. *ICES Journal of Marine Science*, **0**: 1–14. fsad148.

Handling editor: Simon Northridge