



Full length article

Monitoring the acoustic ecology of the shelf break of Georges Bank, Northwestern Atlantic Ocean: New approaches to visualizing complex acoustic data

Sarah G. Weiss^{a,*}, Danielle Cholewiak^a, Kaitlin E. Frasier^b, Jennifer S. Trickey^b, Simone Baumann-Pickering^b, John A. Hildebrand^b, Sofie M. Van Parijs^a

^a NOAA Northeast Fisheries Science Center, 166 Water Street, Woods Hole, MA 02543, USA

^b Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive MC 0205, La Jolla, CA 92037, USA



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ABSTRACT

Within a soundscape, anthropogenic sound often dominates frequency ranges used by various species, leading to signal overlap and potential communication masking. The acoustic niche hypothesis predicts species will avoid competition by vocalizing at unique bandwidths. To evaluate the extent of anthropogenic overlap, it's helpful to understand acoustic niches across time. This study aims to assess the co-occurrence of cetaceans and anthropogenic activities, presenting simple and accessible visualizations of the temporal and spectral overlap. Continuous passive acoustic recordings from 10 Hz to 100 kHz were collected near three deep-water canyons (Heezen, Oceanographer, and Nantucket) along the continental shelf break of Georges Bank between April 2015 and March 2016. Daily presence was documented for five mysticete species (North Atlantic right, fin, blue, sei, humpback), five odontocete species and/or groups combined according to primary frequency ranges (delphinids, sperm whales, *Kogia* spp., Sowerby's, and Cuviers'/True's/Gervais' beaked whales), and four anthropogenic activities (airgun noise, broadband ship noise, echosounders, and explosions). At each site, cetacean and anthropogenic sources were found to be significant contributors. Individual cetacean species/groups were present from 2% to 100% of days across sites, with delphinids, sperm whales, and fin whales detected most consistently. Airgun noise, the most frequently detected anthropogenic signal, ranged from 50% to 91% of days across all sites, followed by broadband ship noise (15–65% of days), echosounders (1–14% of days), and one explosion detected at Oceanographer Canyon. This approach allows for broad comparison of species and anthropogenic activity, providing understanding of variability in acoustic overlap and potential masking between sites.

1. Introduction

The underwater environment is acoustically rich. Produced from geophony (natural processes such as wind, rain, or waves), biophony (biological sources such as marine mammals, fish, or crustaceans), and anthrophony (human activity such as vessel noise or seismic survey exploration), a variety of sounds combine to create what is known as the soundscape [1]. Different sites and habitats are characterized by unique soundscapes, determined by the species, processes, and activities present within [2]. Therefore, soundscapes are site-specific and dynamic across both time and space.

Habitats with high biodiversity are often typified by rich acoustic activity and variation within the soundscape [3]. In some oceanic habitats, marine mammal sounds are an important biophonic component of a site's acoustic ecology. It is well understood that cetaceans utilize and produce sound as an important tool for communication, foraging, navigation, and predator-prey avoidance [4,5]. Mysticetes (baleen whales), emit low-frequency (primarily under 1000 Hz) calls and songs [6,7], which can propagate over large distances. Odontocetes, including dolphins, sperm whales, beaked whales and porpoises, produce higher frequency signals (up to ~130 kHz for some species), which can include echolocation clicks and/or tonal whistles. This reliance on a wide

* Correspondence to: Department of Biology, Syracuse University, 107 College Place, Syracuse, New York 13244, USA.
E-mail address: sarahgweiss2@gmail.com (S.G. Weiss).

¹ Present address: Department of Biology, Syracuse University, 114 Life Science Complex, Syracuse, NY 13244, USA.

variety of sounds by a diverse array of species in offshore ecosystems raises questions of how organisms coexist acoustically and whether they employ mechanisms for optimizing sharing acoustic space.

Characterizing a community's acoustic space as a finite resource, the acoustic niche hypothesis states that each biological sound source is expected to illustrate temporal and/or frequency partitioning in their vocalizations [8,9]. In order to be heard for communication, each source would occupy and utilize their own "puzzle-piece" acoustic niche [2,8,9]. The unique acoustic contribution from each niche would therefore be able to co-occur without conflict within the soundscape puzzle, as the partitioning of acoustic space relies on the basis of frequency and temporal patterns. Other factors, such as signal structure, may also influence, and contribute to acoustic niche formation [9].

However, the addition of other sound sources to the local environment may interfere with different acoustic niches. In particular, anthropogenic noise has grown to become a major contributor to the underwater soundscape over the last century [10]. Vessel noise, airgun noise produced during seismic surveys, explosions, and echosounders are among anthropogenic sources responsible for an increase in noise inputs to the marine soundscape. These anthropogenic sound contributions occur in, and often dominate, frequency ranges shared by many cetacean species, leading to a potential overlap of signals. In high traffic regions, noise from commercial shipping vessels significantly contributes to the marine soundscape below 200 Hz, directly overlapping with the frequency range of communication signals from many mysticetes [10]. Anthropogenic sounds have the potential to disrupt the established acoustic niches of the biophony and thus, change the dynamics of a

soundscape as a whole.

To evaluate the potential for overlap and the true impact of anthropogenic noise on cetaceans within a soundscape, it is necessary to have an understanding of acoustic niche partitioning across space and time [11]. While soundscape analysis is a growing field, to date much of this research has focused on a short time frame [12,13] and often only on particular species, such as reef fishes [14,15] or a subset of large whales [16]. However, the acoustic ecology of the soundscape as a whole, and the overall partitioning of community acoustic space within the soundscape, are not well understood. Critical to developing an understanding of long-term acoustic patterns is the need for simple visualizations of complex acoustic processes. It is only in this way that scientists and managers can begin to compare and interpret broad soundscape information across diverse locations and habitats.

The primary goal of this study is to create a visualization of the acoustic niches utilized by a variety of cetacean groups, concurrent with anthropogenic activities (e.g. [9]), using passive acoustic data collected at three sites along the continental shelf break of Georges Bank along the eastern United States. Located off the New England coast, this shallow underwater plateau forms the boundary between the Gulf of Maine and the Atlantic Ocean. The influence of the Northeast Channel and the Great South Channel, regional ocean circulation patterns, in addition to the topographical nature of the bank, create high levels of primary productivity, contributing to the presence of many species of fish and marine mammals [17,18]. This region is also utilized by a number of anthropogenic activities, particularly commercial fisheries and shipping [17,19]. Quantifying the acoustic overlap between these activities and

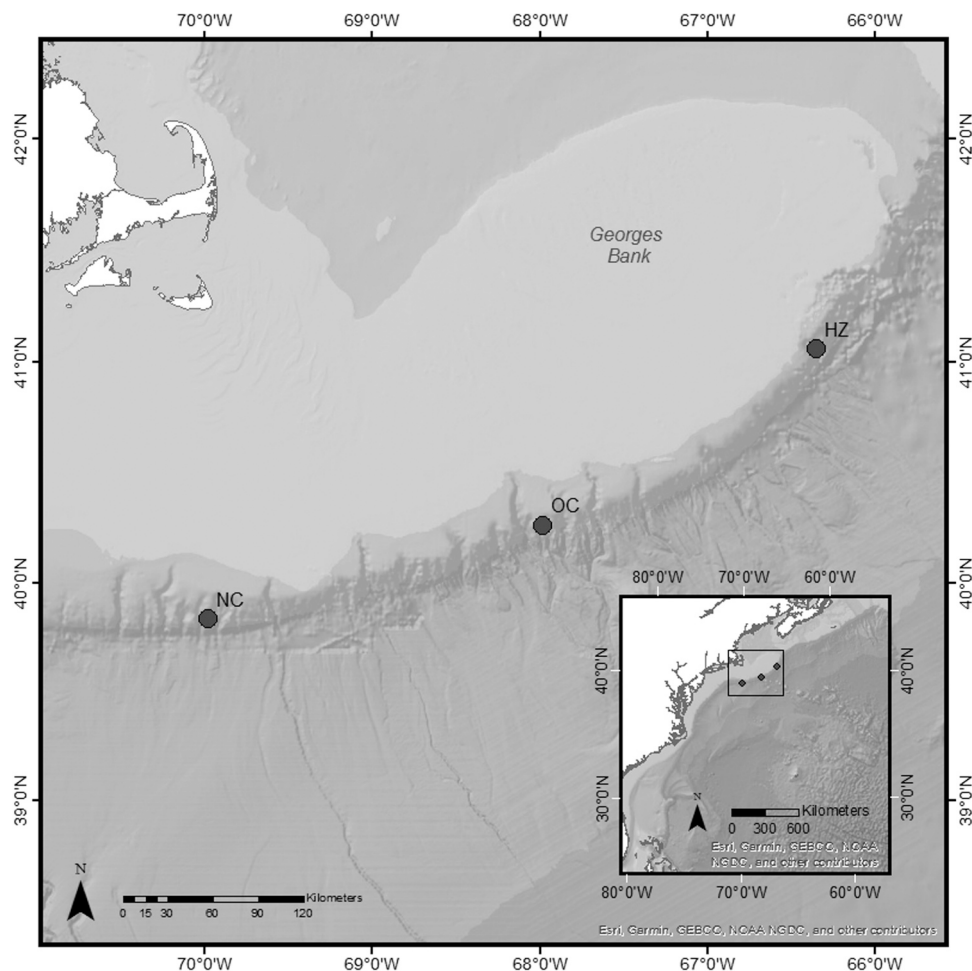


Fig. 1. A map of Georges Bank situated in the western North Atlantic Ocean (inset) and surrounding area with the locations of the three High Frequency Acoustic Recording Packages (HARPs) at Heezen Canyon (HZ), Oceanographer Canyon (OC), and Nantucket Canyon (NC).

marine mammal vocalizations can provide important information for understanding the potential impacts of anthropogenic noise on the marine environment.

2. Methods

2.1. Acoustic data collection

Continuous passive acoustic recordings were collected along the continental shelf break of the northeastern United States at three sites, named according to nearby canyon features. These include: Heezen Canyon, Oceanographer Canyon, and Nantucket Canyon (Fig. 1, Table 1). High-Frequency Acoustic Recording Packages (HARPs) [20], were deployed at depths of 800–1100 m, with the hydrophones suspended approximately 20 m above the seafloor. Recordings lasted from 27 June 2015–25 March 2016 at Heezen Canyon, 26 April 2015–9 February 2016 at Oceanographer Canyon, and from 27 April to 18 September 2015 at Nantucket Canyon (Table 1).

Each HARP was programmed to record continuously at a sampling rate of 200 kHz with 16-bit quantization, providing an effective recording bandwidth from 0.01 to 100 kHz. HARPs include a hydrophone comprised of two types of transducers: a low-frequency (< 25 kHz) stage utilizing Benthos AQ-1 transducers (frequency response – 187 dB re: 1 V/ μ Pa, \pm 1.5 dB, www.benthos.com), and a high-frequency stage (> 25 kHz) utilizing an ITC-1042 hydrophone (International Transducer Corporation, frequency response – 200 dB re: 1 V/ μ Pa, \pm 2 dB), connected to a custom built preamplifier board and bandpass filter [20].

2.2. Acoustic data analyses

Sound files were divided into three separate data sets to facilitate analyses based on the following frequency bands: (1) Low-frequency, 10–1000 Hz; (2) Mid-frequency, 10–5000 Hz; and (3) High-frequency, 1000–100,000 Hz. For the low-frequency band, the acoustic data were downsampled by a factor of 100 to create sound files with an effective sampling rate of 2 kHz. For the mid-frequency band, sound files were downsampled by a factor of 20 to create sound files with an effective sampling rate of 10 kHz.

2.2.1. Mysticete acoustic analysis

The low-frequency acoustic data sets for all three sites were analyzed for presence of five mysticete species: blue (*Balaenoptera musculus*), fin (*Balaenoptera physalus*), humpback (*Megaptera novaeangliae*), North Atlantic right (NARW) (*Eubalaena glacialis*), and sei whales (*Balaenoptera borealis*).

An automated detector, the Low-Frequency Detection and Classification System (LFDCS) [21], was used to identify and distinguish species-specific vocalizations. LFDCS creates a conditioned spectrogram (short-time Fourier transform of 512 samples, 75% overlap, 64 ms time step, 3.9 Hz frequency resolution) and creates contour lines to draw “pitch tracks” through tonal sounds [22]. These pitch tracks are then classified into call types using multivariate discriminant analysis, based on a user-developed call library. Our call library included the following species-specific vocalizations obtained from acoustic data collected in

our region: blue whales (AB song units, $n = 357$), fin whales (20-Hz units, $n = 171$), humpback whales (song units and non-song calls from 2009 to 2017, $n = 1188$), NARW (up-calls, $n = 761$), and sei whales (downsweeps, $n = 217$) [23–30].

The LFDCS outputs were manually reviewed by a trained analyst. Species presence was determined on a daily scale, in which a species was considered “present” on a given day if the number of verified true pitch-tracked detections met or exceeded minimum criteria established for each species. The following criteria were used to conservatively and confidently establish presence for each individual species: for blue whales, one verified detection within a series of at least three A, B, or AB song units; humpback whales, one verified detection within a series of at least three humpback whale vocalizations (song or social sounds); North Atlantic right whales, three verified up-call detections (following [22]); sei whales, one verified doublet or triplet downsweep. For fin whales, a multistep process was used to determine the probability of presence without manual verification of the entire dataset (due to the high number of detections). First, manual verification of fin whale presence on an hourly level was completed for a subsample of the dataset ($n = 216$ h). Second, a logistic regression curve was fitted to the results of the manually-verified data, to determine the number of detections per hour needed to achieve 90% probability of fin whale presence [21]. The LFDCS detections were then summed by hourly bins, and all hours with 29 or more detections were manually reviewed. Fin, humpback, North Atlantic right, and sei whale detections with a Mahalanobis distance (MD) less than or equal to 3.0 were included in the manual verification of daily presence, while blue whale detections with a MD less than or equal to 5.0 were included [21,22].

2.2.2. Odontocete acoustic analysis

The high-frequency acoustic data sets were analyzed for the presence of echolocation clicks from 20 potential odontocete species. These include six beaked whale species: Blainville’s beaked whales (*Mesoplodon densirostris*), Cuvier’s beaked whale (*Ziphius cavirostris*), Gervais’/True’s beaked whale (*Mesoplodon europaeus*/*Mesoplodon mirus* respectively), Northern bottlenose whales (*Hyperoodon ampullatus*), and Sowerby’s beaked whale (*Mesoplodon bidens*), as well as sperm whales (*Physeter macrocephalus*) and *Kogia* spp. At least 12 delphinid species may also occur in the region, including: Atlantic spotted dolphins (*Stenella frontalis*), Atlantic white-sided dolphins (*Lagenorhynchus acutus*), bottlenose dolphins (*Tursiops truncatus*), Clymene dolphins (*Stenella clymene*), Risso’s dolphins (*Grampus griseus*), rough-toothed dolphins (*Steno brendanensis*), short-beaked common dolphins (*Delphinus delphis*), striped dolphins (*Stenella coeruleoalba*), false killer whales (*Pseudorca crassidens*), killer whales (*Orcinus orca*), long-finned pilot whales (*Globicephala melas*), and short-finned pilot whales (*Globicephala macrohynchus*). However, it is not yet possible to reliably differentiate between all delphinid species based on acoustic characteristics. Therefore, for the purpose of this study, delphinids were treated as a single group and were not differentiated by species.

The acoustic presence of each species was determined using a combination of manual review and automated detectors. Using the custom software program Triton [20], executed in MATLAB (Mathworks, Natick, MA), long-term spectral averages (LTSAs) were calculated with a time average of 5 s and a frequency average of 100 Hz, and were

Table 1

HARP deployment sites, recording dates and recording durations. All HARPs recorded continuously at a sampling rate of 200 kHz. The first and last day of each deployment represent partial recording days.

Site	Location	Recorder depth (m)	Recording start date	Recording end date	Recording duration (Days)	Recording duration (Hours)
Heezen Canyon (HZ)	41.062, -66.352	845	06/27/2015	03/25/2016	273	6511
Oceanographer Canyon (OC)	40.263, -67.986	1100	04/26/2015	02/09/2016	290	6941
Nantucket Canyon (NC)	39.832, -69.982	977	04/27/2015	09/18/2015	145	3473

manually reviewed for echolocation clicks by trained analysts. As described below, species-specific spectral and temporal characteristics of echolocation clicks were used to determine call type classification and determine presence on a daily scale.

Echolocation clicks were analyzed using a two-stage automated detector, in which a Teager Kaiser energy detector was used to detect the presence of all echolocation clicks [31–33]. Recordings were then analyzed in 75-second segments; those segments containing 7 or more detections were further considered according to predefined criteria in a trained system to differentiate putative beaked whale detections from delphinids based on the presence of frequency-modulated upsweep pulses [34]. Subsequently an analyst decided upon species labels for beaked whale detections based on known characteristics of their echolocation clicks [35–37]. Detections were classified to species except in the case of Gervais' and True's beaked whales, where overlap in the frequency characteristics of their echolocation clicks currently precludes definitive differentiation between the two species in the absence of visual data [38].

The acoustic presence of sperm whales was determined by a trained analyst's manual verification of the LTSA, based on known species-specific characteristic frequency and temporal attributes [39,40] (Table 2). In this analysis, presence of sperm whale echolocation signals was determined.

The presence of dwarf and pygmy sperm whales (*Kogia sima* & *K. breviceps*) was determined using an automated detector to identify clicks with energy between 70 and 100 kHz but not below (to differentiate them from delphinids). All detected click bouts were manually reviewed and classified based on spectral characteristics. Although *Kogia* spp. echolocation clicks have peak frequencies around 125–130 kHz [41,42], energy from their clicks is evident in HARP data below 100 kHz, likely due to either a low-frequency tail in the click spectra or from aliasing above the Nyquist frequency of 100 kHz [43,44].

Delphinid echolocation click occurrence was determined using an automated energy detector with a minimum received level threshold of 120 dB_{pp} re: 1 µPa [31,45]. The detector output, LTSAs, and mean spectra were manually reviewed by a trained analyst. Detections were divided into successive 5-min windows to determine and automatically identify the dominant click type(s). Recurrent types of clicks were identified by an automated clustering algorithm, which distinguished spectral features and inter-click intervals across an aggregated subset of these 5-min windows across all three sites. Templates were then created from the identified recurrent click types and attributed to a known species or assigned a click type number. While multiple click types were identified, for the purposes of this manuscript they are not differentiated

Table 2

Representative frequency ranges chosen for display of each species' call type(s) or anthropogenic sound source. These frequency ranges were used to construct the spectrographic box displays (SBDs), and are not necessarily intended to represent the full bandwidth that would characterize each of these signal categories, and in some cases are constrained to facilitate the visual display.

Species/Sound source	Frequency range (Hz)
Blue whale	15–20
Fin whale	18–24
Humpback whale	50–2000
North Atlantic right whale	80–300
Sei whale	30–82
Sperm whale	1000–20,000
Delphinid spp.	15,000–50,000
Cuvier's/Gervais'/True's beaked whales	18,000–50,000
Sowerby's beaked whale	60,000–77,000
Pygmy and dwarf sperm whales (<i>Kogia</i> spp.)	120,000–140,000
Airguns	10–200
Broadband ships	20–1000
Explosions	10–1000
Low-frequency echosounders	12,000–19,999
Mid-frequency echosounders	20,000–49,999
High-frequency echosounders	50,000–100,000

but instead are treated as one delphinid category. Based on these analyses, the majority of the delphinid click types in these datasets had peak frequencies between 20 and 40 kHz, so a slightly broader range of 15–50 kHz was applied to be more inclusive for the acoustic niche visualizations.

2.2.3. Anthropogenic acoustic analysis

The HARP data were examined for the presence of four types of anthropogenic signals: broadband ship sounds, airguns, explosions, and echosounders. The mid-frequency dataset was examined for the presence of the first three signal types; the high-frequency dataset was examined for the presence of echosounders. As with the analyses of cetacean signals, analyses of anthropogenic noise incorporated a combination of automated detectors and manual review, using Triton software (Version 1.93) executed in MATLAB (R2014b; MathWorks, Inc., Natick, MA). The beginning and end of each acoustic event was estimated; if any given activity was detected on a day, then the activity was considered “present” for the daily presence analysis.

Broadband ship sound is typically detectable when a ship travels within a few kilometers of an acoustic recording device. These acoustic events may last from several minutes up to several hours, depending on the size of the vessel, distance to the recorder, and sound propagation conditions. Vessel occurrence was manually detected by a trained analyst reviewing LTSAs in 3 h time bins, looking for characteristic frequency-range dependent interference patterns that are associated with ship noise [46] (Table 2).

Airguns are used regularly in seismic exploration, lasting from several hours to days, with most energy between 10 Hz and 200 Hz [47]. The presence of airguns was automatically determined using a matched filter detector, where the timeseries was filtered with a 10th order Butterworth bandpass filter between 25 and 200 Hz. A trained analyst manually verified the airgun detections based on interpulse intervals.

The presence of explosive sounds from sources such as military explosions, sub-seafloor exploration, and fishing industry seal bombs was detected in the acoustic data by a similar automatic matched filter detector with a timeseries filtered with a 10th order Butterworth bandpass filter between 200 and 2000 Hz. A trained analyst manually verified these detections for the presence of explosions.

Echosounders are used for a variety of purposes, including navigation, seafloor mapping, and detection of fish schools. The acoustic presence of echosounders was determined by a trained analyst manually scanning the LTSA plots in 1-h time bins (Table 2). All echosounder events were then reviewed by a second trained analyst to determine the peak frequency(s) of each detected event. If multiple frequencies were observed in a single event, each peak frequency was treated independently and included in the analysis. Echosounder detections were divided into three frequency bands (Table 2).

2.2.4. Data summary and visualization

Acoustic signals were grouped into 14 categories according to primary frequency bands, which include five mysticete and five odontocete categories, as well as four anthropogenic signals (Table 2). This was considered a reasonable number of categories to generally capture the broad frequency range and number of species encompassed in these large datasets, without overwhelming the visual display. Therefore, in several cases species were combined into groups for ease of visual display. For example, delphinids were combined into one category, though they represent multiple species and a broad range of primary frequency distributions. Similarly, Cuvier's, Gervais' and True's beaked whales were combined into one category, as the echolocation clicks of all three species share peak frequencies in a similar range. These species groups could certainly be separated out for more detailed analyses as needed. Additionally, for the purposes of these visualizations, the chosen frequency bands were not necessarily intended to represent the entire frequency range for each of the species groups, but instead to represent the band that captured the majority of their acoustic energy,

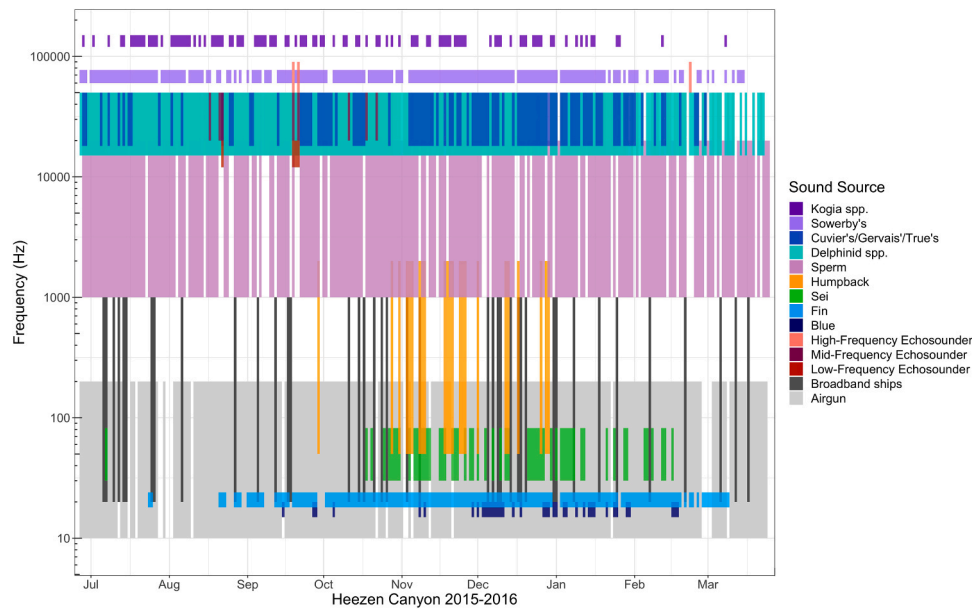


Fig. 2. Spectrographic Box Display for Heezen Canyon. The frequency range and time period is designated by a separate color for each acoustically active species or sound source, highlighting the acoustic niches utilized by a variety of cetacean groups concurrent with anthropogenic activities. Over the 10-month deployment, airgun noise, *Delphinid* spp., sperm whales, fin whales, and Sowerby's beaked whales were the most frequently detected sound sources.

while still allowing for visual discrimination between species groups in the graphics. Northern bottlenose whales and Blainville's beaked whales were never detected in our datasets, so they are not included in the frequency delineations.

For each signal type, the overall frequency range and daily occurrence of that signal were graphed with spectrographic box displays (SBDs) [9]. Data visualizations were created using the software package R (version 3.5.1) and the library *tidyverse*. These "acoustic niche" displays were created for each site on a daily presence scale, over the entire recording period for that site, allowing for visualization of the temporal and spectral overlap between different biological species groups and anthropogenic activities.

3. Results

The HARP deployments at Heezen Canyon (HZ) and Oceanographer Canyon (OC), lasted for approximately 10 months, the former from June

27, 2015 to March 25, 2016 ($n = 273$ days) and the latter from April 26, 2015 to February 9, 2016 ($n = 290$ days) (Table 1). The deployment at Nantucket Canyon (NC) lasted for 5 months, from April 27, 2015 to September 18, 2015 (Table 1). The reduced recording period for this deployment resulted from a hardware issue impacting the available data storage on the HARP.

3.1. Heezen Canyon

At the eastern most site, HZ, four mysticete species were acoustically detected (Fig. 2). Blue whales were present across 6 months from September to February, on a total of 14.3% ($n = 39$) of days across the entire recording period (Table 3). Fin whales were much more commonly detected, on 67.0% ($n = 183$) of days throughout the recording period. In contrast, humpback whale presence was shorter, being detected over 3 months from September to December, on 8.4% ($n = 23$) of days across the entire recording period. Sei whale detections

Table 3

Acoustic presence of each species and anthropogenic sound source at all three sites. Percent of days present at each site, with number of days present in parentheses.

	Heezen Canyon ($n = 273$ days)	Oceanographer Canyon ($n = 290$ days)	Nantucket Canyon ($n = 145$ days)
Blue whale	14.3% (39)	4.5% (13)	0.0% (0)
Fin whale	67% (183)	45.9% (133)	17.9% (26)
Humpback whale	8.4% (23)	8.6% (25)	14.5% (21)
North Atlantic right whale	0.0% (0)	3.4% (10)	2.1% (3)
Sei whale	21.6% (59)	24.1% (70)	11.0% (16)
Cuvier's/Gervais'/True's beaked whales	40.3% (110)	4.0% (11)	27.6% (34)
Sowerby's beaked whale	80.2% (211)	12.9% (36)	12.2% (15)
Sperm whale	81.3% (222)	80.3% (232)	72.4% (105)
<i>Kogia</i> spp.	38.5% (105)	14.5% (42)	40.1% (59)
<i>Delphinid</i> spp.	94.5% (258)	100.0% (290)	100.0% (145)
Broadband ships	14.7% (40)	65.1% (188)	48.6% (70)
Airguns	91.2% (249)	73.7% (213)	50.3% (73)
Explosions	0.0% (0)	0.3% (1)	0.0% (0)
Low-frequency echosounders	1.5% (4)	4.1% (12)	1.4% (2)
Mid-frequency echosounders	2.9% (8)	13.8% (40)	6.2% (9)
High-frequency echosounders	1.1% (3)	11.0% (32)	3.4% (5)

were present primarily across 4 months from October through February, on 21.6% ($n = 59$) of days throughout the recording period. North Atlantic right whales were not acoustically detected at this site.

The presence of all five odontocete categories were detected based on their echolocation clicks: Cuvier's/Gervais'/True's beaked whale, Sowerby's beaked whale, sperm whales, *Kogia* spp., and Delphinid species (Fig. 2). Beaked whale detections were present across all seasons in the deployment, with Cuvier's/Gervais'/True's species detected on 40.3% ($n = 110$) of all recording days and Sowerby's detected nearly ubiquitously, occurring on 80.2% ($n = 211$) of all recording days (Table 3). Sperm whales and delphinids were also nearly ubiquitous across the recording period, detected on 81.3% ($n = 222$), and 94.5% of days ($n = 258$), respectively. *Kogia* spp. were detected on 38.5% ($n = 105$) of days, distributed across all months of the recording period.

Three sources of anthropogenic sounds were detected at this site throughout the deployment (Fig. 2). Airgun signals were nearly ubiquitous, detected throughout all months on 91.2% ($n = 249$) of days (Table 3). Broadband ship activity was present intermittently across all months, detected on 14.7% of days ($n = 40$). Echosounder presence was sparse across frequencies, with low-frequency echosounders detected in August and September on only 1.5% ($n = 4$) of days, mid-frequency echosounders detected across 3 months from August to October on 2.9% ($n = 8$) of days, and high-frequency echosounders detected only in September and February, on 1.1% ($n = 3$) of days. Underwater explosions were not detected at this site.

When considering the overlap between cetaceans and anthropogenic noise, the most frequent source of overlap at the daily level was from airguns, which co-occurred with the presence of mysticetes more than 85% of the time at this site. Airguns were acoustically detectable on 97.4% of days ($n = 38$) when blue whales were acoustically present, on 92.3% of days ($n = 169$) when fin whales were acoustically present, on 87.0% of days ($n = 20$) when humpback whales were acoustically present, and on 96.6% of days ($n = 57$) when sei whales were acoustically present. Broadband ship noise co-occurred with mysticete presence less often overall, with broadband ships detected on 23.1% ($n = 9$) of days when blue whales were acoustically present, on 14.8% ($n = 27$) of days when fin whales were acoustically present, on 13.0% ($n = 3$) of days when humpback whales were acoustically present, and on 10.2% ($n = 6$) of days when sei whales were acoustically present.

At HZ, overlap in daily occurrence between echosounders and four odontocete species or species groups was observed on few days. Low-frequency and mid-frequency echosounders were each detected on 0.9% ($n = 1$) of days when Cuvier's/Gervais'/True's beaked whales were present, and on 1.5% ($n = 4$) and 3.1% ($n = 8$) of days, respectively, when delphinids were present. Finally, overlap between low-frequency echosounders and sperm whales was found to occur on 0.5% ($n = 1$) of days with detected sperm whale presence. Of the 3 days where high-frequency echosounders were detected, overlap occurred on 0.5% ($n = 1$) of days with detected Sowerby's presence.

3.2. Oceanographer Canyon

At OC, all five mysticete species were acoustically detected (Fig. 3). Blue whales were acoustically detected over 3 months from December to February, on a total of 4.5% ($n = 13$) of days throughout the recording period (Table 3). Fin whales were detected on 45.9% ($n = 133$) of days, primarily from August to February. Humpback whale presence was detected on 8.6% ($n = 25$) of days with most detections occurring over a 3-month period from April to June, with sporadic presence detected in August and from November to January. North Atlantic right whales were detected over 3 months from May to July, on 3.4% ($n = 10$) of days throughout the recording period. Sei whale detections were present over 3 months from April to June and across a 4-month period from September to February on 24.1% ($n = 70$) of days throughout the recording period.

Similar to HZ, the presence of all five odontocete categories were detected from echolocation clicks (Fig. 3). Overall, beaked whale detections were sparse, with Cuvier's/Gervais'/True's species detected on only 4.0% ($n = 11$) of days throughout the recording period, peaking in September and occurring across six additional months in May, July, October, and December through February. Sowerby's beaked whales were detected across 9 months from May to August and October to February on 12.9% ($n = 36$) of days throughout the recording period (Table 3). Peak detections of Sowerby's occurred during the summer season. In contrast, sperm whales were nearly ubiquitous across the recording period, detected on over 80.3% ($n = 232$) of days, and delphinids were present on every day throughout the recording period ($n = 290$). *Kogia* spp. were detected on 14.5% ($n = 42$) of days across

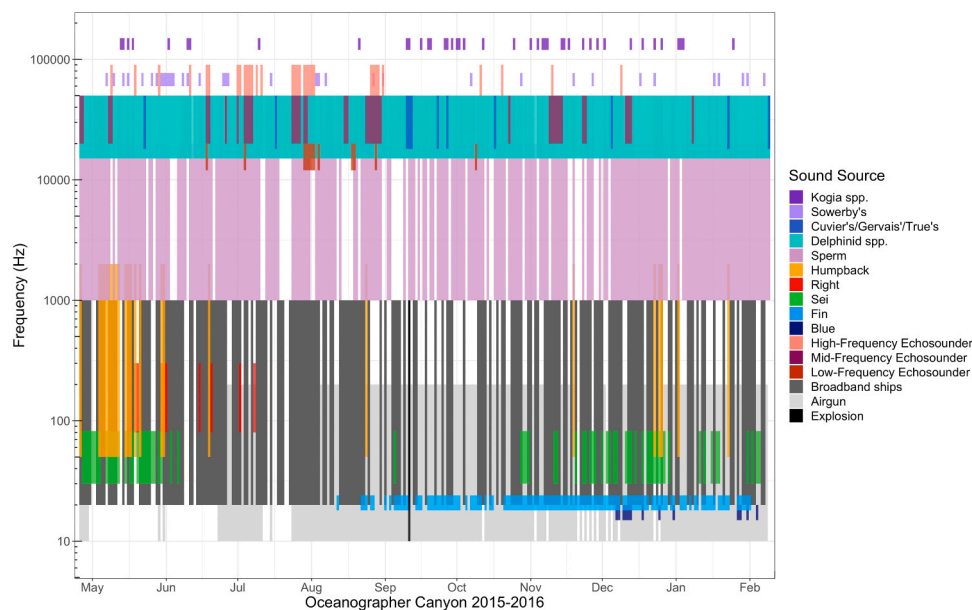


Fig. 3. Spectrographic Box Display for Oceanographer Canyon. The frequency range and time period is designated by a separate color for each acoustically active species or sound source, highlighting the acoustic niches utilized by a variety of cetacean groups concurrent with anthropogenic activities. Over the 5-month deployment, airgun noise, broadband ship noise, *Delphinid* spp., sperm whales, and *Kogia* spp., were the most frequently detected sound sources.

the recording period from May to January.

Four sources of anthropogenic sounds were detected at this site throughout the recording period (Fig. 3). Broadband ship activity was present across all months, detected on 65.1% ($n = 188$) of days throughout the recording period (Table 3). Airgun presence was detected across all months, on 73.7% ($n = 213$) of days throughout the recording period. Low, mid, and high-frequency echosounders were detected intermittently throughout the recording period, on 4.1% ($n = 12$), 13.8% ($n = 40$), and 11.0% ($n = 32$) of days respectively. Mid-frequency echosounders were observed most frequently, detected across 9 months from April to August and October to January. One explosion was detected at this site in September.

At OC, two sources of anthropogenic sound (broadband ship noise and airguns) were found to overlap with five species of mysticetes (blue, fin, humpback, NARW, and sei whales). Similar to HZ, airgun noise was the most frequently detected anthropogenic signal and source of overlap across species. Airguns were acoustically detected on 84.6% ($n = 11$) of days when blue whales were acoustically present, 91.0% ($n = 121$) of days when fin whales were acoustically present, 28.0% ($n = 7$) of days when humpback whales were acoustically present, on 30.0% ($n = 3$) of days when NARW were acoustically present, and 57.1% ($n = 40$) of days when sei whales were acoustically present. Broadband ship noise was also found to co-occur with mysticete presence with broadband ships detected on 53.8% ($n = 7$) of days when blue whales were acoustically present, 57.1% ($n = 76$) of days when fin whales were acoustically present, 60.0% ($n = 15$) of days when humpback whales were acoustically present, 60% ($n = 6$) of days when NARW were acoustically present, and 67.1% ($n = 70$) of days when sei whales were acoustically present. In addition, the single explosion detected in September occurred on a day when fin whales were present.

At OC, overlap between three odontocete species or species groups and echosounders was also observed. Low-frequency echosounders were detected on 4.1% ($n = 12$) when *Delphinid* spp. were acoustically present, and on 3.9% ($n = 9$) of days when sperm whales were acoustically present. Additionally, mid-frequency echosounders were detected on 13.8% ($n = 40$) of days when *Delphinid* spp. were acoustically present. Overlap with high-frequency echosounders was found to only occur with Sowerby's, on 5.6% ($n = 2$) days when Sowerby's were acoustically present.

3.3. Nantucket Canyon

Four baleen whale species were acoustically detected at NC during the 5-month recording period (Fig. 4). Fin whale detections occurred primarily from July to September on 17.9% ($n = 26$) of days throughout the recording period. Humpback whales were detected over 3 months from April to June, on 14.5% ($n = 21$) of days throughout the recording period. North Atlantic right whale presence was sparse, only detected in May, on a total of 2.1% ($n = 3$) of days throughout the recording period. Sei whale detections were also present from April to June, on 11.0% ($n = 16$) of days throughout the recording period. Blue whales were not acoustically detected at this site.

The presence of all five odontocete categories was detected from echolocation clicks (Fig. 4). Beaked whale detections from Cuvier's/Gervais'/True's species were present across nearly all months over the recording period, detected on 27.6% ($n = 34$) of days throughout the recording period (Table 3). Sowerby's presence was detected intermittently, on 12.2% ($n = 15$) of days throughout the recording period. Sperm whales were nearly ubiquitous across the recording period, detected on 72.4% ($n = 105$) of days throughout the recording period. *Delphinid* spp. were present on every day throughout the recording period ($n = 145$). *Kogia* spp. were detected on 40.1% ($n = 59$) of days throughout the recording period.

Three sources of anthropogenic sounds were detected at this site throughout the recording period (Fig. 4). Broadband ship activity was present across all months, detected on 48.6% ($n = 70$) of days throughout the recording period (Table 3). Airgun presence was detected across 3 months from July through September, present on 50.3% ($n = 73$) of days throughout the recording period. In comparison, echosounder presence was sparse, with low-frequency echosounders detected on only 1.4% ($n = 2$) of days, mid-frequency echosounders detected on 5.5% ($n = 8$) of days, and high-frequency echosounders detected on 3.4% ($n = 5$) of days throughout the recording period. There was no detected presence of explosions at this site.

Broadband ships and/or airguns were found to overlap with all four species of mysticetes detected at this site. The greatest percentage of overlap was found to occur between fin whales and airgun noise, as airgun noise was detected on 84.6% ($n = 22$) of days when fin whales were acoustically present. Additionally, airgun noise was detected on 9.5% ($n = 2$) of days when humpback whales were acoustically present and on 12.5% ($n = 2$) of days when sei whales were acoustically present. Airguns were not detected on the three days that NARW were present.

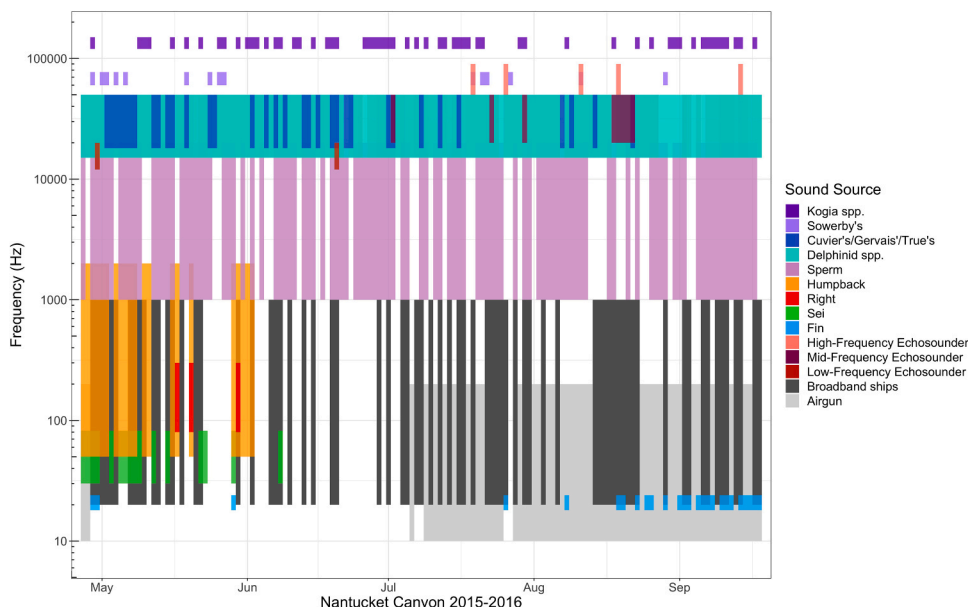


Fig. 4. Spectrographic Box Display for Nantucket Canyon. The frequency range and time period is designated by a separate color for each acoustically active species or sound source, highlighting the acoustic niches utilized by a variety of cetacean groups concurrent with anthropogenic activities. Over the 10-month deployment, broadband ship noise, airgun noise, *Delphinid* spp., sperm whales, and fin whales, were the most frequently detected sound sources. This site showed a marked decrease in the presence of Sowerby's and Cuvier's/Gervais'/True's beaked whales, as well as *Kogia* spp.

Broadband ship noise similarly served as a common source of overlap with mysticete species, occurring on 61.5% ($n = 16$) of days when fin whales were acoustically present, 52.4% ($n = 11$) of days when humpback whales were acoustically present, 33.3% ($n = 1$) of days when NARW were acoustically present, and 62.5% ($n = 10$) of days when sei whales were acoustically present.

In addition, overlap between four odontocete species or species group and echosounders was also observed at NC. Low-frequency echosounders were found to occur on 2.9% ($n = 1$) of days when Cuvier's/Gervais'/True's species were acoustically present, 1.4% ($n = 2$) of days when *Delphinid* spp. were acoustically present, and on 1.9% ($n = 2$) of days when sperm whales were acoustically present. Similarly, mid-frequency echosounders were detected on 5.9% ($n = 2$) of days when Cuvier's/Gervais'/True's species were acoustically present, and on 6.2% ($n = 9$) of days when *Delphinid* spp. were acoustically present. High-frequency echosounders occurred on 13.3% ($n = 2$) of days when Sowerby's were acoustically present.

4. Discussion

Within this simple and accessible visualization technique, examining the soundscape as a whole highlights areas with regard to space, time, and frequency in which sound sources may overlap with one another. In this study, all three sites played host to numerous biological and anthropogenic sources of sound. Across all sites, the most common biological vocalizations recorded were *Delphinid* spp., sperm whales, and fin whales. Dolphins and sperm whales were found to be acoustically present most consistently across all months. Although there is sparse information on the seasonal distribution of delphinid species at these sites, these results are similar to those reported for this region on sperm whales [48]. Other mysticete species, including fin whales, humpback whales and NARW, demonstrated seasonal patterns of acoustic presence, reflecting the migratory nature of each of these species [22,49,50]. In contrast, the presence of beaked whales and *Kogia* spp. did not exhibit clear seasonality. The presence of these species groups varied greatly between canyon sites, with OC showing lower presence of all beaked whales as well as *Kogia* spp., compared to both HZ and NC. For OC, the relative level of daily presence of Sowerby's beaked whale is consistent with the only other passive acoustic study examining year-round beaked whale occurrence on Georges Bank [51], although the detections of Cuvier's, Gervais' and True's beaked whales was lower in our present study. As the acoustic signals from these species are detected over relatively short distances (few hundred meters to few km), variation in detected acoustic activity may reflect fine-scale differences in recorder placement relative to preferred habitat, rather than broader regional patterns. In addition, detectability may differ between sites which could affect detected levels of presence for each species.

In the case of anthropogenic sources of sound, broadband ship noise and airguns were commonly detected across all sites. Broadband ship noise was detected most often at OC, with vessels present in all months throughout the recording period. Modeled outputs of "chronic" anthropogenic sources of underwater noise, specifically from large commercial and passenger vessels, predict relatively high levels of noise at depths of 500–1000 m across this region (see https://cetsound.noaa.gov/sound_data- Cape Cod Chronic).

Airgun presence was found to be ubiquitous across all sites. Airgun blasts, used for both commercial and research seismic surveys, may occur every 10–20 s repetitively for days to weeks at a time [47]. In the current study, airgun noise appeared at the beginning of July and continued to the end of each recording period, which for HZ was a total of ~9 months of activity. In fact, at HZ, airguns were present on over 85% of the days that four mysticete species were also present. This pervasiveness in presence leads airguns to act as a primary contributor to the soundscape's low-frequency range of noise [47]. Although no known seismic activity was conducted on Georges Bank, seismic exploration off of Canadian waters, southern US, or the mid-Atlantic

ridge could have contributed to these results. Airgun noise travels large distances and it is important to remember that the contribution at each site may be composed of seismic activities throughout the Atlantic Ocean. Therefore, the daily airgun presence includes both activities happening nearby and at distance.

In the higher frequency ranges, echosounders were detected on 1–14% of days, depending on site. While the co-occurrence of echosounders on days in which odontocetes were present was relatively low overall, the detection of these higher frequency signals which have more limited propagation distances could indicate relatively close spatial overlap between broadband ship activity and odontocete groups. While little work has been done to evaluate the impact of echosounders on cetaceans, a recent study found that beaked whales detect and respond behaviorally to the presence of shipboard echosounders, potentially moving away from the ship or suspending foraging activity [52]. Echosounders have also been found to affect pilot whale behavior [53].

The growing presence of anthropogenic sources alters the spectral, temporal, and spatial properties of sound levels within a soundscape [54]. The overlap between these various anthropogenic activities and cetaceans has the potential to affect the behavior and/or to mask the communication signals of numerous species for significant periods of time. Anthropogenic noise has been shown to significantly reduce the area over which an animal can communicate [6,54,55]. A study performed in the Hauraki Gulf, New Zealand, found that noise produced from transit vessels reduced the communication space for Bryde's whales by as much as 87.4% [11]. Comparably, studies off the north-western Atlantic found that North Atlantic right whales lost 63–67% of their communication space as a result of masking from large commercial vessels [56], while fin, humpback, and minke whales lost 80% or more of their communication space [55]. Increasing levels of competing background noise can affect the animal's ability to survive and complete major life-functions, including reproduction, navigation, and foraging [56,57]. As a result, cetaceans have to compete for acoustic space in which to be heard. In order to effectively convey and transmit species-specific information, confusion resulting from the presence of other conflicting signals must be reduced [58].

As such, species across a wide range of taxa have been found to compensate for this potential masking by adapting parameters of their vocalizations, such as the frequency, timing, duration, or amplitude of their calls [59–63]. Since these species rely heavily on acoustic signals for major life functions, such acoustic and behavioral changes can be energetically detrimental and costly for cetaceans on both short and long-term scales [6,64,65]. The extent and implications of overlap and potential auditory masking are largely species-specific. Therefore, this visualization tool proves crucial in identifying those direct areas of overlap between sound sources, highlighting critical areas to focus on and evaluate in further species-specific studies.

It is important to remember that daily presence of a given call type was used as a metric for determining species presence at all sites. This is a crude metric for looking at species presence since the activity level can vary greatly across a day from constantly present to only present during 1 h. However, daily presence is a standard methodology for quantifying broad species presence across large time frames and areas and provides a useful insight into species composition at different sites [22]. In addition, using acoustics as an indication of presence presumes that species are vocal when in the area, however, it is understood that not all species are vocally active at all times and that this activity can vary depending on their behavior [66].

The present study aimed to expand on a new visualization approach introduced by Van Opzeeland and Boebel [9] to demonstrate how this approach can improve access to complex acoustic information derived from soundscape analyses as a whole, allowing for broad comparison of species and anthropogenic activity composition. By understanding how different biological species and human sources of sound utilize different acoustic niches within a soundscape, one can better understand the

extent of the temporal and spectral overlap in these site-specific acoustic niches, and the potential for communication masking. Quantifying the acoustic overlap provides improved understanding of the potential impacts and pervasiveness of anthropogenic noise on the marine environment. As such, this visualization technique contributes to our understanding of ecology and the soundscape, influenced by the resident, seasonal, or occasional-nature of each sound source and the interactions between those sources. Its accessibility will allow for improved interpretation of the scientific data in both management and science fora.

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CRediT authorship contribution statement

SGW: Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **DC:** Conceptualization, Visualization, Supervision, Writing - review & editing. **KEF:** Formal analysis, Writing - review & editing. **JST:** Formal analysis. **SBP:** Formal analysis, Writing - review & editing. **JAH:** Formal analysis, Funding acquisition. **SMVP:** Conceptualization, Supervision, Writing - review & editing, Project administration, Funding acquisition.

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Declarations of interest

None.

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