Vol. 47: 265–289, 2022
https://doi.org/10.3354/esr01176

ENDANGERED SPECIES RESEARCH
Endang Species Res

Published April 21

Acoustic occurrence of baleen whales, particularly blue, fin, and humpback whales, off eastern Canada, 2015–2017

Julien J.-Y. Delarue[1,*], Hilary Moors-Murphy[2], Katie A. Kowarski[1], Genevieve E. Davis[3], Ildar R. Urazghildiiev[1], S. Bruce Martin[1]

[1]JASCO Applied Sciences (Canada) Ltd., Halifax, NS B3B 1Z1, Canada
[2]Fisheries and Oceans Canada (Maritimes Region), Bedford Institute of Oceanography, Dartmouth, NS B2Y 4A2, Canada
[3]Northeast Fisheries Science Center, National Oceanic and Atmospheric Administration, Woods Hole, MA 02543-1026, USA

ABSTRACT: Six baleen whale species occur off eastern Canada, but little is known of their year-round occurrence across this large region. This complicates identifying areas that are important to them and may require critical habitat designation, especially for those species considered at risk. This is particularly true between fall and spring because of a lack of visual survey effort. The main objective of this paper is to provide a year-round and pluriannual description of the minimum acoustic occurrence of baleen whales, particularly blue *Balaenoptera musculus*, fin *B. physalus*, and humpback whales *Megaptera novaeangliae*. We deployed 25 acoustic recorders off eastern Canada between May 2015 and November 2017, and the data were analyzed using a combination of automated detectors and manual validation to identify vocalizations produced by these species. Blue, fin, and humpback whales occurred off eastern Canada year-round, a finding which contrasts the traditional seasonal latitude migration narrative for these species. The Scotian Shelf region and Flemish Pass–Orphan Basin areas seem particularly important for these animals and should be the focus of future research. Sei *B. borealis*, minke *B. acutorostrata*, and North Atlantic right whale *Eubalaena glacialis* vocalizations also occurred in the data but were not adequately captured by the adopted methodology. Coarse patterns of occurrence are presented for these species as a foundation for more detailed analyses. This study is the first to cover eastern Canadian waters for an extended continuous period and provides a baseline against which future changes can be assessed.

KEY WORDS: Baleen whale · Acoustic occurrence · Blue whale · Fin whale · Humpback whale · Eastern Canada

1. INTRODUCTION

Eastern Canadian waters are home to a rich marine mammal community, with 34 species having reasonable probability of occurrence. Canada's Species at Risk Act (SARA) lists 6 of these species (SARA 2002), including endangered Atlantic blue *Balaenoptera musculus* and North Atlantic right whales *Eubalaena glacialis* and special concern Atlantic fin whales *B. physalus*. Atlantic sei whales *B. borealis* were assessed as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2019 (COSEWIC 2019) and are currently under consideration for listing under the SARA. Commercial whaling has severely reduced these populations in the past, and the extent to which they have recovered varies but is generally poorly understood. Anthropogenic threats, particularly entanglements in fishing gear, vessel strikes, and underwater noise, affect all baleen whales and are linked directly to the ongoing

*Corresponding author: julien.delarue@jasco.com

Publisher: Inter-Research · www.int-res.com

decline of the North Atlantic right whale (Vanderlaan et al. 2008, 2011, van der Hoop et al. 2017, Kenney 2018), and possibly that of Atlantic fin whales in the Gulf of St. Lawrence (GSL) (Schleimer et al. 2019a, Ramp et al. 2021).

The SARA mandates that the Canadian government prepare a recovery strategy defining threats, recovery potential, and management objectives that will sustain species recovery and survival for threatened and endangered species/populations. Critical habitat is a key element of recovery strategies. Important habitats for North Atlantic right whales in Canadian waters were first identified in 2009 (Brown et al. 2009) and legally protected as critical habitat under the SARA in 2017 (DFO 2017). While important habitats of Atlantic blue whales have been assessed (DFO 2018, Lesage et al. 2018), they have yet to be formally identified under the SARA.

One factor affecting the identification of important habitats for baleen whales off eastern Canada is the large range occupied by each of these highly mobile species. Logistical constraints caused by unfavorable weather and sea state conditions that are prevalent in non-summer months make it difficult to provide complete year-round coverage of these ranges via vessel- or aircraft-based surveys. While long-term studies on the occurrence, life history, and habitat preferences of some baleen whales have been conducted in certain areas off eastern Canada (e.g. in the Bay of Fundy or GSL; Johnston et al. 2005, Ramp et al. 2006, 2010, 2014, Doniol-Valcroze et al. 2007, 2011, Ramp & Sears 2013, Gavrilchuk et al. 2014, Davies et al. 2019, Schleimer et al. 2019b), and some large-scale surveys have been conducted (Lawson & Gosselin 2011, 2018), relatively limited information exists about whale occurrence and habitat use throughout most of this region, especially in winter. This leads to uncertainty in identifying potential high-use areas or aggregation sites worthy of protection.

Most current knowledge on Atlantic blue whales in eastern Canada comes from the GSL, an area used only by a proportion of the population (Ramp & Sears 2013). Here they are acoustically present year-round in ice-free areas (Simard et al. 2016). Outside the GSL, important habitat areas have been identified based on habitat and prey modeling, visual sightings, and acoustic detections, which include areas along the Scotian Shelf edge and the southern edge of the Grand Banks off Newfoundland (Gomez et al. 2017, 2020, Lesage et al. 2018, Moors-Murphy et al. 2019). A low number of sightings during large-scale, systematic, aerial surveys off eastern Canada precluded abundance estimates (Lawson & Gosselin 2011, 2018) but are consistent with the presumed small population size (<250 mature individuals) (COSEWIC 2002). Limited recruitment (COSEWIC 2002) and threats such as entanglements (Ramp et al. 2021) and underwater noise (McKenna 2011, Melcón et al. 2012) highlight the urgent need to designate and protect critical habitat for this species, both inside and outside the GSL.

Atlantic fin whales are considered common off eastern Canada. They range broadly from the Bay of Fundy to Labrador, including throughout the Scotian Shelf, GSL, and Grand Banks. They were the most sighted and harvested species on the Scotian Shelf in the 1960s to 1970s, while the vast majority of fin whales caught off eastern Canada occurred off Labrador and northeastern Newfoundland (Sergeant 1966, Mitchell 1974, Breiwick 1994, Lawson 2006). Visual sightings from 1945 to 2015 off eastern Canada, although uncorrected for effort, suggest a broad distribution of fin whales with potential highly suitable habitats identified along the Newfoundland coast, on the southern Labrador Shelf, on the outer Grand Banks, and in Orphan Basin (Lawson 2006, Gomez et al. 2020). Despite evidence of one localized decline in abundance (Schleimer et al. 2019a), there are currently no data to suggest that this trend applies to the Atlantic fin whale population as a whole, with preliminary summer abundance estimates ranging between 3000 and 4000 individuals (Lawson & Gosselin 2011, 2018). Although visual sighting records are strongly biased towards summer, some fin whales remain in eastern Canadian waters in winter (Lawson 2006, Roy et al. 2018).

The summer presence of humpback whales off eastern Canada is well documented. In some areas, their distribution parallels that of fin whales, possibly due to trophic niche overlap (Whitehead & Carscadden 1985, Gavrilchuk et al. 2014). They are distributed across several feeding aggregations, which can be summarized as the Gulf of Maine–Scotian Shelf (including the Bay of Fundy), GSL, and Newfoundland–Labrador (Katona & Beard 1990). They occur broadly off Newfoundland and Labrador (Gomez et al. 2020), although predictable aggregations occur in coastal areas in relation with spawning aggregations of capelin *Mallotus villosus* (Whitehead et al. 1982, Johnson & Davoren 2021). Preliminary summer abundance estimates derived from large-scale systematic surveys indicate that about 6000 humpback whales occur off eastern Canada (Lawson & Gosselin 2011, 2018). Humpback whales generally migrate from northern summer feeding grounds to lower-latitude winter breeding grounds. However, passive acoustic monitoring (PAM) studies have revealed that a portion of the population remains in high-latitude waters in winter, or migrates late in the season, such that the species is present in Canadian waters for most of the year (Kowarski et al. 2018, 2021a, Davis et al. 2020).

PAM has become a commonly used method for studying marine mammal occurrence over space and time (Zimmer 2011, Browning et al. 2017). PAM is a cost-effective means for year-round monitoring in areas otherwise hard to access and costly to survey using visual methods. Technological and data-processing advances have made the collection and timely treatment of large data sets possible (Kowarski & Moors-Murphy 2021). PAM has been widely applied to monitor baleen whales worldwide. Indeed, the widespread production of stereotypical songs by males (mostly seasonal) with generally high source levels and long propagation ranges (Širović et al. 2007, Stafford et al. 2007, Garcia et al. 2019) makes many baleen whale species ideal subjects for PAM. Non-song vocalizations produced by either sex can also be used to monitor species presence when songs are absent, rare, or are not the dominant vocalization type, although these types of vocalizations tend to be less consistent and regularly produced (see e.g. Simard et al. 2016).

Here, we aimed to provide a year-round pluri-annual description of the minimum occurrence of blue, fin, and humpback whales in subarctic eastern Canadian waters using PAM data collected at 25 recording stations from 2015 to 2017. The analysis methodology applied in this study proved inadequate for a thorough description of North Atlantic right, sei, and minke whale occurrence. The acoustic occurrence of these species will be presented briefly here, with more detailed analyses either ongoing (North Atlantic right and sei whales) or left for future work (minke whales). The findings of this study are intended to serve as a baseline for the long-term assessment of changes in the occurrence of blue, fin, and humpback whales off eastern Canada, to guide future research and monitoring efforts, and to inform the identification of important habitats for management and conservation purposes.

2. MATERIALS AND METHODS

2.1. Data collection

Acoustic recorders (n = 25) were deployed between 2015 and 2017 (Fig. 1). A 2 yr study funded by the Environmental Studies Research Fund (ESRF) allowed the deployment of 20 recorders (Stns 1–20) throughout the Scotian Shelf, Newfoundland Shelf, and the southern Labrador Shelf. The study focused on areas where anthropogenic activities were concentrated or expected in the near future and where marine mammal occurrence has been poorly described. For that reason, areas where baleen whale occurrence is well documented (e.g. GSL, Bay of Fundy, inshore areas of Newfoundland) were not included. Stns 21–25 were deployed as part of an ongoing PAM program conducted by Fisheries and Oceans Canada (DFO) to help address knowledge gaps for species at risk (including blue and North Atlantic right whales) and for marine protected area monitoring purposes around Nova Scotia. Spacing between stations ranged from ca. 40 to 260 km.

All acoustic data were acquired using autonomous multichannel acoustic recorders (AMARs; JASCO Applied Sciences) configured to sample at 8 kHz with a 24-bit resolution and a duty cycle of 11 min 18 s every 20 min. The AMARs were equipped with M36-V35-100, M8Q-51 (GeoSpectrum Technology, GTI), or HTI-99-HF hydrophones (High Tech, HTI). All hydrophones had a flat frequency response between 10 and 100 000 Hz. GTI hydrophones have a sensitivity of −165 dB re 1 V μPa^{-1} and noise floor of 165 dB re 1 μPa. HTI hydrophones have a sensitivity of −164 dB re 1 V μPa^{-1} and noise floor of 165 dB re 1 μPa. Recording systems were calibrated using a reference tone at 250 Hz produced by a pistonphone type 42AC precision sound source (GRAS Sound & Vibration) before and after each deployment. The location of Stn 19 was shifted during the second year of data collection, and recorders deployed at Stns 3 and 7 were lost during the first and second deployments, respectively. Data collection was uninterrupted between both years in the ESRF study (except Stns 9 and 10) but not in the DFO study and started earlier and ended later in the DFO study (Table 1).

2.2. Detection range modeling

An important parameter for interpreting data on marine mammal acoustic occurrence is the detection range, which in this study represents the maximum range from a recorder at which a signal of a given source level can be identified by an automated detector in given background sound conditions (see Section 2.4 for description of automated detectors). Modeling detection ranges also allows assessing the potential overlap in the detection area of adjacent stations. Detection range modeling was applied to the

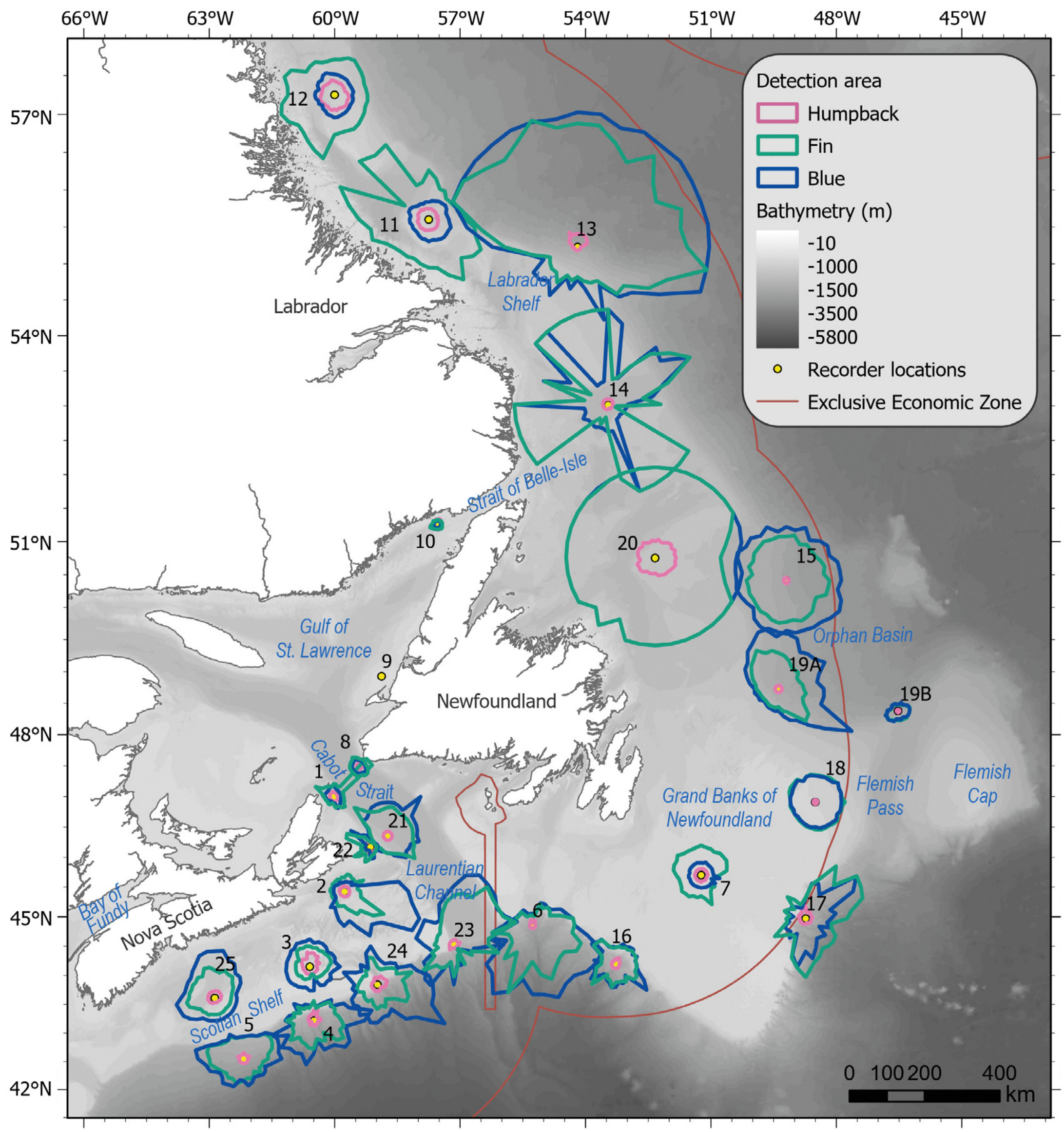

Fig. 1. Study area in eastern Canada and location of the 25 acoustic recorders deployed between May 2015 and November 2017. Also shown are blue, fin and humpback whale detection areas assuming 50% probability of detection under median ambient noise conditions. Bathymetric features are responsible for the uneven shapes of the detection areas (e.g. Stn 14)

song notes of blue, fin, and humpback whales, which are the vocalizations on which this study is focused (see Section 2.3). Detection ranges were modeled for the fall (September to November), when these species were most acoustically abundant throughout the area.

To evaluate the detection ranges, the received level, RL(r) (in dB re 1µPa), measured at the distance r from the source, was modeled as:

$$RL(r) = SL - PL(r) \quad (1)$$

where SL is the source level (in dB re 1µPa), modeled as a Gaussian distribution with a mean and standard deviation. Vocalization SL, bandwidth, and calling depth were obtained from the literature (see Table S1 in the Supplement at www.int-res.com/articles/suppl/n047p265_supp.pdf). A broad range of SL values for song notes of blue, fin, and humpback whales have been published, not all directly applicable to our focal species and study area, but nonetheless complicating the choice of what value to use in the modeling. For blue whales, we used the midpoint of estimates for the northern subspecies *Balaenoptera musculus musculus*, adjusted down by 1 dB to account for the narrower frequency band of North Atlantic song notes,

Table 1. Location, depth, and deployment time frame for the 25 recording locations. For continuous recording periods, the service date refers to the date when the recorder deployed during the first year was retrieved and a new recorder was deployed for the second year of monitoring. na: not applicable, either because data were recorded during one year only or because there was an interruption between both recording years. The location of Stn 19 was different in both years and is referred to as 19A and 19B

Station	Latitude (°N)	Longitude (°W)	Depth (m)	Deployment	Service date	Retrieval/record end
1	46.99134	60.02403	186	17-Aug-15	8-Jul-16	10-Jul-17
2	45.42599	59.76398	126	18-Aug-15	21-Jul-16	9-Jul-17
3	44.14955	60.596	72	22-Jul-16	na	8-Jul-17
4	43.21702	60.49943	1830	19-Aug-15	22-Jul-16	8-Jul-17
5	42.54760	62.17624	2002	19-Aug-15	23-Jul-16	8-Jul-17
6	44.85309	55.27108	1802	22-Aug-15	20-Jul-16	23-Jul-17
7	45.70082	51.23315	78	23-Aug-15	19-Jul-16	19-Jul-16
8	47.49307	59.41325	428	16-Aug-15	8-Jul-16	10-Jul-17
9	48.92733	58.87786	44	16-Aug-15 9-Jul-16	na na	26-Apr-16 10-Jul-17
10	51.26912	57.53759	121	3-Aug-15 10-Jul-16	na na	5-Jul-16 11-Jul-17
11	55.60300	57.75040	158	9-Aug-15	13-Jul-16	14-Jul-17
12	57.25273	60.00175	143	10-Aug-15	13-Jul-16	14-Jul-17
13	55.22797	54.19047	1750	8-Aug-15	11-Jul-16	15-Jul-17
14	53.01567	53.46022	582	4-Aug-15	14-Jul-16	16-Jul-17
15	50.41327	49.19638	2000	14-Aug-15	16-Jul-16	18-Jul-17
16	44.19230	53.27441	1602	23-Aug-15	20-Jul-16	22-Jul-17
17	44.97141	48.73373	1282	24-Aug-15	18-Jul-16	21-Jul-17
18	46.90877	48.50418	111	25-Aug-15	18-Jul-16	20-Jul-17
19A	48.72873	49.38087	1282	25-Aug-15	na	17-Jul-16
19B	48.38020	46.5254	1547	17-Jul-16	na	19-Jul-17
20	50.75232	52.33602	237	13-Aug-15	15-Jul-16	18-Jul-17
21	46.35540	58.72768	341	17-Jun-15 23-Sep-16	na na	1-May-16 23-Nov-17
22	46.16837	59.14563	87	16-Jun-15 24-Sep-16	na na	1-May-16 29-Oct-17
23	44.52339	57.14949	478	22-Sep-15 11-Nov-16	na na	13-Jan-16 2-Dec-17
24	43.83924	58.97786	1610	23-May-15 20-Sep-16	na na	10-May-16 1-Dec-17
25	43.60871	62.86832	200	24-May-15 16-Sep-16	na na	20-Apr-16 25-Nov-17

even though several other estimates are available for Antarctic *B. m. intermedia* and pygmy *B. m. brevicauda* blue whales (Širović et al. 2009, Samaran et al. 2010, Bouffaut et al. 2021). For fin whales, we selected a value near the midpoint of 2 SL estimates in the North Atlantic, weighting more heavily the estimate by Wang et al. (2016) derived for the Gulf of Maine, close to our study area, and acknowledging that the range of SL is much broader (see e.g. Charif et al. 2002, Garcia et al. 2019). For humpback whales, we used a value near the upper end of the range of SL for various song units under the assumption that the louder units are those most likely to be detected. PL(r) (in dB re 1µPa) is the range-dependent propagation loss that is a non-random parameter computed using JASCO's Marine Operations Noise Model (MOMN). MONM is a range-dependent parabolic equation model based on the range-dependent acoustic model (Collins 1994) for frequencies below 2 kHz. Propagation loss was calculated within a 3-dimensional volume (easting, northing, and depth) around each recorder up to 150 km (except 200 km for Stn 13) for fin and blue whale calls and 50 km (except 100 km at Stn 20) for humpback whales, with a horizontal separation of 20 m between receiver points along the modeled radials. The sound fields were modeled with a horizontal angular resolution of 10° for a total of 36 radial planes. Receiver depths were chosen to span the entire water column over the modeled areas, from 2 m to a maximum of 3000 m, with step sizes that increased with depth. Water depths throughout the modeled area were extracted from the SRTM15+ grid (Smith & Sandwell 1997, Becker et al. 2009). The propagation loss value was calculated using a sound speed profile characteristic of the selected season (fall, i.e. September to December). The sound speed profiles for the modeled site were derived from temperature and salinity profiles of the US Naval Oceanographic Office's Generalized Digital Environmental Model V 3.0 (GDEM; Teague et al. 1990, Carnes 2009). The GDEM temperature–salinity profiles were converted to sound speed profiles according to Coppens (1981).

Where possible, geoacoustic profiles were obtained via inversion modeling performed at 15 of the monitoring sites (Deveau et al. 2018). At the sites where locally derived profiles were unavailable, the profile of the nearest site or a default profile used in previous modeling exercises by JASCO for similar areas was used (see Table S2).

The automated detection of marine mammal vocalization is assumed to occur if RL is greater than the local noise level in the frequency band of vocalizations (NL) by a constant threshold c:

$$\mathrm{RL}\,(r) \geq \mathrm{NL} + c \qquad (2)$$

The threshold c must be chosen such that there is very little chance of a false positive (FP) due to ambient noise, and such that the probability that the automated algorithms will detect a signal when present is at least 50%. Depending on the species of interest, JASCO's automated detectors use constants of 3–6 dB, which satisfies these constraints.

The distribution of NL was determined empirically from the measurements performed on the data recorded at each station. We used sound pressure level percentiles (see Delarue et al. 2018 for Stns 1–20; JASCO unpubl. data for Stns 21–25) for the deployment that was least influenced by flow, mooring, and seismic noise, which can be dominant at the low frequencies of interest. Thus, NL has discrete values and the final probability of detection, P_D, as a function of range is:

$$P_D(r) = 1 - \sum_{\mathrm{NL}_i} P(\mathrm{NL}_i)\ \mathrm{CDF}_{\mathrm{SL}}(\mathrm{NL}_i + c + \mathrm{PL}(r)) \qquad (3)$$

where $\mathrm{CDF}_{\mathrm{SL}}(\mathrm{NL}_i + c + \mathrm{PL}(r))$ is the cumulative probability of the source level exceeding $\mathrm{NL}_i + c + \mathrm{PL}(r)$. To further constrain the modeling so that the predicted ranges do not become unreasonably long, the maximum SL considered is the 90^{th} percentile of the SL distribution, and the minimum noise level is the 10^{th} percentile of the noise distribution. We then discretized the signal model and noise measurements into 0.5 dB bins (SL_j and NL_i) and computed $\mathrm{PL}(r)$ for all combinations of NL_i and SL_j. We extracted the 10^{th} and 50^{th} percentiles of this distribution for generating plots and tables of maximum and median detection ranges, respectively.

2.3. Targeted marine mammal signals

Baleen whales generally produce stereotyped species-specific signals, at least seasonally. In blue, fin, and humpback whales, these signals form the basis of songs, which are defined as a series of notes arranged in a stereotyped pattern (Payne & McVay 1971) and are produced by males (Croll et al. 2002, Darling et al. 2006, Oleson et al. 2007). Although minke and sei whales produce patterned vocalizations, these have not been formally characterized as songs to date, although it has been suggested for sei whales (Tremblay et al. 2019). The song-forming vocalizations targeted in this study are the fin whale 20 Hz pulses (Watkins et al. 1987), blue whale A-B vocalizations (Mellinger & Clark 2003, Berchok et al. 2006), and humpback whale tonal vocalizations, which form the basis of song units in various forms (Au et al. 2006, Girola et al. 2019) but also occur as non-song vocalizations (Dunlop et al. 2007). The other stereotyped vocalizations identified during analysis were sei whale downsweeps (Baumgartner et al. 2008), North Atlantic right whale upcalls (Parks et al. 2011, Davis et al. 2017), and minke whale pulse trains (Risch et al. 2014b) (Fig. 2).

The songs of blue, fin, and humpback whales generally occur between August and April coincident with the breeding season in the northern hemisphere, including the study area (Watkins et al. 2000, Stafford et al. 2007). They have been recorded year-round in some areas, though less frequently than during the breeding season (Morano et al. 2012, Vu et al. 2012, Simard et al. 2016, Roy et al. 2018). Minke whales follow the same seasonal pattern of sound production, with pulse trains essentially absent from late spring to late summer (Risch et al. 2013, 2014a). Our understanding of sei whale seasonal acoustic behavior is poor, but there is evidence for year-round downsweep production (Davis et al. 2020). Right whales also produce upcalls year-round (Davis et al. 2017).

Outside of the breeding season, balaenopterid whale vocalization rates and stereotypy generally decrease. In addition, non-song vocalizations of blue and fin whales, which are the main signals produced

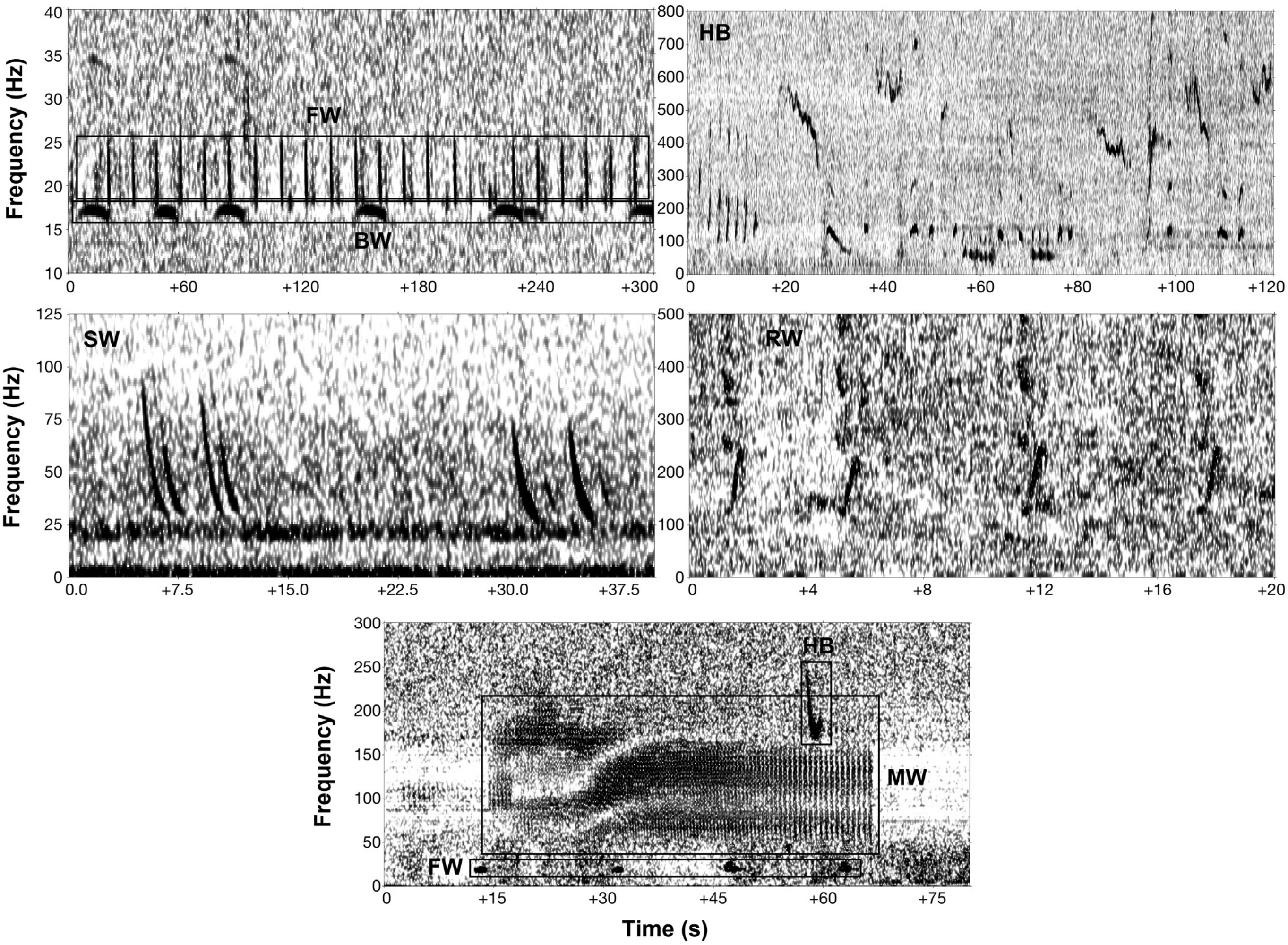

Fig. 2. Spectrograms of vocalizations targeted for automated or manual detections. The calls of each species are coded as follows. FW: fin whale 20 Hz pulse; BW: blue whale A-B call; HB: humpback whale tonal call; SW: sei whale downsweep; RW: right whale upcall; MW: minke whale pulse train

from late spring to mid-summer, and sei whale downsweeps show higher similarity in contours (Ou et al. 2015), limiting the efficacy of automated detectors and increasing the difficulty of reliable species identification. These ‘summer’ non-song vocalizations for blue whales (Berchok et al. 2006) and fin whales (Watkins 1981) were identified manually while validating automated detections (see Section 2.4).

2.4. Automated detection and manual validation

Baleen whale acoustic signals were automatically detected using a JAVA-based contour-following algorithm that matched contour parameters to a library of templates representing the vocalizations of the target species. The only exceptions were minke whale pulse trains, for which an automated detector was not implemented when the data were analyzed. For each automated detector, specific spectrogram parameters were applied (Table S3) before the algorithm searched the spectrogram for contours. Contours were assigned to a species if they were within the range of values in the template for the corresponding signal (Table S4). The automated detection algorithms applied to the data were described in detail by Kowarski et al. (2020).

A subset of acoustic files was selected from each station and deployment for manual validation by experienced analysts to evaluate automated detector performance, using the methodology described by Kowarski et al. (2021b). An automatic data selection for validation algorithm selected files for validation such that the file subset matched the corresponding data set's distribution of (1) the number of automated detections per file for each automated detector; (2) the number of automated detectors triggered per file; and (3) the temporal spread of files containing detections for each automated detector across the recording period. This multi-species approach allowed the performance of multiple automated detectors in diverse background noise conditions to be assessed simultaneously. The size of the validation subset chosen for this study was 0.5% of the sound files in each data set (11.5 min files, n = ~160 per station per year, or ~7680 files total representing 1472 h of data) due to analysis time constraints and the overall size of the data set. Although the automated detectors classify individual signals, we validated the presence/absence of species at the file level, not the detection level.

The following restrictions were further applied to the automated detector results. If a species was automatically detected at a location but no vocalizations were found by analysts during the manual validation process (either during a specific period or the whole recording period), all automated detections during the relevant period were deemed FPs and excluded from further processing. For example, the automated humpback whale detector was falsely triggered by ice noise in northern stations through winter when the species was never manually confirmed to be acoustically present. Therefore, all automated humpback whale detections from these locations and times were deemed FPs and were excluded from the final occurrence results. Periods during which detections were excluded are referred to as exclusion periods (see Tables S6–S8 and see Figs. 4, 6, & 8).

The performance of each automated detector and any necessary thresholds (minimum number of automated detections per file to consider species present) was determined using a maximum likelihood estimation algorithm. This algorithm compared the automated and validated results and maximized the probability of detection while minimizing the number of false alarms using the Matthews correlation coefficient (MCC):

$$\mathrm{MCC} = \frac{\mathrm{TP} \times \mathrm{TN} - \mathrm{FP} \times \mathrm{FN}}{\sqrt{(\mathrm{TP}+\mathrm{FP})(\mathrm{TP}+\mathrm{FN})(\mathrm{TN}+\mathrm{FP})(\mathrm{TN}+\mathrm{FN})}} \quad (4)$$

$$P = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FP}}; R = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FN}} \quad (5)$$

where TP (true positive) is the number of files with valid automated detections, FP is the number of files with false detections, and FN (false negative) is the number of files with missed detections. The performance of the automated detectors was then described using precision (P) and recall (R). P represents the proportion of files with detections that are TPs. R represents the proportion of files containing the signal of interest that were identified by the detector.

Where the number of validated detections was too low, or the overlap between manual and automated detections was too limited for the calculation of P, R, and MCC, automated detections were ignored, and only validated results were used to describe the acoustic occurrence of a species.

The automated detector performance algorithm determines a threshold based on the number of detections per 11.5 min file for each species, station, and deployment combination that maximizes the MCC score. A species was considered absent if the automated detection count was below that threshold. Here, we only used results from automated detectors whose post-threshold $P \geq 0.75$. When $P < 0.75$, the manual detections were instead used to describe the acoustic occurrence of a species. This was the case for North Atlantic right and sei whale vocalizations at all stations. Because the manual detections of these, along with minke whale vocalizations, were not obtained in a systematic manner, their acoustic occurrence was summarized as overall presence/absence per station, where a single detection during the study was needed to indicate presence.

The minimum acoustic occurrence of blue, fin, and humpback whales is presented following the templates used by Davis et al. (2020). Where automated detections are shown, the exclusion periods and detection count threshold, if any, have been applied. Time series showing the number of days per week with automated and/or manual detections for each station over the 2 study years are provided. In addition, the proportion of days with automated detections during the entire recording period was plotted at each station by season. Spring is defined as 1 March to 31 May, summer as 1 June to 31 August, fall as 1 September to 31 November, and winter as 1 December to 28/29 February. The total number of detection (manual and/or automated) days was divided by the total number of recording days to account for recording effort. Sea ice extent (© 2021 EUMETSAT) for 15 March 2016 and 2017 (approximate seasonal maximum) was displayed on the spring plot, when the minimum acoustic occurrence was observed. A detailed analysis of sea ice as a driver of seasonal occurrence was beyond the scope of this paper, but this is intended to illustrate the loss of physical habitat to marine mammals occurring in winter off eastern Canada.

3. RESULTS

3.1. Detection range modeling

The detection ranges presented here should be considered with the following points in mind. The results are based on ambient background sound levels as recorded near the ocean bottom by the recorders during fall, when most automated detections occurred. Expected detection ranges could differ under different deployment scenarios (e.g. recorder in the sound channel or at the surface) or different seasons (due to different sound speed profiles or presence of sea ice, which would reduce detection ranges due to increased refraction caused by the irregular under-ice surface). Perhaps more importantly, although the modeling is based on a range of source levels (SL ±3–5 dB) which represent a consensus across several relevant publications (see Section 2.2 and Table S1), the actual source level range is likely broader, which could result in substantial variations in detection ranges compared to those presented here. However, these results are valuable to understand the typical acoustic coverage of recorders for each species/ vocalization type in eastern Canada.

The median and maximum detection ranges for fin, blue, and humpback whale vocalizations are provided in Table S5 and Fig. 1. Table S5 specifically lists the minimum and maximum detection ranges for the 10^{th} and 50^{th} percentile of noise levels across all modeled radials, further highlighting the wide spectrum of possible ranges. Humpback whale song notes can be detected over much smaller areas than those of blue and fin whales. Overlapping detection ranges at adjacent stations suggest that fin and blue whale vocalizations could be heard at multiple recorders simultaneously. This was confirmed opportunistically for both species at Stns 1 and 8, on either side of the Cabot Strait (73 km apart). The longest detection ranges (using the highest source levels and lowest noise levels in Eq. 3) were limited to the maximum modeling extent (150 km) at 11 and 8 of 25 stations for fin and blue whales, respectively, and 10 of 25 stations for humpback whales (50–100 km extent), indicating that longer maximum ranges are possible.

Most stations along the continental slope showed large variation in detection ranges depending on source direction, reflecting the effect of bathymetry in relation to the source-receiver orientation (e.g. see blue whales at Stn 13, Fig. 1). Northern stations (Stn 19A and all stations north of Stn 19A) had generally larger detection areas for fin and blue whales than those further south. Stn 20 had noticeably longer detection ranges than any other station for all species. The shorter ranges at Stn 19B reflect the effects of high noise levels between 13 and 30 Hz due to flow-induced mooring noise (see Delarue et al. 2018).

3.2. Automated detector performance

The evaluation of automated detector performance was based on the manual review of 1472 h of data. The automated detector performance metrics are presented in Tables S6–S8 and summarized in Fig. 3. Automated detector performance varied between species, stations, and year. The fin whale detector performed best overall, while the humpback whale detector had the lowest performance. Fin, blue, and humpback whales had 3, 8, and 14 data sets, respectively, for which *P* was below 0.75 or none of the automated detections were manually validated. *R* was generally lower than *P*, the detectors identifying on average 40–70% of sound files containing vocalizations. However, daily *R* can be expected to be higher than per-file *R* (Kowarski et al. 2020). Indeed, a single file (out of 72 files per day) with detection is required for daily presence to be confirmed, and it is

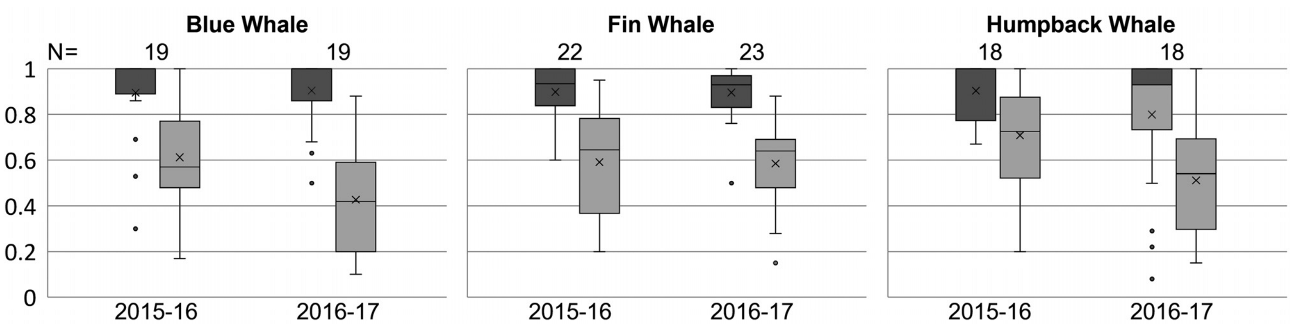

Fig. 3. Precision (dark grey) and recall (light grey) scores for blue, fin, and humpback whale automated detectors across the stations where they were detected (sample size shown above each bar group) for both recording years. Boxes show the 25th, 50th and 75th percentiles, crosses show the mean, whiskers show the 5th and 95th percentiles, and dots show outliers

therefore unlikely that relatively low per-file *R* would have a significant impact on the detections presented here. Nevertheless, the results should be considered estimates of the minimum presence of each species.

3.3. Blue whale minimum presence

Blue whale A-B vocalization detections (both automated and manual) occurred year-round in eastern Canadian waters (Figs. 4 & 5). Detections started as early as late July, increased in August, and continued throughout the fall, albeit more regularly in the southern half of the study area. They stopped as early as November off Labrador and ceased increasingly later from north to south. The acoustic occurrence of blue whales was at its lowest in late spring and early summer.

In fall and winter, blue whales were most consistently detected at stations associated with the Laurentian Channel, the southern edge of the Grand Banks, and the Scotian Shelf. They were almost never heard in the Strait of Belle Isle or on the southern Labrador shelf. Off Newfoundland, blue whale vocalizations were more common at stations along the slope of the Grand Banks than on the shelf, particularly at the northern end of the Flemish Pass (Stn 19B) despite much shorter detection ranges than at nearby sites (Table S5). In waters surrounding Nova Scotia, blue whale vocalizations in fall and winter were more common in the Laurentian Channel and on the Scotian Shelf than at deep stations along the slope of the Scotian Shelf.

3.4. Fin whale minimum presence

Fin whale 20 Hz pulses generally occurred following a well-defined seasonal pattern with an increase in the fall/winter and decrease in the spring/summer, with the contraction more prominent at northern stations (Figs. 6 & 7). Some of the southern stations (Stns 24 and 25) had detections year-round. The detection periods were notably shorter at northern stations, specifically on and off the Labrador shelf (Stns 11–13), on the northern Banks (Stns 14 and 20), and in the Strait of Belle Isle. At many stations, the end of the detection period in the spring represents the start of the exclusion period.

The sustained occurrence of fin whale vocalizations at Stn 19B well into the spring is worth noting due to the short signal detection ranges modeled there (see Fig. 1). The abrupt detection onset in October at that station is an artefact of the exclusion period applied to exclude FPs caused by seismic airgun pulses. During spring, fin whale vocalizations occurred more frequently at the Flemish Pass and adjacent areas (Stns 17, 19A, and 19B), as well as the western Scotian Shelf (Stn 25) than throughout the rest of the study area. Summer acoustic occurrence was generally low, except on the western Scotian Shelf and in the Gully Canyon (Stns 25 and 24).

3.5. Humpback whale minimum presence

Humpback whale vocalizations were detected (manually and/or automatically) at all stations except Stn 9 (Figs. 8 & 9). Detections were notably high in the Strait of Belle Isle (Stn 10), eastern Scotian Shelf (Stns 2 and 22), and southern Grand Banks (Stn 7). In the Strait of Belle Isle, humpback whales were detected nearly daily in both years from June to December. Stn 7 was only monitored during the first year but saw sustained detections throughout the monitoring period with a peak in summer and fall. A high number of weekly detection days at Stns 10 and 7 in summer indicate that positive detections are not reliant on the presence of songs, which were not observed in this season during manual validation.

In the Cabot Strait (Stns 1 and 8), detections were consistently higher on the south side. Similarly, along the southern edge of the Laurentian Channel, detections were consistently higher on the shelf (Stn 22) than along the slope of the channel (Stn 21). At deep stations along the continental slope, detections were generally lower than at stations on the shelf and close to shore. Notable exceptions were in the Gully Canyon (Stn 24) and north of the Flemish Pass (Stn 19B). Humpback whales were rarely detected at the northern stations (Stns 11–14), except during fall 2015 at Stn 14. Where detections were rare, they were generally concentrated during the winter months, sometimes with a secondary peak in spring (e.g. Stns 4 and 5). During winter, detections occurred at almost all stations with a predominance at southern stations. In contrast, spring and summer had the fewest stations with detections.

3.6. Other baleen whale species

North Atlantic right whale upcalls were manually detected sporadically at Stns 1, 2, 22, and 25 from June to December. Isolated detections occurred in September 2016 at Stn 10 and November 2016 at

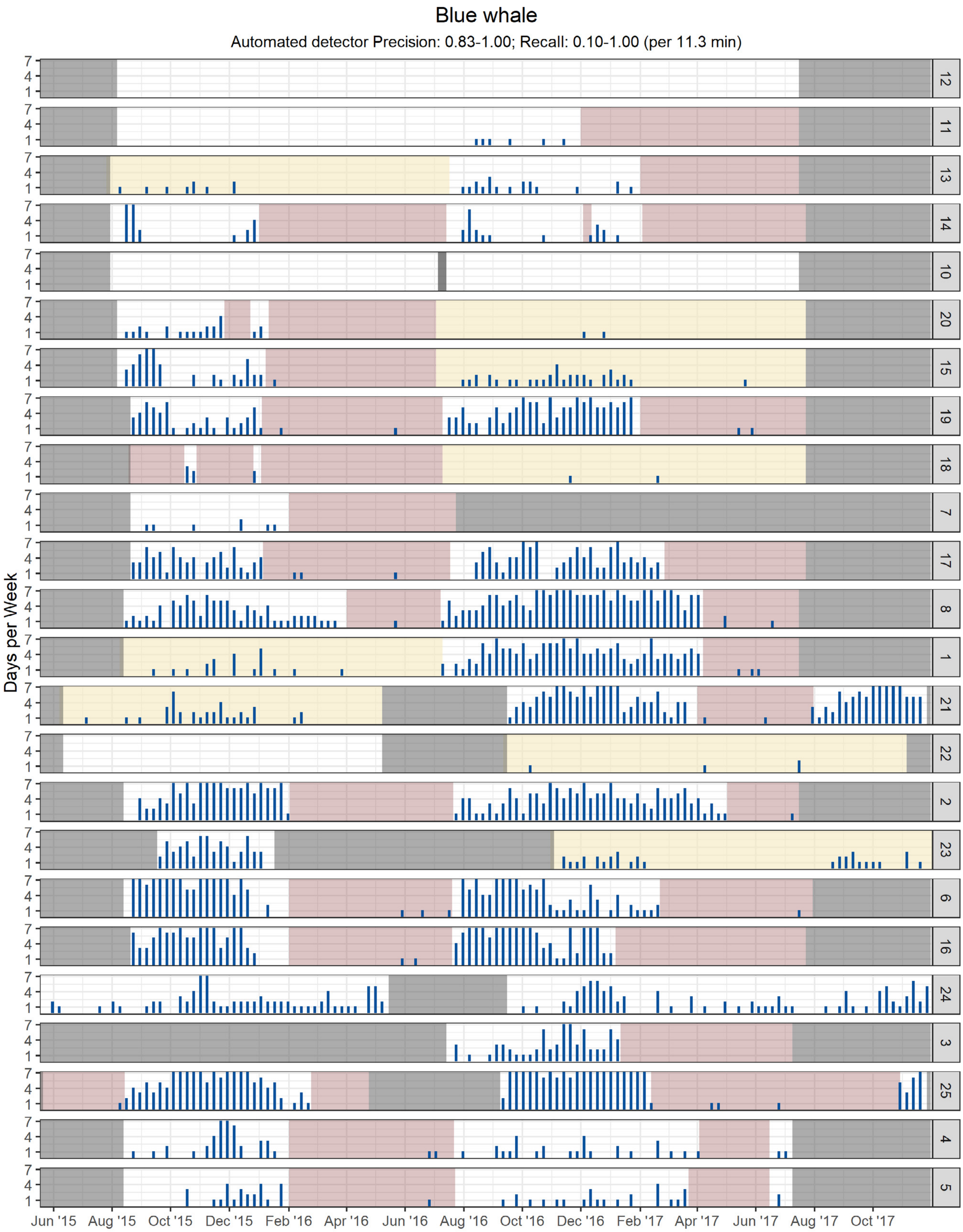

Fig. 4. Weekly presence summary, showing the number of days per calendar week with confirmed blue whale acoustic presence for each recording site (except Stn 9) between May 2015 and November 2017. Stations (numbers on the right) are arranged north to south. Grey blocks indicate weeks with no available data. Pink blocks indicate exclusion periods (when automated detections were ignored). Yellow areas represent deployments for which the output of the automated detector was not used when there was at least one manual detection. The first half of data for Stn 19 represents data collected at Stn 19A, while the second half represents data collected at Stn 19B

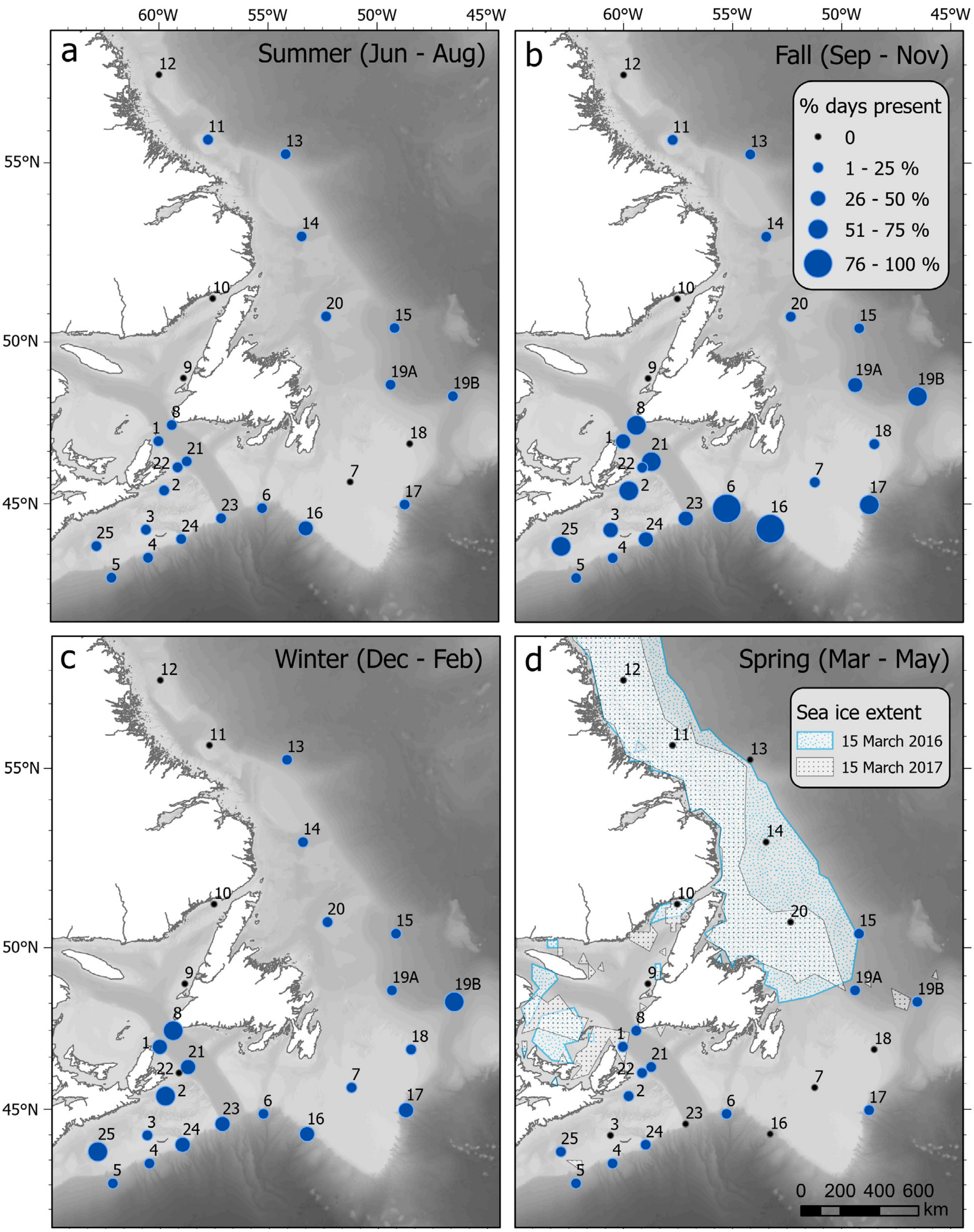

Fig. 5. Blue whale seasonal occurrence. Proportion of recording days per season with confirmed Atlantic blue whale acoustic detections, summarized for all available recording locations between June 2015 and November 2017. Sea ice data: © 2021 EUMETSAT

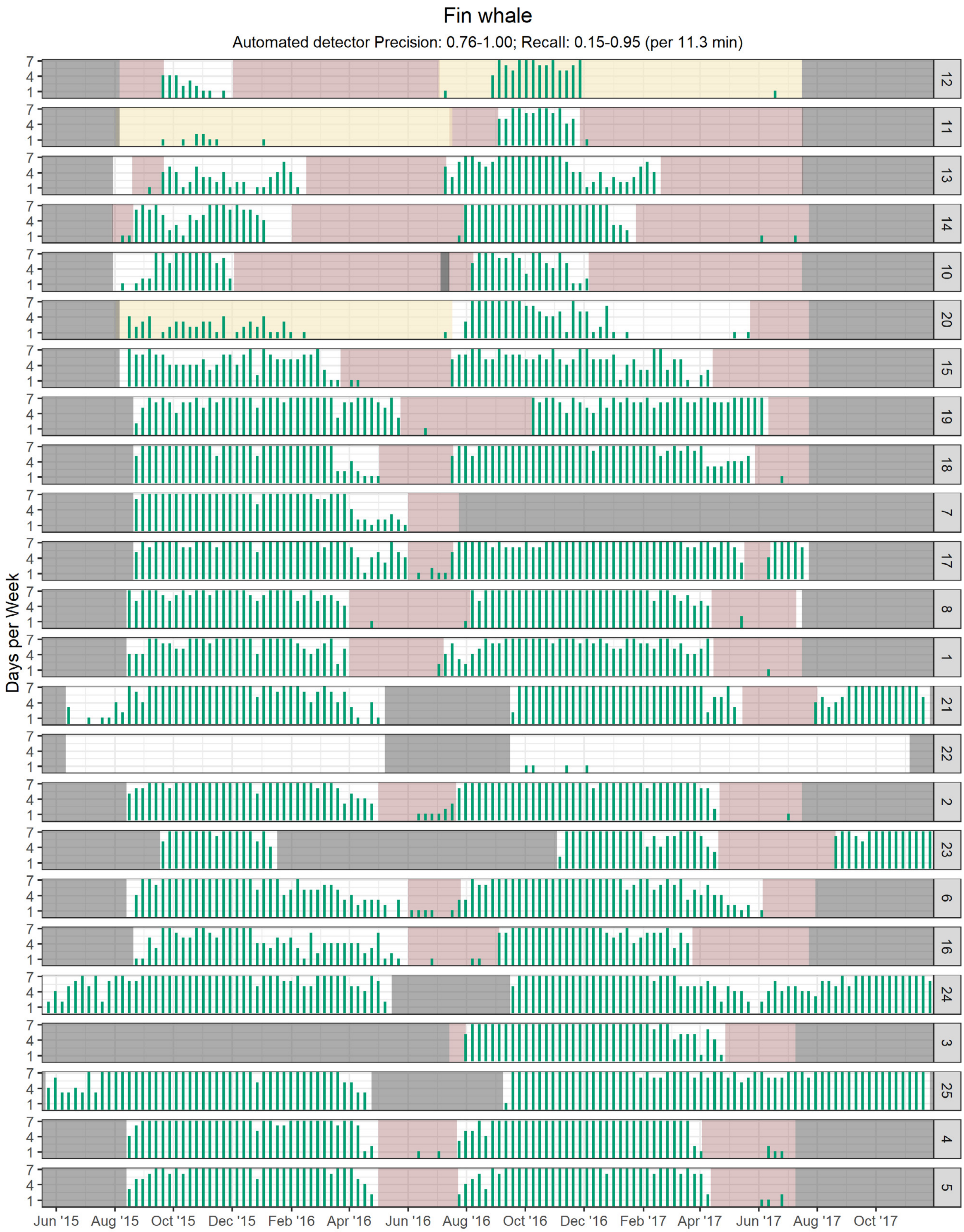

Fig. 6. Same as Fig. 4, but for fin whales

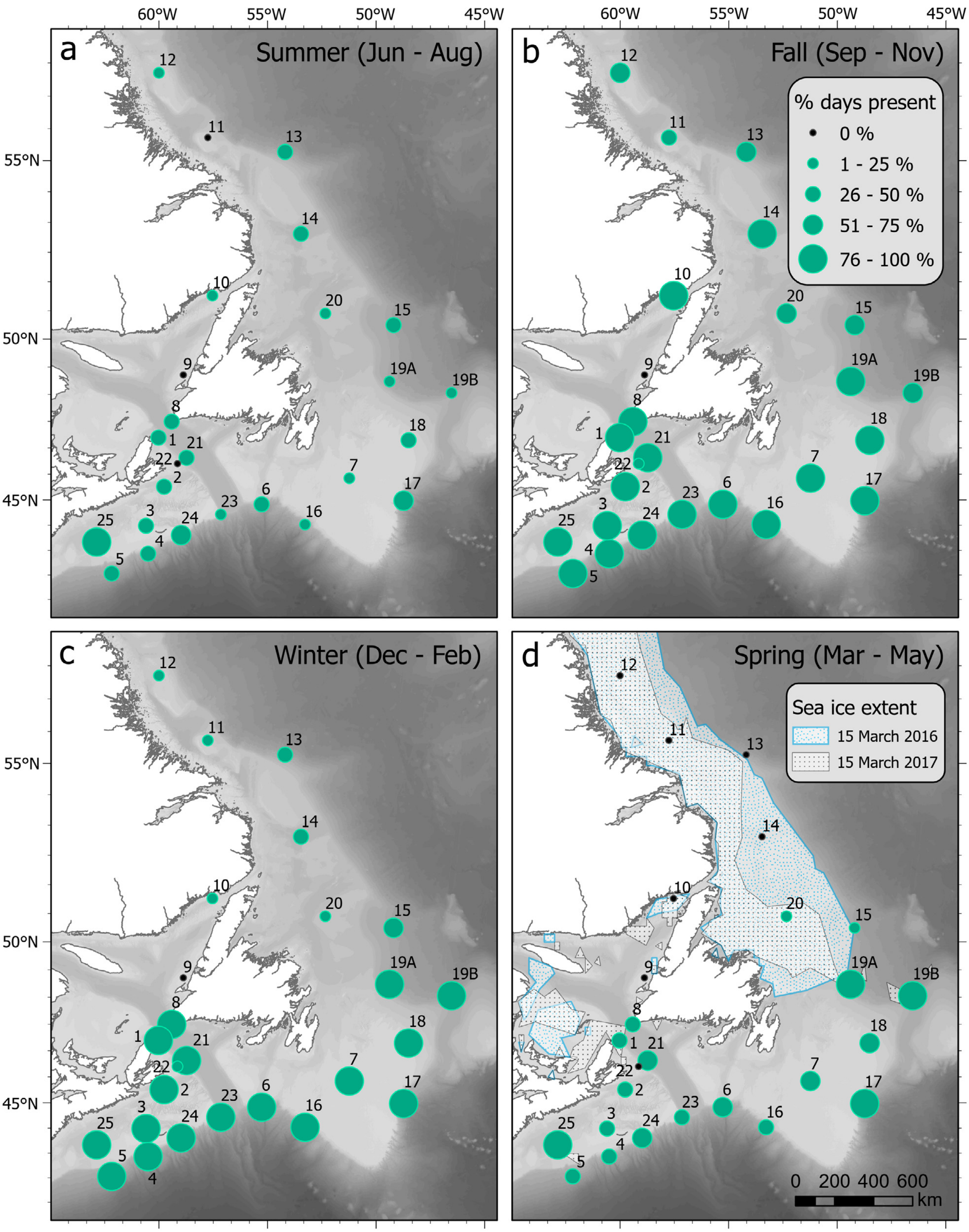

Fig. 7. Same as Fig. 5, but for fin whales

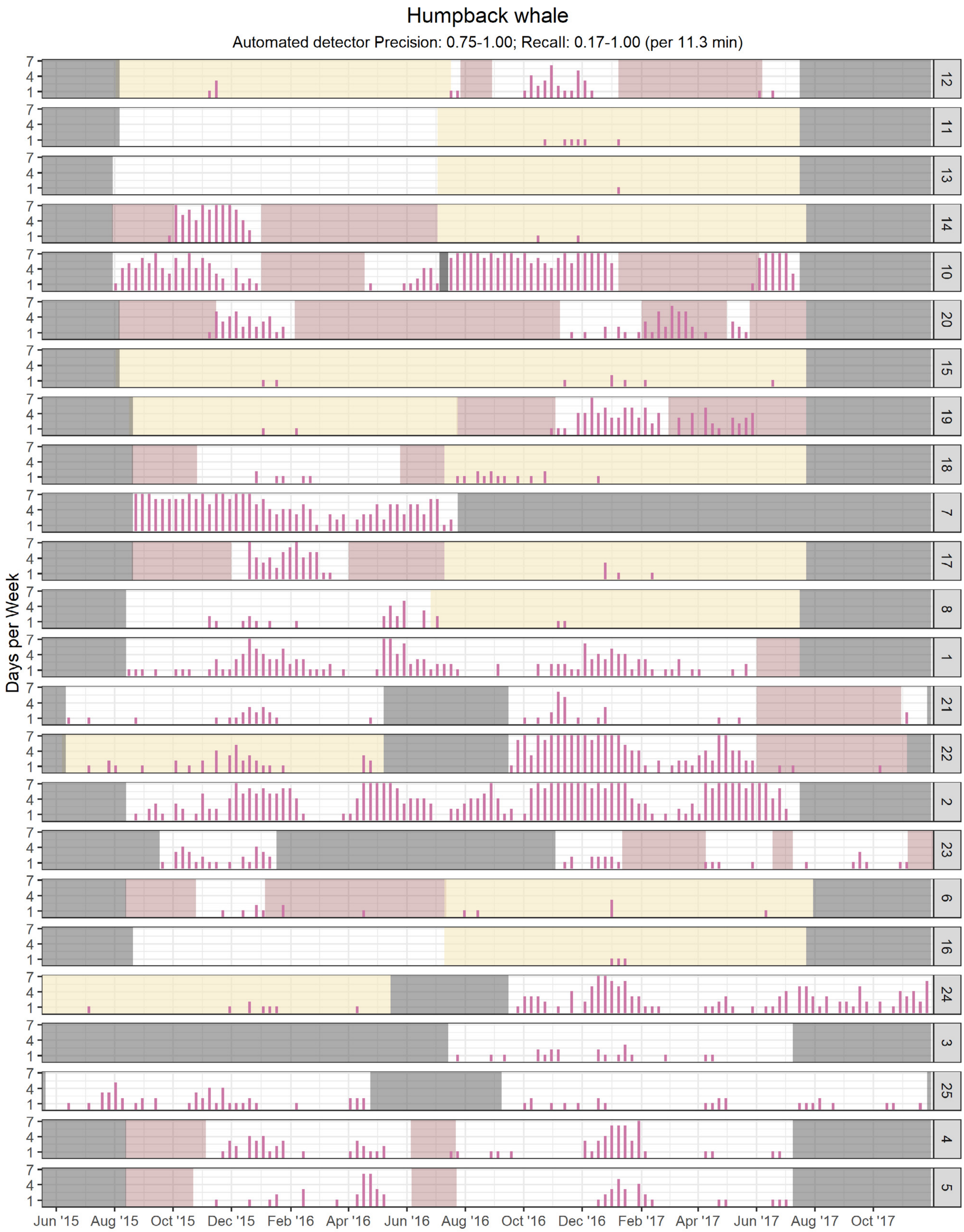

Fig. 8. Same as Fig. 4, but for humpback whales

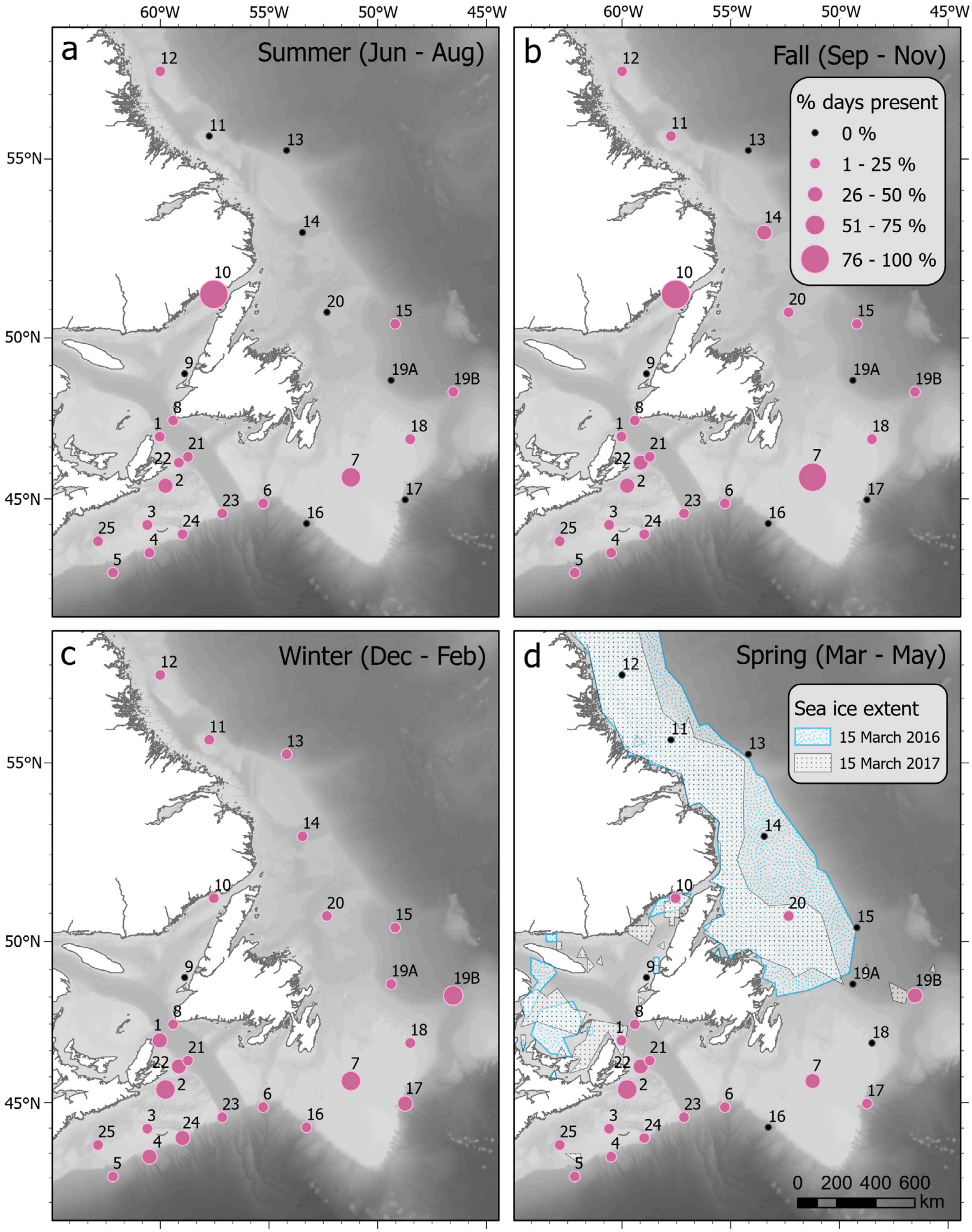

Fig. 9. Same as Fig. 5, but for humpback whales

Stn 6 (Fig. 10). Several tentative detections were made at other stations, suggesting that a dedicated manual analysis of the data could reveal a broader acoustic presence of this species in eastern Canadian waters.

Minke whale pulse trains were manually detected at Stns 1, 2, 3, 5, and 16 (Fig. 10). Detections occurred sporadically between late July and mid-December, except at Stn 3, where minke whales were consistently detected from August until mid-November 2016.

Sei whales were manually detected at all stations except those associated with the GSL (Stns 1, 8, 9, and 10) and Stn 3. The prime detection area was off the southern Labrador Shelf (Stn 13) and in the Orphan Basin (Stns 15, 19A, and 19B) where detections occurred almost exclusively from May to November. The Scotian Slope (Stns 4, 5, and 24), and to a lesser extent the Scotian Shelf (Stn 25), also had relatively high detections with vocalizations recorded primarily from late winter to early summer and again in fall (Fig. 10). Detections occurred more frequently at the deep stations off the continental shelf than on the shelf. Although an automated detector was designed to find sei whale downsweeps, the presence of seismic airgun pulses off northeastern Newfoundland affected its performance. Off Nova Scotia, where blue whales are more common, the similarity between sei whale downsweeps and blue whale D-calls also impacted automated detector performance.

4. DISCUSSION AND CONCLUSIONS

The acoustic detections presented here represent the minimum occurrence of baleen whales off eastern Canada within the detection range of each re-

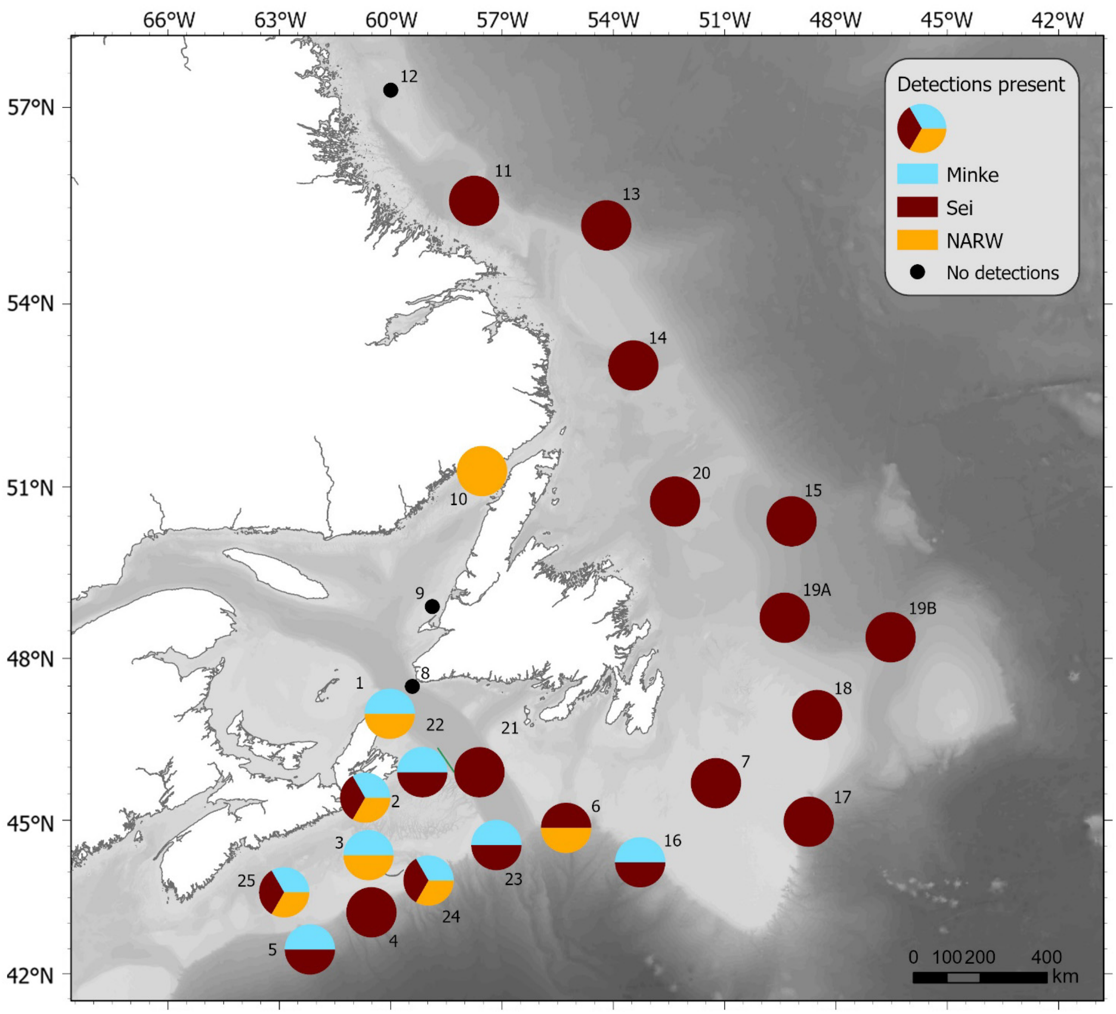

Fig. 10. Stations where minke, sei, and North Atlantic right whale (NARW) vocalizations were acoustically detected at least once

corder. The detection areas shown in Fig. 1 are based on a subset of source level values that does not encompass the full possible range of source levels for each species. In addition, detection ranges are the result of the interaction of variable source levels and time-varying background noise and sound propagation conditions, making it difficult to know the area being actually monitored at any given time. A lack of detections (particularly when relying on the manual review results only) does not indicate the absence of non-vocalizing animals. Animals may be present but not vocalizing, may be producing vocalizations not targeted by the automated detectors, or their vocalizations may be masked by ambient or anthropogenic noise. Although the manual validation effort was distributed across the duration of each data set, the relatively low number of validated files may have resulted in analysts missing isolated vocalization events when exclusion periods were implemented. However, the results are unlikely to mischaracterize the overall species occurrence.

Call stereotypy and species specificity are key factors that affect the ability of automated detectors to accurately represent species presence. The vocalizations of fin, blue, minke, and sei whales fulfill these requirements. Humpback whale tonal vocalizations are less stereotyped. However, they generally occur in predictable frequency bands. Generic automated detectors developed for humpback whale vocalizations within these bands can have limited performance in noisy environments but perform well in areas where humpback whales vocalize actively (Kowarski et al. 2018). Because of their potential similarity to humpback whale vocalizations, confidence in the output of the automated right whale upcall detector can be compromised in areas where humpback whales co-occur and are abundant.

Variable performance of the same automated detectors across stations or even between years at the same stations highlights the need to evaluate automated detector results on a case-by-case basis (Kowarski & Moors-Murphy 2021). Inter-annual variations in performance reflect varying background noise conditions and species presence. Factors influencing performance included a low number of TPs and the presence of confounding signals (e.g. vessel-associated tonal sounds in the case of the blue whale detector; airgun pulses in the case of fin and sei whale detectors; humpback whale vocalizations in the case of the North Atlantic right whale detector). For fin and blue whale vocalizations, lower calling rates, greater call variability, and overlap in call characteristics outside of the song production months (August to April) remain a challenge for automated detectors and, to some extent, also for experienced analysts.

4.1. Blue whales

The occurrence of blue whales in eastern Canada was reviewed by Lesage et al. (2018) and Moors-Murphy et al. (2019), and several areas of importance to blue whales for migration and foraging were proposed. These include several foraging areas in the GSL and a migration corridor through the Cabot Strait in and out of the GSL. Our consistent acoustic detections in the Cabot Strait, extending from late July to April, suggest a steady flow of individuals in and out of the GSL throughout most of the year but could also indicate that some individuals use this area for purposes beyond migration (e.g. mating and foraging). Indeed, satellite tagging studies have demonstrated individuals foraging in the Cabot Strait (Lesage et al. 2017). The entirety of the Laurentian Channel appears to be important to blue whales with detections near its end (Stns 23 and 6) and beyond along the southern Grand Banks (Stn 16), extending well into February. Although most satellite-tagged blue whales headed towards the Scotian Shelf after passing through the Cabot Strait (Lesage et al. 2017), the intensity of acoustic detections in fall along the southern edge of the Grand Banks suggests that at least some individuals head east after exiting the Laurentian Channel. The only station in the GSL was Stn 10, located at the eastern edge of the Mecatina Trough area, which was identified by Lesage et al. (2018) as important blue whale habitat based on high predicted krill aggregations and high blue whale catches during whaling operations between 1925 and 1958, despite a scarcity of more recent sightings in the area. The lack of blue whale acoustic detections at Stn 10, which is consistent with the lack of detections during an earlier 1 yr acoustic study in the same area (Simard et al. 2016), suggests that this area is not regularly used by blue whales, although this may reflect short detection ranges and the recorder being located at the edge of the Mecatina Trough.

Two other areas of higher blue whale acoustic occurrence outside the GSL were the Scotian Shelf and the Flemish Pass. Several tagged blue whales transited near Stn 2 on the eastern Scotian Shelf, sometimes repeatedly, on their way out of the GSL (Lesage et al. 2017). Blue whale vocalizations were recorded at this station regularly between late July and the end of April, suggesting that this area may not be just a migratory corridor. In fall and winter, the recorder deployed in Emerald Basin on the Scotian Shelf (Stn 25) also consistently recorded a high number of detections. P and R values for these stations were high in both years, indicating that the acoustic occurrence of blue whales was accurately characterized. This area partially overlaps a cluster of blue whale sightings recorded during a short period of whaling off Nova Scotia (1967–1972), which extended towards the shelf break (Sutcliffe & Brodie 1977). Interestingly, the closest stations along the Scotian Slope (Stns 4, 5, and 24) did not record the same level of detections. These recorders were located inside the shelf edge important foraging habitat identified by Lesage et al. (2018), which consists of a narrow (~50 km) strip encompassing the shelf break of the Scotian Shelf, and the southern and southeastern Grand Banks up to the southern edge of the Flemish Pass. The detection range modeling results indicate that in the most likely scenarios, the blue whales producing vocalizations recorded at Stn 25 were located on the Scotian Shelf within 40–90 km of that recorder. Stations along the Scotian Slope had restricted detection ranges towards the Scotian Shelf and a larger listening area seaward. There appears to be some potential for individuals present on the outer continental shelf to have gone undetected, even in the best-case scenarios. Nevertheless, our results suggest that the Scotian Shelf region may be equally, if not more, important to blue whales than the Scotian Slope. This is further supported by blue whale habitat suitability models, which indicate potentially highly suitable habitat on the central Scotian Shelf as well as the Scotian Slope (Moors-Murphy et al. 2019).

The detections on either end of the Flemish Pass (Stns 19B and 17) are noteworthy, particularly in light of the relatively small detection ranges modeled for these areas and low automated detector *R*. Detections extended into January to the north and February to the south of the pass. Stns 19A/B and 15 had similar detection periods in both years, even though occurrence at Stn 15 is based on manual detections only. This suggests that Orphan Basin could have a similar importance as the Flemish Pass. Blue whales were comparatively rare at outer shelf locations on the Grand Banks and southern Labrador Shelf (Stns 18, 14, 20, 11, and 12), despite rather extensive detection areas. This points to a preference for slope habitat in the Newfoundland region, in contrast to what is suggested by detections on and off the Scotian Shelf.

4.2. Fin whales

Uniformity in the acoustic occurrence of fin whales observed throughout the study area suggests a broad distribution across eastern Canadian waters from late summer to winter and makes it difficult to identify specific areas that may be of greater importance to this species, if any. It may be that their varied diet, made of zooplankton and small schooling fish (Gavrilchuk et al. 2014), provides them more flexibility in habitat choice depending on prey availability and distribution, resulting in a more uniform apparent distribution. In contrast, blue whales may be more restricted in terms of potential foraging because of their euphausiid-restricted diet (Yochem & Leatherwood 1985). However, some areas are worth highlighting due to a greater presence of fin whale vocalizations in spring and early summer. Emerald Basin on the Scotian Shelf (Stn 25), the Gully Canyon (Stn 24), and stations associated with the Flemish Pass and southern Orphan Basin (Stns 15 and 19A/B) maintained relatively high call presence during this period. Late spring and early summer detections are noteworthy because the quasi-absence of songs and decrease in calling rates and in the proportion of 20 Hz calls in the vocal repertoire of fin whales (Watkins 1981, Stafford et al. 2007, Roy et al. 2018) generally makes the species more acoustically cryptic during this season. At most stations, the scarcity or absence of automated 20 Hz call detections and manual detections of any type of calls in spring and summer indicate, at least, a limited acoustic presence of fin whales, but we cannot rule out that a greater manual review effort to compensate for reduced calling rates would reveal more consistent occurrence. In the Flemish Pass area, the exclusion periods in late spring and summer generally coincided with the presence of seismic airgun pulses. The lack of TP detections (no manual detections) may reflect reactions of fin whales to airgun pulses, as shown in other areas (Castellote et al. 2012).

The uninterrupted occurrence of 20 Hz calls in Emerald Basin and the Gully in summer compared to other areas could reflect a higher density of fin whales, better call detectability (e.g. closer proximity of vocalizing whales, lower background noise), or other factors causing higher acoustic activity. The Gully Canyon has significantly higher cetacean sighting rates compared to adjacent slope and shelf areas, including baleen whales (Moors-Murphy 2014), which could result in a greater concentration of fin whales and higher calling rates.

There is uncertainty regarding the winter migratory patterns of fin whales that feed in eastern Canadian waters in summer. Our results suggest that non-negligible numbers of fin whales remain in the study area in winter. Although the total number of fin whales off eastern Canada is considered healthy, fin whales in some areas appear to be declining (Schleimer et al. 2019a). Atlantic fin whales in Canada are managed as a single population, even though evidence indicates some level of population structure (Mitchell 1974, Delarue et al. 2009). Potential spatial and demographic isolation should be considered when assessing areas that may be important for some but not all individuals, especially if they belong to populations with different abundance trajectories.

4.3. Humpback whales

The Strait of Belle Isle (Stn 10) was the only known humpback whale aggregation site (Stevick et al. 2006, Comtois et al. 2010) monitored during this study and was found to be consistently utilized from June, when the earliest humpback whale arrivals are typically recorded in the northern GSL (Ramp et al. 2015), until December, when ice starts forming in this area. Detections persisted nearly year-round on the southern Grand Banks (Stn 7), suggesting that some individuals remain in Canadian waters throughout winter, as previously observed in other North Atlantic areas such as the Gulf of Maine (Davis et al. 2020) and Gully Canyon (Kowarski et al. 2018). None of the deep stations along the continental slope saw sustained periods of humpback whale acoustic occurrence.

Among the 3 baleen whales discussed in this paper, the humpback whale adheres most closely to the typical model of baleen whale migration patterns. Most stations saw detections constrained to well-defined periods which are presumably associated with the movement of migrating animals. A late fall-winter detection wave was apparent at all stations. A spring wave was generally only visible at stations in the southern half of the study area. These fall and spring waves of acoustic occurrence were investigated in more detail by Kowarski et al. (2019) and are consistent with seasonal patterns of detections observed in feeding grounds in the Gulf of Maine (Vu et al. 2012). Migratory movements of humpback whales from and to Canadian waters are poorly documented. Of 22 whales tagged on Caribbean breeding grounds, only 2 returned to Canadian waters. They migrated in deep offshore waters until reaching the Gully Canyon and the junction of the Grand Banks and the Laurentian Channel, near Stn 6. Both individuals started foraging upon reaching these areas (Kennedy et al. 2014). Whitehead et al. (1982) described the migration of humpback whales in Newfoundland. Whales first arrived on the south coast and progressively moved to the northeast coast near Bonavista Bay before crossing to the southern Labrador coast.

Our detections suggest that humpback whales exit the GSL predominantly along the southern edge of the strait. The discrepancy in the number of detections between the eastern Scotian Shelf (Stns 2 and 22) and stations farther south suggest that the whales disperse after leaving the former instead of following an established migration corridor. However, the intensity of detections downstream from the eastern Scotian Shelf region was highest in the Gully Canyon area, indicating that some whales may transit via this area before heading south in deep oceanic waters (Kowarski et al. 2018). It is unclear whether the waves of detections noted at stations along the slope of the Grand Banks represent animals summering in Canadian waters, for instance off Labrador, or whales migrating from feeding areas farther north, particularly off West Greenland. The differences in acoustic detections at Stns 19A and 19B are noteworthy, suggesting that the northern Flemish Pass (and possibly the Flemish Cap) may act as a migration transit point. Interestingly, Stn 17 at the southern end of the Flemish Pass had very few detections while they peaked at the northern end (Stn 19B).

4.4. Other species

The main summer feeding grounds of North Atlantic right whales in eastern Canada were historically located in the Bay of Fundy and in Roseway Basin (Davies et al. 2015, 2019). Although individuals were also occasionally sighted in the GSL, since 2015 most right whale summer observations come from the southern GSL. Despite the limitations of our analysis protocol for establishing the acoustic occurrence of this species, our detections suggest, at the very least, that some individuals wander beyond the main aggregations site in the southern GSL, both inside and outside the GSL.

Minke whale detections were concentrated in the southern half of the study area. However, minke whales are also abundant off Newfoundland (Lawson & Gosselin 2011), both inshore and offshore. A lack of pulse trains at high-latitude feeding grounds in the western North Atlantic was also noted by Risch et al. (2014a). Under the assumption that pulse trains are produced by males, as is the case for songs produced by blue, fin, and humpback whales (Croll et al. 2002, Darling et al. 2006, Oleson et al. 2007), the lack of pulse trains in the northern half of the study area could be explained by sexual segregation and a female-biased sex ratio, as observed in minke whales at other high-latitude feeding grounds such as the GSL (Gavrilchuk et al. 2014) and off West Greenland (Laidre et al. 2009). Although PAM for minke whales has been successful in some areas of the North Atlantic (Risch et al. 2014a,b), it may not be as broadly applicable as in other species, depending on the study area. Reassessing this data set using an automated pulse train detector could provide more robust answers regarding the occurrence of these signals in eastern Canadian waters.

The limited manual review of data identified potentially important areas for sei whales. Although detected at nearly all stations (except those in or near the GSL), deep-water stations in the Orphan Basin and off the southern Labrador Shelf concentrated the bulk of the manual detections. These areas coincide with the migratory destinations of sei whales tagged in the Azores in the spring (Prieto et al. 2014) and are consistent with their preference for deep oceanic waters. Given the recent listing of the species as endangered in Canada (COSEWIC 2019), conservation and management of this species would benefit from a dedicated analysis of this data set.

4.5. Final remarks

This study highlighted the broad spatio-temporal distribution of blue, fin, and humpback whales and identified areas that may deserve further attention, particularly the Scotian Shelf region and Flemish Pass–Orphan Basin areas. The latter is noteworthy due to ongoing oil and gas exploration and the potential for prolonged noise exposures and behavioral disruption. Further, some areas with active exploration programs (e.g. Flemish Pass) are in international waters. Although seafloor resource extraction is regulated by Canada under the United Nations Convention on the Law of the Sea, the question of the responsibility for the management of free-ranging species affected by the relevant activities has yet to be addressed.

As noted by Davis et al. (2020), baleen whale distribution can change over relatively short time frames. Climate change is likely to accelerate marine mammal distributional changes (Moore & Huntington 2008, Silber et al. 2017). In this study, the apparent range contraction observed in spring in blue, fin, and humpback whales coincided with the maximum sea ice extent in eastern Canadian waters (Figs. 5, 7, & 9). Declining sea ice cover will increase habitat available in winter and spring, and changes in prey type or distribution may induce changes in foraging areas (Nøttestad et al. 2015). The patterns of occurrence presented here are the first to cover this extensive area for a continuous period and provide a baseline against which future changes can be assessed. This data set (of which data recorded at Stns 1–20 are publicly available) could also be used to investigate which environmental variables influence habitat use by these species.

Going beyond presence–absence, further evaluation of the relative significance of different areas is required. This is particularly relevant for blue whales because some individuals sighted in eastern Canadian waters do not frequent the GSL (Ramp & Sears 2013), which remains the only substantial aggregation site known in the northwest Atlantic. In fin whales, quantifying sound pressure levels within the band of their vocalizations (18–25 Hz) by week or month could allow an assessment of the relative importance of different areas over time (Nieukirk et al. 2012), especially if this metric can be corrected for the size of the listening area. A closer look at acoustic behavior could provide information about the use of habitats by these species. For instance, blue whale A-B calls emitted as song units are produced by lone traveling males, presumably as part of the species' reproductive behavior, while singular A-B calls are produced by males generally associated with other individuals in various behavioral states, including foraging (Oleson et al. 2007).

Davis et al. (2020) investigated the acoustic occurrence of baleen whales between 2004 and 2014 between Florida and the Scotian Shelf. They noted a decline in the occurrence of blue, fin, and humpback whales on the Scotian Shelf after 2010. Whitehead (2013) noted a decline in sighting rates of fin and humpback whales in the Gully Marine Protected Area and an increase in blue whale observations between 1993 and 2011. Although not directly comparable to Davis et al. (2020), our results indicate that the Scotian Shelf region remains an important habitat for all 3 species and that ongoing changes in distribution may be occurring. These observations strengthen the call for continued monitoring of the ranges of these species to track distributional shifts and allow for adaptive management.

Acknowledgements. We acknowledge the Environmental Studies Research Fund and the Department of Fisheries and Oceans' Species at Risk Implementation Funds and National Conservation Plan for funding the data acquisition and analysis. We thank Ron Kessel for his critical review of the detection range modeling methodology. Special thanks to Emily Maxner and Jessica Wingfield for their contribution to the manual analysis; Jeff MacDonnell, Carmen Lawrence, and Eric Lumsden for their participation to the fieldwork effort; Karen Scanlon and Dara Carr for editorial review; and the JASCO equipment team for ensuring the success of the monitoring program thanks to their skilled preparation of recorders. The crews of the FV 'Shirley & Philip', FV 'Labrador Venture', RV 'Coriolis II', and RV 'Leeway Odyssey' contributed to the logistical and operational success of the deployment and retrieval cruises.

LITERATURE CITED

Au WWL, Pack AA, Lammers MO, Herman LM, Deakos MH, Andrews K (2006) Acoustic properties of humpback whale songs. J Acoust Soc Am 120:1103–1110

Baumgartner MF, Van Parijs SM, Wenzel FW, Tremblay CJ, Esch HC, Warde AM (2008) Low frequency vocalizations attributed to sei whales (*Balaenoptera borealis*). J Acoust Soc Am 124:1339–1349

Becker JJ, Sandwell DT, Smith WHF, Braud J and others (2009) Global bathymetry and elevation data at 30 arc seconds resolution: SRTM30_PLUS. Mar Geod 32:355–371

Berchok CL, Bradley DL, Gabrielson TB (2006) St. Lawrence blue whale vocalizations revisited: characterization of calls detected from 1998 to 2001. J Acoust Soc Am 120: 2340–2354

Bouffaut L, Landrø M, Potter JR (2021) Source level and vocalizing depth estimation of two blue whale subspecies in the western Indian Ocean from single sensor observations. J Acoust Soc Am 149:4422–4436

Breiwick JM (1994) Population dynamics and analyses of the fisheries for fin whales (*Balaenoptera physalus*) in the northwest Atlantic Ocean. PhD dissertation, University of Washington, Seattle, WA

Brown MW, Fenton D, Smedbol K, Merriman C, Robichaud-Leblanc K, Conway JD (2009) Recovery strategy for the North Atlantic right whale (*Eubalaena glacialis*) in Atlantic Canadian Waters [Final]. Species at Risk Act Recovery Strategy Series. Fisheries and Oceans Canada, Ottawa

Browning E, Gibb R, Glover-Kapfer P, Jones KE (2017) Passive acoustic monitoring in ecology and conservation. WWF Conservation Technology Series 1(2). WWF-UK, Woking

Carnes MR (2009) Description and evaluation of GDEM-V 3.0. NRL Memo Rep 7330-09-9165. US Naval Research Laboratory, Stennis Space Center, MS. https://apps.dtic.mil/dtic/tr/fulltext/u2/a494306.pdf

Castellote M, Clark CW, Lammers MO (2012) Acoustic and behavioural changes by fin whales (*Balaenaptera physalus*) in response to shipping and airgun noise. Biol Conserv 147:115–122

Charif RA, Mellinger DK, Dunsmore KJ, Fristrup KM, Clark CW (2002) Estimated source levels on fin whale (*Balaenoptera physalus*) vocalizations: adjustment for surface interference. Mar Mamm Sci 18:81–98

Collins MD (1994) Generalization of the split-step Padé solution. J Acoust Soc Am 96:382–385

Comtois S, Savenkoff C, Bourassa MN, Brêthes JC, Sears R (2010) Regional distribution and abundance of blue and humpback whales in the Gulf of St. Lawrence. Can Tech Rep Fish Aquat Sci 2877. https://publications.gc.ca/collections/collection_2011/mpo-dfo/Fs97-6-2877-eng.pdf

Coppens AB (1981) Simple equations for the speed of sound in Neptunian waters. J Acoust Soc Am 69:862–863

COSEWIC (Committee on the Status of Endangered Wildlife in Canada) (2002) COSEWIC assessment and update status report on the blue whale *Balaenoptera musculus* (Atlantic population and Pacific population) in Canada. https://www.sararegistry.gc.ca/virtual_sara/files/cosewic/sr_blue_whale_e.pdf

COSEWIC (2019) COSEWIC assessment and status report on the sei whale *Balaenoptera borealis*, Atlantic population, in Canada. https://publications.gc.ca/collections/collection_2020/eccc/CW69-14-335-2019-eng.pdf

Croll DA, Clark CW, Acevedo-Gutiérrez A, Tershy B, Flores S, Gedamke J, Urban J (2002) Only male fin whales sing loud songs. Nature 417:809

Darling JD, Jones ME, Nicklin CP (2006) Humpback whale songs: Do they organize males during the breeding season? Behaviour 143:1051–1101

Davies KTA, Vanderlaan ASM, Smedbol RK, Taggart CT (2015) Oceanographic connectivity between right whale critical habitats in Canada and its influence on whale abundance indices during 1987–2009. J Mar Syst 150: 80–90

Davies KTA, Brown MW, Hamilton PK, Knowlton AR, Taggart CT, Vanderlaan ASM (2019) Variation in North Atlantic right whale *Eubalaena glacialis* occurrence in the Bay of Fundy, Canada, over three decades. Endang Species Res 39:159–171

Davis GE, Baumgartner MF, Bonnell JM, Bell J and others (2017) Long-term passive acoustic recordings track the changing distribution of North Atlantic right whales (*Eubalaena glacialis*) from 2004 to 2014. Sci Rep 7:13460

Davis GE, Baumgartner MF, Corkeron PJ, Bell J and others (2020) Exploring movement patterns and changing distributions of baleen whales in the western North Atlantic using a decade of passive acoustic data. Glob Change Biol 26:4812–4840

Delarue J, Todd SK, Van Parijs SM, Di Iorio L (2009) Geographic variation in Northwest Atlantic fin whale (*Balaenoptera physalus*) song: implications for stock structure assessment. J Acoust Soc Am 125:1774–1782

Delarue J, Kowarski KA, Maxner EE, MacDonnell JT, Martin SB (2018) Acoustic monitoring along Canada's east coast: August 2015 to July 2017. Doc No. 01279. ESRF Rep No. 215, Version 1.0. Tech Rep prepared by JASCO Applied Sciences for Environmental Studies Research Fund. https://www.esrfunds.org/sites/www.esrfunds.org/files/publications/ESRF215_Delarue,%20J_et%20al.pdf

Deveau TJ, Delarue J, Martin SB, Lucke K (2018) Transmission loss modelling of seismic airgun sounds: predicted received levels, with frequency weighting, off Atlantic Canada. Doc No. 0162. ESRF Rep No. 217, Version 2.0. Tech Rep prepared by JASCO Applied Sciences for Environmental Studies Research Fund. https://www.esrfunds.org/sites/www.esrfunds.org/files/publications/ESRF217_Deveau,%20T_J%20et%20al.pdf

DFO (Department of Fisheries and Oceans Canada) (2017) Critical habitat of the North Atlantic right whale (*Eubalaena glacialis*). Order SOR/2017-262. https://laws-lois.justice.gc.ca/PDF/SOR-2017-262.pdf

DFO (2018) Identification of habitat important to the blue whale in the western North Atlantic. Science Advisory Report 2018/003. Canadian Science Advisory Secretariat, Quebec Region. https://waves-vagues.dfo-mpo.gc.ca/Library/40687776.pdf

Doniol-Valcroze T, Berteaux D, Larouche P, Sears R (2007) Influence of thermal fronts on habitat selection by four rorqual whale species in the Gulf of St. Lawrence. Mar Ecol Prog Ser 335:207–216

Doniol-Valcroze T, Lesage V, Giard J, Michaud R (2011) Optimal foraging theory predicts diving and feeding strategies of the largest marine predator. Behav Ecol 22: 880–888

Dunlop RA, Noad MJ, Cato DH, Stokes D (2007) The social vocalization repertoire of east Australian migrating humpback whales (*Megaptera novaeangliae*). J Acoust Soc Am 122:2893–2905

Garcia HA, Zhu C, Schinault ME, Kaplan AI and others (2019) Temporal–spatial, spectral, and source level distributions of fin whale vocalizations in the Norwegian Sea observed with a coherent hydrophone array. ICES J Mar Sci 76:268–283

Gavrilchuk K, Lesage V, Ramp C, Sears R, Bérubé M, Bearhop S, Beauplet G (2014) Trophic niche partitioning among sympatric baleen whale species following the collapse of groundfish stocks in the Northwest Atlantic. Mar Ecol Prog Ser 497:285–301

Girola E, Noad MJ, Dunlop RA, Cato DH (2019) Source levels of humpback whales decrease with frequency suggesting an air-filled resonator is used in sound production. J Acoust Soc Am 145:869–880

Gomez C, Lawson J, Kouwenberg AL, Moors-Murphy H and others (2017) Predicted distribution of whales at risk: identifying priority areas to enhance cetacean monitoring in the Northwest Atlantic Ocean. Endang Species Res 32:437–458

Gomez C, Konrad CM, Vanderlaan A, Moors-Murphy HB and others (2020) Identifying priority areas to enhance monitoring of cetaceans in the Northwest Atlantic Ocean. Can Tech Rep Fish Aquat Sci 3370. https://waves-vagues.dfo-mpo.gc.ca/Library/40869155.pdf

Johnson KF, Davoren GK (2021) Distributional patterns of humpback whales (*Megaptera novaeangliae*) along the Newfoundland East Coast reflect their main prey, capelin (*Mallotus villosus*). Mar Mamm Sci 37:80–97

Johnston DW, Thorne LH, Read AJ (2005) Fin whales *Balaenoptera physalus* and minke whales *Balaenoptera acutorostrata* exploit a tidally driven island wake ecosystem in the Bay of Fundy. Mar Ecol Prog Ser 305:287–295

Katona SK, Beard JA (1990) Population size, migrations and feeding aggregations of the humpback whale (*Megaptera novaeangliae*) in the western North Atlantic Ocean. Rep Int Whaling Comm 12:295–306

Kennedy AS, Zerbini AN, Vásquez OV, Gandilhon N, Clapham PJ, Adam O (2014) Local and migratory movements of humpback whales (*Megaptera novaeangliae*) satellite-tracked in the North Atlantic Ocean. Can J Zool 92:9–18

Kenney RD (2018) What if there were no fishing? North Atlantic right whale population trajectories without entanglement mortality. Endang Species Res 37:233–237

Kowarski KA, Moors-Murphy H (2021) A review of big data analysis methods for baleen whale passive acoustic monitoring. Mar Mamm Sci 37:652–673

Kowarski KA, Evers C, Moors-Murphy H, Martin B, Denes SL (2018) Singing through winter nights: seasonal and diel occurrence of humpback whale (*Megaptera novaeangliae*) calls in and around the Gully MPA, offshore eastern Canada. Mar Mamm Sci 34:169–189

Kowarski KA, Moors-Murphy H, Maxner EE, Cerchio S (2019) Western North Atlantic humpback whale fall and spring acoustic repertoire: insight into onset and cessation of singing behavior. J Acoust Soc Am 145:2305–2316

Kowarski KA, Gaudet BJ, Cole AJ, Maxner EE and others (2020) Near real-time marine mammal monitoring from gliders: practical challenges, system development, and management implications. J Acoust Soc Am 148:1215–1230

Kowarski KA, Cerchio S, Whitehead H, Moors-Murphy H (2021a) Where, when, and why do western North Atlantic humpback whales begin to sing? Bioacoustics, doi:10.1080/09524622.2021.1972838

Kowarski KA, Delarue JJY, Gaudet BJ, Martin SB (2021b) Automatic data selection for validation: a method to determine cetacean occurrence in large acoustic data sets. JASA Express Lett 1:051201

Laidre KL, Heagerty PJ, Heide-Jørgensen MP, Witting L, Simon M (2009) Sexual segregation of common minke whales (*Balaenoptera acutorostrata*) in Greenland, and the influence of sea temperature on the sex ratio of catches. ICES J Mar Sci 66:2253–2266

Lawson JW (2006) Preliminary information on distribution and abundance of fin whales (*Balaenoptera physalus*) in Newfoundland and Labrador, Canada. Document Number SC/14/FW/21-SC/M06/FW21. International Whaling Commission, Impington. https://iwc.int/home

Lawson JW, Gosselin JF (2011) Fully-corrected cetacean abundance estimates from the Canadian TNASS survey. Working Paper 10. National Marine Mammal Peer Review Meeting. Department of Fisheries and Oceans, Ottawa

Lawson JW, Gosselin JF (2018) Estimates of cetacean abundance from the 2016 NAISS aerial surveys of eastern Canadian waters, with a comparison to estimates from the 2007 TNASS. NAMMCO SC/25/AE/09. NAMMCO Secretariat, Tromsø

Lesage V, Gavrilchuk K, Andrews RD, Sears R (2017) Foraging areas, migratory movements and winter destinations of blue whales from the western North Atlantic. Endang Species Res 34:27–43

Lesage V, Gosselin JF, Lawson JW, McQuinn I and others (2018) Habitats important to blue whales (*Balaenoptera musculus*) in the western North Atlantic. Doc No. 2016/080. DFO Canadian Science Advisory Secretariat. https://waves-vagues.dfo-mpo.gc.ca/Library/40681373.pdf

McKenna MF (2011) Blue whale response to underwater noise from commercial ships. PhD dissertation, University of California, San Diego, CA

Melcón ML, Cummins AJ, Kerosky SM, Roche LK, Wiggins SM, Hildebrand JA (2012) Blue whales respond to anthropogenic noise. PLOS ONE 7:e32681

Mellinger DK, Clark CW (2003) Blue whale (*Balaenoptera musculus*) sounds from the North Atlantic. J Acoust Soc Am 114:1108–1119

Mitchell ED (1974) Present status of northwest Atlantic fin and other whale stocks. In: Schevill WE (ed) The whale problem: a status report. Harvard University Press, Cambridge, MA, p 108–169

Moore SE, Huntington HP (2008) Arctic marine mammals and climate change: impacts and resilience. Ecol Appl 18:S157–S165

Moors-Murphy HB (2014) Submarine canyons as important habitat for cetaceans, with special reference to the Gully: a review. Deep Sea Res II 104:6–19

Moors-Murphy HB, Lawson JW, Rubin B, Marotte E, Renaud G, Fuentes-Yaco C (2019) Occurrence of blue whales (*Balaenoptera musculus*) off Nova Scotia, Newfoundland, and Labrador. Res Doc 2018/007. DFO Canadian Science Advisory Secretariat. https://waves-vagues.dfo-mpo.gc.ca/Library/40779336.pdf

Morano JL, Salisbury DP, Rice AN, Conklin KL, Falk KL, Clark CW (2012) Seasonal and geographical patterns of fin whale song in the western North Atlantic Ocean. J Acoust Soc Am 132:1207–1212

Nieukirk SL, Mellinger DK, Moore SE, Klinck K, Dziak RP, Goslin J (2012) Sounds from airguns and fin whales recorded in the mid-Atlantic Ocean, 1999–2009. J Acoust Soc Am 131:1102–1112

Nøttestad L, Krafft BA, Anthonypillai V, Bernasconi M, Langård L, Mørk HL, Fernö A (2015) Recent changes in distribution and relative abundance of cetaceans in the Norwegian Sea and their relationship with potential prey. Front Ecol Evol 2:83

Oleson EM, Calambokidis J, Burgess WC, McDonald MA, Leduc CA, Hildebrand JA (2007) Behavioral context of call production by eastern North Pacific blue whales. Mar Ecol Prog Ser 330:269–284

Ou H, Au WWL, Van Parijs SM, Oleson EM, Rankin S (2015) Discrimination of frequency-modulated baleen whale downsweep calls with overlapping frequencies. J Acoust Soc Am 137:3024–3032

Parks SE, Searby A, Célérier A, Johnson MP, Nowaceck DP, Tyack PL (2011) Sound production behavior of individual North Atlantic right whales: implications for passive acoustic monitoring. Endang Species Res 15:63–76

Payne RS, McVay S (1971) Songs of humpback whales. Science 173:585–597

Prieto R, Silva MA, Waring GT, Gonçalves JMA (2014) Sei whale movements and behaviour in the North Atlantic inferred from satellite telemetry. Endang Species Res 26: 103–113

Ramp C, Sears R (2013) Distribution, densities, and annual occurrence of individual blue whales (*Balaenoptera musculus*) in the Gulf of St. Lawrence, Canada from 1980–2008. Res Doc 2012/157. DFO Canadian Science Advisory Secretariat. https://waves-vagues.dfo-mpo.gc.ca/Library/348690.pdf

Ramp C, Bérubé M, Hagen W, Sears R (2006) Survival of adult blue whales *Balaenoptera musculus* in the Gulf of St. Lawrence, Canada. Mar Ecol Prog Ser 319:287–295

Ramp C, Hagen W, Palsbøll P, Bérubé M, Sears R (2010) Age-related multi-year associations in female humpback whales (*Megaptera novaeangliae*). Behav Ecol Sociobiol 64:1563–1576

Ramp C, Delarue J, Bérubé M, Hammond PS, Sears R (2014) Fin whale survival and abundance in the Gulf of St. Lawrence, Canada. Endang Species Res 23:125–132

Ramp C, Delarue JJY, Palsbøll PJ, Sears R, Hammond PS (2015) Adapting to a warmer ocean — seasonal shift of baleen whale movements over three decades. PLOS ONE 10:e0121374

Ramp C, Gaspard D, Gavrilchuk K, Unger M and others (2021) Up in the air: drone images reveal underestimation of entanglement rates in large rorqual whales. Endang Species Res 44:33–44

Risch D, Clark CW, Dugan PJ, Popescu M, Siebert U, Van Parijs SM (2013) Minke whale acoustic behavior and multi-year seasonal and diel vocalization patterns in Massachusetts Bay, USA. Mar Ecol Prog Ser 489:279–295

Risch D, Castellote M, Clark CW, Davis GE and others (2014a) Seasonal migrations of North Atlantic minke whales: novel insights from large-scale passive acoustic monitoring networks. Mov Ecol 2:24

Risch D, Siebert U, Van Parijs SM (2014b) Individual calling behaviour and movements of North Atlantic minke whales (*Balaenoptera acutorostrata*). Behaviour 151: 1335–1360

Roy N, Simard Y, Aulanier F & Giard S (2018) Fin whale continuous frequentation of St. Lawrence habitats detected from multi-year passive acoustic monitoring (PAM). Res Doc 2018/059. Canadian Science Advisory Secretariat. https://waves-vagues.dfo-mpo.gc.ca/Library/40803612.pdf

Samaran F, Guinet C, Adam O, Motsch JF, Cansi Y (2010) Source level estimation of two blue whale subspecies in southwestern Indian Ocean. J Acoust Soc Am 127: 3800–3808

SARA (Species at Risk Act) (2002) Species at Risk Act. In: Government of Canada (ed) SC 2002, c 29. Government of Canada. https://laws.justice.gc.ca/PDF/S-15.3.pdf

Schleimer A, Ramp C, Delarue J, Carpentier A and others (2019a) Decline in abundance and apparent survival rates of fin whales (*Balaenoptera physalus*) in the northern Gulf of St. Lawrence. Ecol Evol 9:4231–4244

Schleimer A, Ramp C, Plourde S, Lehoux C, Sears R, Hammond PS (2019b) Spatio-temporal patterns in fin whale *Balaenoptera physalus* habitat use in the northern Gulf of St. Lawrence. Mar Ecol Prog Ser 623:221–234

Sergeant DE (1966) Populations of large whale species in the western North Atlantic with special reference to the fin whale. Doc No. 9. Fisheries Research Board of Canada, Arctic Biological Station

Silber GK, Lettrich MD, Thomas PO, Baker JD and others (2017) Projecting marine mammal distribution in a changing climate. Front Mar Sci 4:413

Simard Y, Roy N, Aulanier F, Giard S (2016) Blue whale continuous frequentations of St. Lawrence habitats from multi-year PAM series. Res Doc 2016/091. Canadian Science Advisory Secretariat, Quebec Region. https://waves-vagues.dfo-mpo.gc.ca/Library/40577028.pdf

Širović A, Hildebrand JA, Wiggins SM (2007) Blue and fin whale call source levels and propagation range in the Southern Ocean. J Acoust Soc Am 122:1208–1215

Širović A, Hildebrand JA, Wiggins SM, Thiele D (2009) Blue and fin whale acoustic presence around Antarctica during 2003 and 2004. Mar Mamm Sci 25:125–136

Smith WHF, Sandwell DT (1997) Global sea floor topography from satellite altimetry and ship depth soundings. Science 277:1956–1962

Stafford KM, Mellinger DK, Moore SE, Fox CG (2007) Seasonal variability and detection range modeling of baleen whale calls in the Gulf of Alaska, 1999–2002. J Acoust Soc Am 122:3378–3390

Stevick PT, Allen J, Clapham PJ, Katona SK and others (2006) Population spatial structuring on the feeding grounds in North Atlantic humpback whales (*Megaptera novaeangliae*). J Zool (Lond) 270:244–255

Sutcliffe WH Jr, Brodie PF (1977) Whale distributions in Nova Scotia waters. Fisheries and Marine Service Tech Rep 722. Fisheries and Environment Canada. https://waves-vagues.dfo-mpo.gc.ca/Library/18300.pdf

Teague WJ, Carron MJ, Hogan PJ (1990) A comparison between the Generalized Digital Environmental Model and Levitus climatologies. J Geophys Res 95:7167–7183

Tremblay CJ, Van Parijs SM, Cholewiak D (2019) 50 to 30-Hz triplet and singlet down sweep vocalizations produced by sei whales (*Balaenoptera borealis*) in the western North Atlantic Ocean. J Acoust Soc Am 145:3351–3358

van der Hoop J, Corkeron P, Moore M (2017) Entanglement is a costly life-history stage in large whales. Ecol Evol 7: 92–106

Vanderlaan ASM, Taggart CT, Serdynska AR, Kenney RD, Brown MW (2008) Reducing the risk of lethal encounters: vessels and right whales in the Bay of Fundy and on the Scotian Shelf. Endang Species Res 4:283–297

Vanderlaan ASM, Smedbol RK, Taggart CT (2011) Fishing-gear threat to right whales (*Eubalaena glacialis*) in Canadian waters and the risk of lethal entanglement. Can J Fish Aquat Sci 68:2174–2193

Vu ET, Risch D, Clark CW, Gaylord S and others (2012) Humpback whale song occurs extensively on feeding grounds in the western North Atlantic Ocean. Aquat Biol 14:175–183

Wang D, Huang W, Garcia H, Ratilal P (2016) Vocalization source level distributions and pulse compression gains of diverse baleen whale species in the Gulf of Maine. Remote Sensing 8(11):881

Watkins WA (1981) Activities and underwater sounds of fin whales. Sci Rep Whales Res Inst 33:83–117

Watkins WA, Tyack PL, Moore KE, Bird JE (1987) The 20-Hz signals of finback whales (*Balaenoptera physalus*). J Acoust Soc Am 82:1901–1912

Watkins WA, Daher MA, Reppucci GM, George JE, Martin DL, Dimarzio NA, Gannon DP (2000) Seasonality and distribution of whale calls in the North Pacific. Oceanography 13:62–67

Whitehead H (2013) Trends in cetacean abundance in the Gully submarine canyon, 1988–2011, highlight a 21% per year increase in Sowerby's beaked whales (*Mesoplodon bidens*). Can J Zool 91:141–148

Whitehead H, Carscadden JE (1985) Predicting inshore whale abundance — whales and capelin off the Newfoundland Coast. Can J Fish Aquat Sci 42:976–981

Whitehead H, Silver R, Harcourt P (1982) The migration of humpback whales along the northeast coast of Newfoundland. Can J Zool 60:2173–2179

Yochem PK, Leatherwood S (1985) Blue whale *Balaenoptera musculus* (Linnaeus, 1758). In: Ridgway SH, Harrison R (eds) Handbook of marine mammals. Academic Press, London, p 193–240

Zimmer WMX (2011) Passive acoustic monitoring of cetaceans. Cambridge University Press, Cambridge

Editorial responsibility: Ana Cañadas, Durham, North Carolina, USA
Reviewed by: J. Roberts, T. Yack and 1 anonymous referee

Submitted: July 30, 2021
Accepted: December 13, 2021
Proofs received from author(s): April 5, 2022