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Exposure of satellite tagged bowhead whales (*Balaena mysticetus*) to transiting vessels in the Eastern Canadian Arctic

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Abstract

Climate change poses new challenges to Arctic marine mammals, with increasing vessel traffic and associated underwater noise pollution emerging as significant threats. The bowhead whale (*Balaena mysticetus*), an endemic Arctic cetacean, faces these new threats. The Eastern Canada-West Greenland (ECWG) bowhead whale population migrates through areas with the highest levels of vessel traffic in the Canadian Arctic. Here, we document the spatial and temporal overlap between 36 satellite-tagged ECWG bowhead whales and vessels equipped with Automatic Identification System (AIS) transponders during 2012–2017. We report 1,145 instances where vessels were within 125 km of a tagged whale, with 306 occurrences within distances ≤50 km. Overlap between vessels and tagged bowhead whales was quantified monthly within years to investigate individual whale encounter rates. Results indicate that ECWG bowhead whales encounter the majority (79%) of vessels annually during August–October,

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with the highest number of encounters (42%) observed in September. Encounter rates ranged from 0.25 to 0.51 vessels encountered per day per whale during August–October compared to <0.07 vessels per day in all other months in this study. To better inform conservation strategies, further research is required to assess bowhead whale behavioral responses relative to distance from vessels.

KEYWORDS
acoustic disturbance, anthropogenic noise, automatic identification system, bio-logging tags, cetacean, Northwest Passage, vessel strike, vessel traffic

1 | INTRODUCTION

There are two distinct populations of bowhead whales (*Balaena mysticetus*) in the Canadian Arctic: the Bering-Chukchi-Beaufort (BCB) in the west, and the Eastern Canada-West Greenland (ECWG) population in the east (Rugh et al., 2002). The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has assessed the BCB and ECWG populations to be of Special Concern (Committee on the Status of Endangered Wildlife in Canada, 2009; Fisheries and Oceans Canada, 2014). Both populations were heavily impacted by commercial whaling and are slowly recovering to pre-exploitation numbers (Frasier et al., 2015). Bowhead whales are a culturally important species to Inuit communities in the Canadian Arctic and in West Greenland, where limited and regulated subsistence hunts contribute to traditional practices including food security (Nunavut Wildlife Management Board, 2000; Reeves & Lee, 2022; Suydam & George, 2021).

Bowhead whales are considered highly vulnerable to vessel traffic due to the overlap of their seasonal distribution with Arctic vessel sea routes (Figure 1; Halliday et al., 2021, 2022a,b; Hauser et al., 2018; Martin et al. 2023). In the eastern Canadian Arctic, bowhead whale annual migrations follow the oscillation of sea ice formation and retreat (Fortune et al., 2020a). During winter, ECWG bowhead whales are found in Hudson Strait, northern Hudson Bay, eastern Baffin Island, and the ice edge off West Greenland (Koski et al., 2006; Reeves & Heide-Jørgensen, 1996). In spring, whales from this population reside along the west coast of Greenland, Cumberland Sound, Foxe Basin and Lancaster Sound (Ferguson et al., 2010; Pomerleau et al., 2011). During summer, ECWG bowhead whales are found in bays and fjords in the Canadian High Arctic, such as the Gulf of Boothia, Foxe Basin, eastern Baffin Island, and as far south as Hudson Bay (Cosens & Innes, 2000; Cosens et al., 1997; Ferguson et al., 2010; Higdon & Ferguson, 2010; Pomerleau et al., 2011). Bowhead whales feed on zooplankton (e.g., calanoid copepods; Fortune et al., 2020b,c; Pontbriand et al., 2023), primarily during late summer through autumn (e.g., Finley, 2001; Pomerleau et al., 2011, 2012). However, stable isotope analysis and movement data from tagged whales have revealed that bowhead whales likely feed year-round, although at a lower rate in winter (Fortune et al., 2023; Matthews & Ferguson, 2015; Pomerleau et al., 2018). In autumn, ECWG bowhead whales are found along the east coast of Baffin Island, the west coast of Greenland, and Foxe Basin (Fortune et al., 2023; Reeves & Mitchell, 1990; Reeves et al., 1983). Due to their migration and seasonal movement patterns, ECWG bowhead whales potentially encounter a high number of vessels and associated underwater vessel noise annually, particularly during the open-water season in late summer through autumn (Figure 1; Halliday et al., 2022b).

Economic, geopolitical, and environmental changes resulting from a rapidly warming Arctic climate (Council of Canadian Academies, 2019; Intergovernmental Panel on Climate Change., 2022), has led to a tripling in vessel traffic in the Canadian Arctic over the past three decades (Dawson et al., 2018; Intergovernmental Panel on Climate

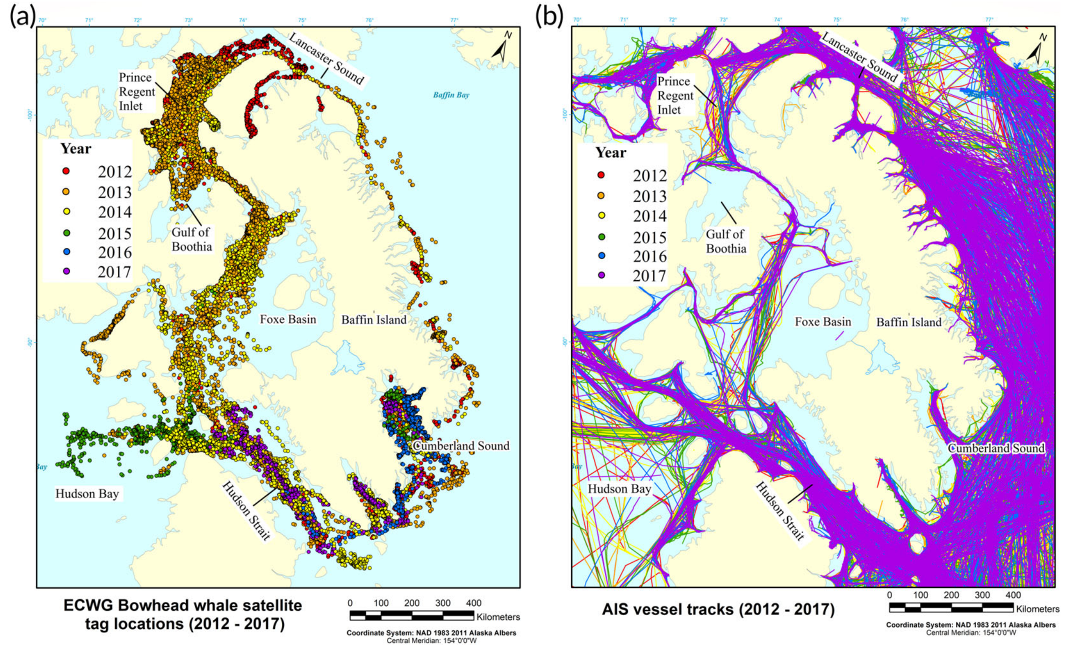

FIGURE 1 (A) Map of the satellite locations of the 36 telemetry-tagged Eastern Canada-West Greenland (ECWG) bowhead whales during 2012–2017. Whale locations are color coded by year. (B) Map of the vessel track-lines derived from Automatic Identification System (AIS) data during 2012–2017. Vessel track-lines are color coded by year.

Change., 2022). Continued increases in vessel traffic are expected as Arctic shipping routes become ice-free (Bennett et al., 2020; Mudryk et al., 2021; Zeng et al., 2020). Increased vessel traffic can negatively impact bowhead whales in a variety of ways including through an increased risk of collision with vessels, oiling events, and disruption of behavior through vessel presence or noise they generate (George et al., 2017; Halliday, 2020a; Protection of the Arctic Marine Environment, 2019).

Although vessel strike risk and entanglement are presently lower for bowhead whales than for temperate large whale populations residing along heavily developed coastal regions, bowhead whale behavior and increasing vessel traffic due to sea ice reduction elevate these threats (Huntington et al., 2020; Reeves et al., 2012). Bowhead whales are expected to be as vulnerable to vessel strikes as their close relative, the critically endangered North Atlantic right whale *(Eubalaena glacialis)*, because they share similar body morphology and frequently spend time performing surface behaviors, including skim feeding, socializing, nursing, and mating (Dombroski et al., 2021; Laist et al., 2001).

Bowhead whales are continuous ram filter feeders, and may experience reduced feeding efficiency if baleen plates are contaminated by petroleum or become entangled in fishing gear or marine debris (Lambertson et al., 2005). A vertical shift in bowhead prey seasonally occurs during spring and early summer, where aggregations of copepods are found near the surface (Fortune et al., 2023) grazing on phytoplankton. The shallow concentration of prey elevates the risk of vessel strikes. Furthermore, vessel noise is mostly emitted at low frequencies (i.e., <1 kHz) where hearing sensitivity of bowhead whales is inferred to be the most acute (Erbe, 2002; Ketten et al., 2016), although vessels do produce broadband noise that can reach frequencies >10 kHz (Veirs et al., 2016). The presence of vessels and vessel noise has elicited avoidance behavior in some bowhead whales at distances up to 15 km, which can lead to displacement from biologically important areas (Koski & Johnson, 1987; Richardson & Malme, 1993; Richardson et al., 1985a,b; Wartzok et al., 1989). Recent studies have begun to examine the potential overlap or exposure between some Arctic marine mammal populations and vessels or vessel noise (e.g., Halliday, 2020b; Halliday et al., 2018, 2021, 2022a,b; Hauser et al., 2018; Martin et al., 2022, 2023; Reeves et al., 2014). However, a quantitative assessment of the degree of exposure or overlap is needed for effective management.

The current study reports ECWG bowhead whale location data from satellite-linked time and depth transmitters (i.e., bio-logging tags) relative to vessel locations derived from satellite Automatic Identification System (AIS) data. Combining spatial–temporal information about whale and vessel location, we summarize vessel encounter rates for individual whales. The scope of this study encompasses ECWG bowhead whale encounters with vessels from 2012 to 2017 over their range throughout the Eastern Canadian Arctic.

2 | MATERIALS AND METHODS

2.1 | Study area and focal animals

This study focuses on the Eastern Canadian Arctic and West Greenland region, encompassing northern Hudson Bay, Hudson Strait, Foxe Basin, Gulf of Boothia, and Baffin Bay to the west coast of Greenland (Figure 1). During 2012, 2013, and 2016, bowhead whales from the ECWG population were tagged in Cumberland Sound and Foxe Basin, Nunavut (Table S1). Methods for tag deployment are detailed in Ferguson et al. (2010) and Fortune et al. (2020a).

Whales were instrumented with Wildlife Computers location-only SPOT tags, or SPLASH Mk10 tags, which provided information on diving behavior in addition to location data (Wildlife Computers Inc., Redmond, WA; Table S1). Location data were obtained via Doppler effect and the Argos satellite system for the tagged bowhead whales during 2012–2017 (Figure 1a).

Argos satellite tags have been widely used to track large-scale animal movements; however, these tags provide relatively coarse quality locations typically with an accuracy of several hundred meters to several kilometers (https://www.argos-system.org). Each Argos location is assigned a location accuracy designated by a number or letter dependent on the number of orbiting satellites via which the transmission is received, among other factors (https://www.argos-system.org; accuracy categories: 3 [<250 m], 2 [250–500 m], 1 [500–1,500 m], 0 [>1,500 m], A and B [unbounded], Z [invalid]). Consideration of these location accuracies is important when examining fine scale movements of individuals. To increase tag longevity, tags were programmed to limit transmissions to <400 per day during summer, and to <100 transmissions every second day during winter. Depending on satellite reception, programming, and animal behavior (i.e., a tag can only transmit while the animal is at the surface), this transmission rate could lead to temporal gaps of days between satellite-derived locations.

We modeled bowhead locations to account for accuracy issues associated with Argos data using a continuous-time Correlated Random Walk (CRW) model developed by Johnson et al. (2008) and implemented in the "crawl" package (version 2.2/1; Johnson & London, 2018) in R (R Core Team, 2021). The CRW algorithm performs poorly when Argos error greatly exceeds measured values and CRW model priors. Consequently, extreme outliers were removed by filtering the raw location data through the *sdafilter* in the R package "argosfilter" (Freitas et al., 2008; Freitas, 2012). We used the default velocity threshold of 2 m/s, which is identical to the method used by Fortune et al. (2020a) that fit a hierarchical switching-state-space model for the satellite locations from the same tagged individuals. The filter can also be specified to remove outliers which create acute angles in the path of movement (i.e., "spikes"). We used default values for specifying the angular components of the filter; specifically, we removed values that formed angles <15° when they were >2.5 km from the previous location and angles <25° when they were >5 km from the prior location.

The CRW model treats movement as a velocity process with two parameters, β, the autocorrelation in velocity and σ, the variation in velocity. Location error was assumed to be normally distributed with a mean of 0 and a standard deviation equal to that declared by the system operator, Collecte Localisation Satellites, for least-squares location classes 3, 2, and 1 (Collecte Localisation Satellites, 2016). We treated error for the remaining three location classes as parameters to be estimated and fit them to half normal distributions with semi-informative priors. Locations with classes 0, A, and B should have more error than those with a class of 1 (*SD* = 1,500 m). Hence, our half normal distributions had a lower bound of 1,500 m. Using data from Vincent et al. (2002), our priors had a mean error of 1,500 m and a standard deviation of 5,000 m for location classes 0 and A, and 7,500 m for location class B. We also set a Laplace prior (double exponential) for β and σ. The Laplace prior had a mean of 3 and a variance of 0.5 on a natural log scale, which is approximately the value of β and σ observed for most species. Note that this is only significant when tracks have few locations. This is the same model and error estimation used for Bering-Chukchi-Beaufort (BCB) bowhead whales in Citta et al. (2018) and Martin et al. (2023). We used the model to better estimate actual bowhead whale locations relative to Argos locations. Whale locations were not regularly spaced in time, and we did not use the model to predict where a whale might be located between Argos locations.

2.2 | Spatial and temporal analysis of ECWG bowhead whales and vessels

Vessel tracks from all months during 2012–2017 were derived from preprocessed satellite AIS data (Spire Global Inc., Cambridge, ON, Canada) in the Eastern Canadian Arctic spanning from Hudson Bay to the west coast of Greenland (Figure 1b), including both class A (mandatory) and class B (voluntary) transmissions. Preprocessing the AIS data involved removing spurious points that were on land, single positions from vessels with no other positions in the vicinity (~100 km), and positions with no maritime mobile service identity (MMSI) number. These former errors are related to either improperly installed AIS equipment or human manipulation to mask true positions of vessels (Jankowski et al., 2021). Positions from AIS data are otherwise assumed to be accurate, given that these locations are based on GPS on board the vessel. For example, one ground truthing study found that AIS positions were accurate to within <100 m of the vessel's actual location (Jankowski et al., 2021). AIS transponders transmit signals that provide the geographic coordinates and other information about individual vessels at regular intervals (e.g., every 2–120 s, depending on vessel behavior and context), and these signals can be received by dedicated satellites and land-based receivers. In earlier years (2012–2015), satellite coverage for AIS was lower in the Arctic, thus leaving some gaps between consecutive locations. However, satellite coverage increased after 2015, leaving smaller gaps between locations and often no gaps for vessels with class A AIS. Vessel traffic in the Eastern Canadian Arctic consists of a variety of vessels including bulk carriers, container ships, cruise ships, government icebreakers and research vessels, tankers, military vessels, ferries, fishing vessels, recreational vessels (i.e., pleasure craft), and local community boats (Arctic Council, 2009; Pizzolato et al., 2016; see Halliday et al., 2022b for a summary).

Several steps were taken to calculate the number of unique vessels that encountered individual tagged whales as well as the closest point of approach (CPA) for each encounter. We used satellite AIS data to calculate the number of unique vessels transiting in the same area (<125 km) and time (<1 hr time differential) as individual tagged whales. We acknowledge this may be a conservative estimate considering that additional vessels may have been present but not transmitting AIS data (i.e., note that only vessels >300 T or with 12 or more passengers are legally required to use AIS, which is class A AIS). Consequently, it is possible that small (~8 m) recreational vessels and local boats are likely underrepresented; however, with the decreasing price of AIS transponders, more recreational vessels are utilizing the technology, particularly in the Arctic where it can be an important safety feature. One vessel class not included in the data set is local boats, which are mostly used for subsistence activities and only range within tens of kilometers from communities and are not typically in the offshore areas preferred by bowhead whales. When a vessel track overlapped in time and space with a tagged bowhead whale, AIS data were used to calculate the range of distances between the vessel and the whale including the CPA during encounters.

A spatial and temporal analysis was completed in ArcGIS using ArcMap 10.8 (ESRI, 2011). First, a buffer radius of 125 km was created around each individual CRW predicted whale location. We selected a 125 km radius because previous modeling suggested that vessel noise can be greater than ambient levels at distances over 100 km in the region (Halliday et al., 2017). Vessel noise can theoretically contribute to ambient sound >125 km, although it is difficult to quantify at this distance (Aulanier et al., 2017). Next, we separated whale location and AIS vessel location data by "day" (i.e., 24-hr period) and paired these data sets in space and time. Individual whale and vessel data from the same day occurring within a radius of 125 km were then extracted and designated as being potentially coincident in the encounter zone. The maximum allowed time differential between a paired whale and vessel location was 1 hr, and the average (± *SD*) time differential was 24.5 (± 17.8) min, with a median of 22.5 min. Vessel speed was not accounted for when pairing locations, therefore, calculated distances between whale and vessel locations represent a snapshot in time. This process was completed separately for each tagged whale to ensure that all possible encounter zones between whales and vessels were included in the analysis. Next, the derived paired whale and vessel locations within each encounter zone were sorted by time to generate a time series of consecutive potential encounters while retaining all underlying data and geographic positional information. The "Points to Line" tool in ArcMap 10.8 was used to calculate the distance (meters) between the closest whale and vessel location as they approached each other within a given encounter zone. For each potential encounter occurring within a radius of 125 km on a given day, the CPA was calculated as the shortest distance observed between the whale and vessel.

If multiple vessels came within 125 km of an individual whale during an encounter, the CPAs from each whale-vessel encounter were compiled and sorted by date and time. This also allowed manual removal of duplicate encounters that resulted from an encounter spanning past midnight where it was included twice based on the original subsetting of data by "day." Once duplicates were removed, all encounters were sorted by the CPA distance and summarized by whale ID (Table S1). Potential hotspots for vessel encounters with distances <50 km were assessed by calculating bivariate normal kernel densities using the CPAs from each whale-vessel encounter using the "ks" package in R (Duong, 2019) with the smoother cross validation (SCV) bandwidth selector. This 50 km radius was chosen because other Arctic whales have been shown to exhibit avoidance responses at this range to vessel noise (Finley et al., 1990; Martin et al., 2022). We defined utilization distributions as the 5%, 25%, 50%, 75%, and 95% probability contours, representing concentration areas (Börger et al., 2006).

2.3 | Ethics approval

This research was conducted in accordance with the Marine Mammal Regulations of the Canadian Fisheries Act. Bowhead whale research was approved under the Fisheries and Oceans Canada License to Fish for Scientific Purposes Nos. S-12/13–1024-NU, S-13/14-1009-NU and S-16/17 1005-NU, and Animal Care Protocols FWI-ACC-3013-018, FWI-ACC-2014-011, FWI-ACC-2016-009.

3 | RESULTS

In the Eastern Canadian Arctic, 36 bowhead whales were tagged during 2012 ($n = 18$), 2013 ($n = 9$), and 2016 ($n = 9$), 19 of which were tagged in Cumberland Sound and 17 in Foxe Basin (see details in Fortune et al., 2020a; Table S1). The sample was composed of 18 females, 16 males, and two whales of unknown sex. Most whales ($n = 28$, 78%) were considered immature based on visually estimated body length (≤13 m), seven whales (19%) were adults (>13 m), and one whale was of an unknown length (Table S1). All bowhead whales in this study were tagged in July or August, which influenced the overall number of encounters (Table S2).

Vessel traffic varied between months and years between 2012 and 2017 (Table 1, Figure 2), such that vessel traffic was always higher between July and November than between December and June, often by nearly an order of magnitude for the number of unique vessels in the study region and by more than an order of magnitude for the distance traveled by all vessels (Table 1). For example, in January to June and December of 2012, 12 unique vessels were present, and they traveled a total distance of 8,482 km, whereas between July and November of the same year, 95 unique vessels were present and they traveled 438,604 km. The number of vessels present and distance traveled

TABLE 1 Summary statistics of vessel traffic traveling in the areas of tagged Eastern Canada-West Greenland bowhead whales between 2012 and 2017 when tags were transmitting locations. The area of interest for these statistics is roughly 200 km offshore the east side of Baffin Island up to Devon Island in the north, across to Somerset Island in the west, and south to include all waters of Hudson Bay and Hudson Strait. Months are grouped into the core shipping season (July to November) and the offseason (January to June and December). *N* unique vessels is the number of unique vessels present in the area. See Figure 2 for a display of these same variables by month.

Year	Season	*n* unique vessels	Distance traveled (km)
2012	July–November	95	438,604
	January–June, December	12	8,482
2013	July–November	105	537,229
	January–June, December	15	11,102
2014	July–November	111	556,817
	January–June, December	7	8,945
2015	July–November	113	513,729
	January–June, December	7	9,710
2016	July–November	113	603,778
	January–June, December	18	19,700
2017	July–November	156	685,957
	January–June, December	14	24,812

also generally increased across years, such that in 2017, 156 vessels were present in July to November and they traveled 685,957 km. In every year, the highest number of vessels and distance traveled was in August and September, and the lowest were between January and May (Figure 2), typically with ≤3 vessels per month compared to 57–119 vessels present per month in August and September.

3.1 | Summary of bowhead whale encounters with vessels

During 2012–2017, there were a total of 1,145 encounters within a radius of 125 km among 33 of the 36 tagged whales and tracked vessels (Tables S1 and S2, Figure 3). Three whales (ID numbers: 94542, 114494, and 128149) were never exposed to vessels within this distance radius and were not considered further (Table S1). The 33 exposed whales transmitted location data for variable periods (range: 12–737 days; mean ± *SD*: 303 ± 251 days), with 12 whales transmitting data for over 1 year (Table S1). The number of encounters with AIS vessels for these whales ranged from 1 to 88 per year.

Encounter rate (ER) was scaled to account for the number of days within each month that contained individual whale location transmissions. Whale ID 114500 was tagged in 2012 in Foxe Basin and had the highest encounter rate of all tagged whales (Table S2). Between January and December 2013, this whale encountered 88 AIS vessels, including 65 encounters in September alone, for a daily rate of 2.2 vessels (Table S2). Whale ID 114499 was also tagged in 2012 in Foxe Basin and had the second highest number of encounters with vessels per annum with 87 encounters, during July to December 2012, including 42 encounters in the month of October (ER = 1.4 vessels/day) (Table S2). Not accounting for irregular tagging dates, the month of September in the Eastern Canadian Arctic contained 41.8% of the encounters with vessels (n = 478) in this study (Table S2). August and October also contained high numbers of encounters (n = 199 and n = 231, respectively) between vessels and tagged bowhead whales (Table S2). August, September, and October had the overall highest encounter rates with vessels, with a range of

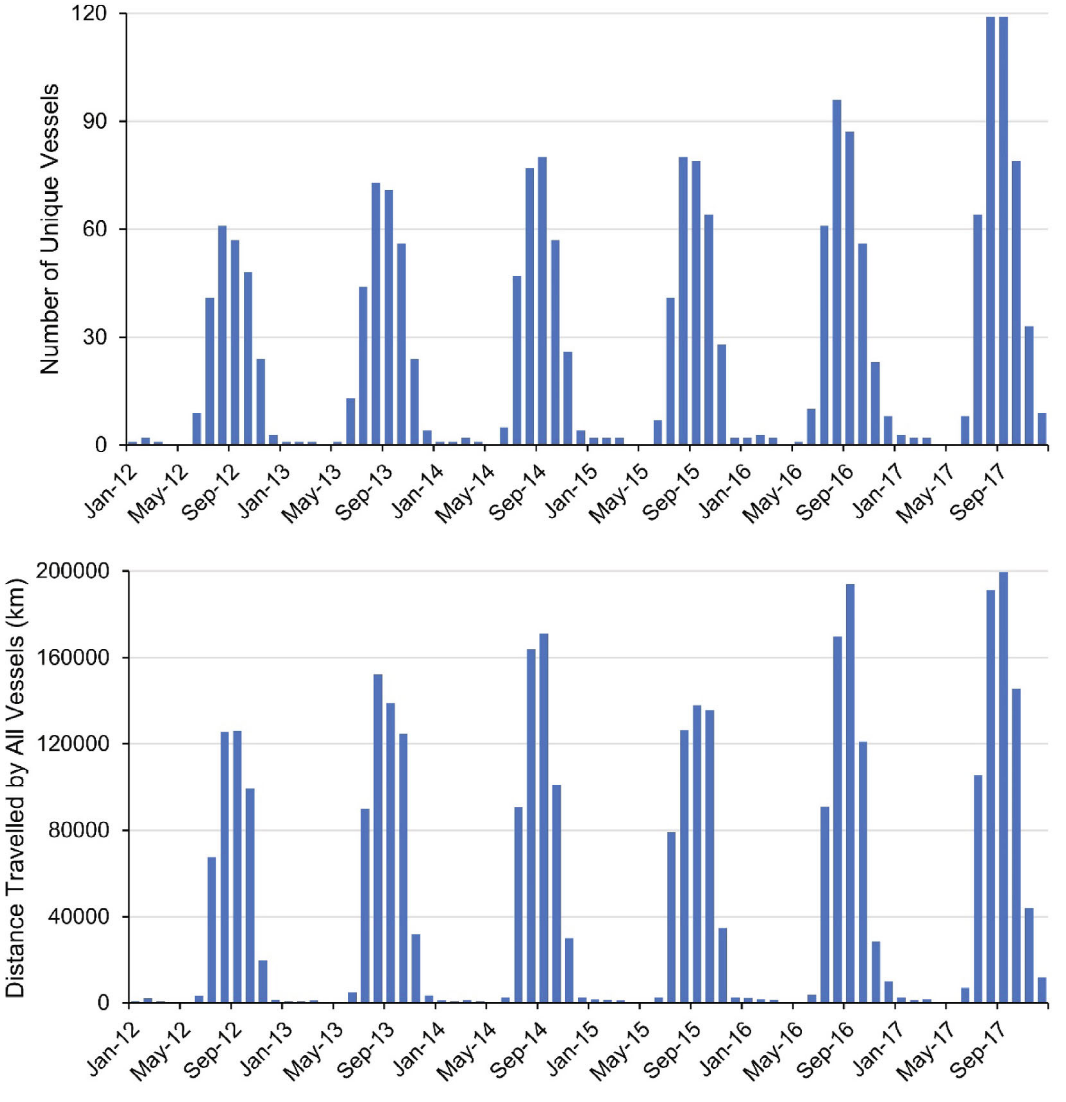

FIGURE 2 Number of unique vessels (top) and the cumulative distance traveled by all vessels (bottom) in each month between January 2012 and December 2017 in the areas used by satellite tagged Eastern Canada-West Greenland bowhead whales. The area of interest for these statistics is roughly 200 km offshore the east side of Baffin Island up to Devon Island in the north, across to Somerset Island in the west, and south to include all waters of Hudson Bay and Hudson Strait.

0.25–0.51 vessels encountered per day compared to <0.07 vessels per day in all other months in this study (Table S2). April ($n = 9$), May ($n = 1$), and June ($n = 14$) had the lowest numbers of encounters and encounter rates annually; however, the overall number of vessel encounters were generally low during November through July compared to August through October for this time series (Table S2). During this time series, a minimum of one whale encountered at least one vessel in each month of the year (Table S2).

The average (± *SD*) CPA between a tagged whale and a vessel was 73.1 (± 31.1) km; however, there were 30 individual whales that had CPAs to vessels at distances ≤50 km for a total of 306 unique encounters (Table S1, Figure 3b). The closest CPA to a vessel was estimated at approximately 2.5 km, and the largest number of

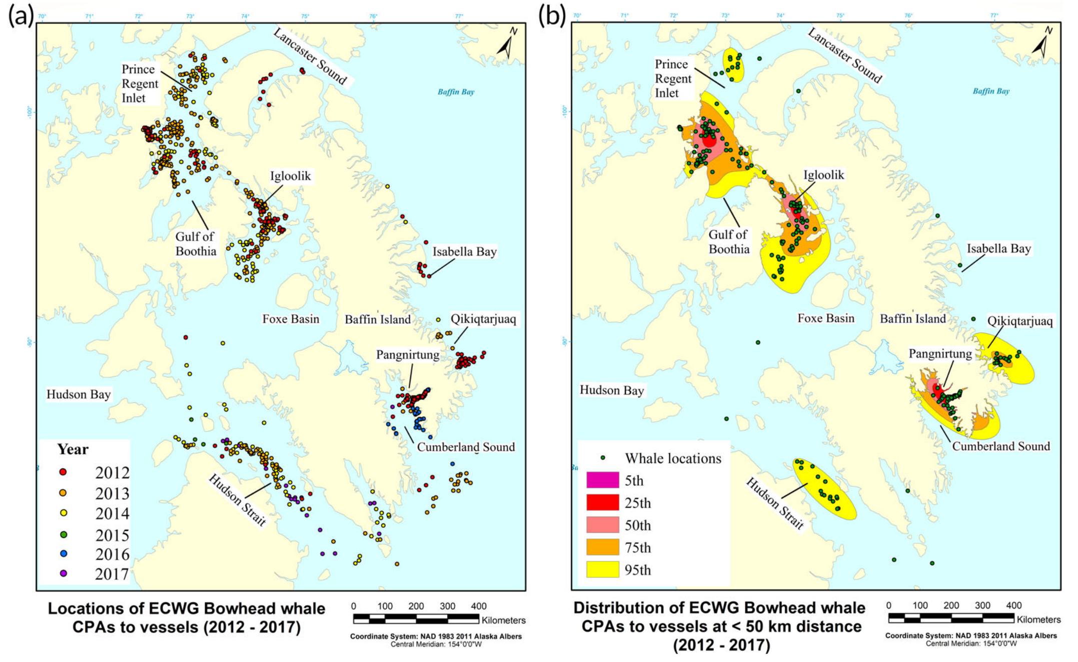

FIGURE 3 (A) Map of the 1,145 closest points of approach (CPA) for all encounters between telemetry-tagged Eastern Canada-West Greenland (ECWG) bowhead whales and vessels within a radius of 125 km during 2012–2017. CPAs are color coded by year. (B) Map of the distribution of the 306 CPAs for encounters between tagged ECWG bowhead whales and vessels within a radius of 50 km during 2012–2017. Utilization distributions, calculated via kernel densities, are provided for the 5th, 25th, 50th, 75th, and 95th percentiles.

encounters per year for a single whale at distances ≤50 km was 29 (Table S1). The areas of highest concentrations of ECWG bowhead encounters with vessels at distances ≤50 km were near the two tagging sites, Cumberland Sound and near Igloolik in Foxe Basin, with a third high concentration area in the western Gulf of Boothia (Figure 3b). Additional concentrated distributions of CPA locations at distances ≤50 km were in Hudson Strait, near the community of Qikiqtarjuaq, and in Prince Regent Inlet (Figure 3b).

4 | DISCUSSION

This study summarizes the number of known vessel encounters for tagged ECWG bowhead whales during 2012–2017 in the Eastern Canadian Arctic. Consistently across years, the majority (79.3%) of encounters occurred during August through October (Table S2). Tagged bowhead whales occurred within 3 km from AIS detected vessels. This result differs from the other two species of endemic Arctic cetaceans, beluga whales (*Delphinapterus leucas*) and narwhals (*Monodon monoceros*), which may exhibit strong avoidance reactions to vessels at greater distances (13–50 km; Finley et al., 1990; Martin et al., 2022). However, it is possible certain avoidance behaviors (e.g., vertical avoidance; Senigaglia et al., 2016) occurred and were not captured within the resolution of our data set. This demonstrates the importance of understanding species-specific and context-dependent behavioral responses to vessels for effective management and conservation (see Gomez et al., 2016 for a review). Further research is needed to examine individual bowhead whale behavioral responses, including dive responses, age/sex-related responses, and the potential for habituation or sensitization to vessels at a range of distances. If bowhead whales fail to exhibit an avoidance reaction to vessels, this could place them at higher risk of vessel strikes (Halliday et al., 2022b).

Richardson and Malme (1993) described bowhead whale avoidance behavior as an increase in swimming speed away from the vessel with a decrease in dive duration and number of blows per surfacing. Avoidance responses in bowhead whales have been documented at distances <1–4 km and rarely beyond 8 km from standard vessels when underway (Richardson & Malme, 1993; Richardson et al., 1985a,b). Bowhead whale avoidance responses to seismic survey vessels have been reported at distances between 20 and 30 km (Koski & Johnson, 1987; Miller et al., 1997, 1999; Richardson et al., 1999). Studies suggest bowhead whales that are socializing or foraging appear more tolerant of potential sources of anthropogenic disturbance than migrating whales (Koski et al., 2009; Miller et al., 2005; Quakenbush et al., 2010; Robertson et al., 2013; Wartzok et al., 1989). This information is important in the interpretation of the results from this study, which indicate that the highest concentrations of ECWG bowhead encounters with vessels at ≤50 km distance occurred when whales are presumed to be feeding during August–October near Igloolik in Foxe Basin, the Gulf of Boothia, and Cumberland Sound (Figure 3b). During our time series in the Gulf of Boothia, government vessels were the most frequent vessel class, followed by tanker ships (Halliday et al., 2022b). Vessel traffic in Cumberland Sound is comprised of low levels of bulk carriers, cruise ships, government vessels, and recreational boats, and very low levels of ferries and tanker ships (Halliday et al., 2022b). These areas host large annual congregations of bowhead whales which promote more social encounters and serve as feeding grounds and migratory corridors during the late summer through autumn seasons (Fortune et al., 2020a; Pomerleau et al., 2011).

A modeling study by Halliday et al. (2022b) reported the highest relative vessel strike risk areas for ECWG bowhead whales were the Gulf of Boothia, Cumberland Sound, and near Isabella Bay (eastern coast of Baffin Island), Nunavut, Canada. Vessel strike risk was highest in August and September, corresponding with monthly levels of vessel traffic (Halliday et al., 2022b). Our study and Halliday et al. (2022b) used some of the same input data; however, Halliday et al. (2022b) included data prior to 2012 and from whales tagged in West Greenland. The inclusion of whales from West Greenland showed that Isabella Bay could be a potential hotspot for overlap between bowhead whales and vessel traffic, because whales from West Greenland tend to spend their summers foraging near Isabella Bay (Chambault et al., 2018). Conversely, whales from this study, which were tagged in Foxe Basin and Cumberland Sound, did not use Isabella Bay. We therefore stress the need for caution when interpreting our results, because our study did not include whales tagged in West Greenland as those tag data (2001–2011) do not overlap in time with the satellite AIS vessel tracking data (post 2011). Isabella Bay appears to be an important area for a segment of the population of bowhead whales during the summer, which was not captured by the data used in our study and warrants further study. Regardless, the collective findings of our study and Halliday et al. (2022b) highlight the need for vessel management within these high use areas (Figure 3b) particularly during late summer and autumn to reduce the potential for vessel strikes and noise disturbance.

There are other emerging threats to bowhead whales that are also important to consider in addition to impacts from increasing vessel traffic in the Eastern Canadian Arctic. Climate change has led to increased predation risk from killer whales (*Orcinus orca*) (Breed, 2021; Matthews et al., 2020), and the potential for thermal stress from increased sea temperatures (Chambault et al., 2018). Furthermore, changes have been identified in zooplankton species composition and abundance as an index of ocean productivity and prey quality with more lipid-poor copepod species recently found in bowhead whale habitats (Fortune et al., 2020b; Møller & Nielsen, 2020). These cumulative threats may impact the species' predation risk, habitat use patterns, and foraging success which may ultimately affect the health of individuals and survival of the species at the population level.

There are caveats associated with this study that need to be considered. These include (1) the inherent spatial accuracy in some whale location data derived from the Argos satellite system; however, the CRW model accounts to some degree for issues associated with spatial accuracy. Many encounters between bowhead whales and vessels at distances ≤50 km could not be investigated further primarily due to insufficient tag location data. This resulted in the inability to model the encounters to identify any specific bowhead whale behavioral responses to vessels. (2) The whales tagged in this study may not represent the full population due to sample size and potential differences in behavior based on individual differences, specific areas, and seasons (i.e., spatial segregation based on age and sex;

Heide-Jørgensen et al., 2010). For example, the lack of data from Isabella Bay, as mentioned previously. (3) Two of the regions with the highest concentrations of whale encounters with vessels at distances ≤50 km predominantly align with the two tagging sites, Cumberland Sound and near Igloolik in Foxe Basin (Figure 3). It is plausible that these concentrations were influenced by the proximity of telemetry locations to the tagging sites, indicating a potential spatial bias in the recorded encounters. (4) It is possible that there were vessels present which did not carry AIS transponders. Due to these limitations, our results underestimate bowhead whale encounters with vessels within the 125-km radius in the Eastern Canadian Arctic.

Given the cultural and ecological importance of this vulnerable species, this summary of encounters provides evidence that further studies are needed, possibly including controlled experiments, to better understand how bowhead whales may respond to vessels or vessel noise at known distances and across behavioral states. Future studies also should include focused recordings of underwater noise unique to each vessel and vessel class, including measurements of source levels and frequency spectra. With developments in tag technology, future incorporation of 3-dimensional movement and acoustic recordings would provide the opportunity to examine changes in the acoustic behavior of bowhead whales, identify the acoustic signature, received level, and exact time when vessel noise is received at the whale, and ultimately allow an in-depth examination of bowhead whale behavioral response to the type and received level of vessel noise and other sounds. Similarly, long-term tag technology has also advanced, and the use of tags equipped with Fastloc GPS and higher resolution dive profiles (e.g., Martin et al., 2022) could yield more data on reactions of bowhead whales to vessels.

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AUTHOR CONTRIBUTIONS

Morgan Jennifer Martin: Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; software; visualization; writing – original draft; writing – review and editing. **William David Halliday:** Conceptualization; data curation; funding acquisition; methodology; project administration; software; supervision; validation; writing – review and editing. **Steven Ferguson:** Conceptualization; data curation; funding acquisition; resources; writing – review and editing. **Brent G Young:** Data curation; writing – review and editing. **Rachel Charish:** Formal analysis; software; writing – review and editing. **Jackie Dawson:** Data curation; writing – review and editing. **Sarah M.E. Fortune:** Data curation; methodology; writing – review and editing. **Francis Juanes:** Supervision; writing – review and editing. **Levi Qaunaq:** Data curation; resources. **Steve J. Insley:** Conceptualization; funding acquisition; project administration; supervision; writing – review and editing.

COMPETING INTERESTS

The authors declare there are no competing interests.

DATA AVAILABILITY

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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