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The Grand Challenges in Researching Marine Noise Pollution from Vessels: A Horizon Scan for 2017

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Chronic anthropogenic underwater noise, such as vessel noise, is now recognized as a world-wide problem. Marine noise from vessels, ranging from super tankers to small motorboats is increasingly recognized as being both a persistent and pervasive pollutant. Furthermore, due to its spatial and temporal variability, vessel noise pollution represents a particular challenge for marine conservation, management, and planning. This paper presents the outputs of a horizon scanning exercise that brought together a group of 40 individuals from across Canada, including: researchers, policy makers, NGOs and other end-users who work in the field of marine acoustics. The goal was to identify priority information needs, related to marine vessel acoustics, to inform new research and address policy needs. Via an iterative Delphi style process, participants identified 10 priority research questions related to marine vessel acoustic science; for example, How important is it to identify and maintain acoustic refugia? What attributes of marine vessels are the most effective indicators of marine noise? The questions were then further considered in terms of extent of current knowledge, time scale by which they can be achieved, the financial resources required and the importance of answering the question. Subsequently, the authors conducted a search of the peer-reviewed literature to situate the challenges highlighted by the horizon scanning exercise within the broader global research. Results show that investigating the attributes of marine vessels that are the most effective indicators of marine noise is a viable research question to tackle first. In addition, underpinning many of these questions is the need of long-term data collection and monitoring of both vessel traffic and marine mammal populations.

Keywords: marine noise, marine mammals, vessel noise, horizon scanning, Delphi

INTRODUCTION

The Emerging Issue of Chronic Noise Pollution from Vessels

The recognition of marine anthropogenic noise as a pollutant is comparatively new (Williams et al., 2015b). Indeed, it is only in the last few decades that marine noise, as a source of disturbance to marine life, has become a recognized field of study (OSPAR Commission Report, 2009; Simmonds et al., 2014).

It is now also widely recognized that marine anthropogenic noise can have negative impacts on a broad variety of marine species (Codarin et al., 2009; Merchant et al., 2014; Williams et al., 2015a,b; Farcas et al., 2016; Garrett et al., 2016; Pine et al., 2016; Todd, 2016). Until relatively recently, loud impulsive sounds such as pile driving and active sonar were the only form of noise pollution considered to pose a major threat to marine species, specifically mammals (Southall et al., 2007). A significant amount of research has already focused on this type of acute noise pollution (Weilgart, 2007). However, it is now accepted that rising persistent/chronic/background anthropogenic sound levels (McDonald et al., 2006; Garrett et al., 2016), mainly attributed to an increase in global shipping (Ross, 2005), are also having an impact on some marine species (Wright, 2008; Clark et al., 2009; Merchant et al., 2014; Williams et al., 2014b; Garrett et al., 2016).

Scanning a Noisy Horizon

Horizon scanning can be defined as the systematic search of potentially significant threats or opportunities that are not well-recognized or defined within a particular field (Sutherland et al., 2014). It is useful to identify potential management and policy challenges along with research needs associated with an increase in noise producing activities, before these challenges become insurmountable. For example, increased shipping in the Arctic due to climate change, or expansion of whale watching industries on endangered or threatened populations and species (Erbe, 2002; Huntington, 2009), could reduce the probability of sudden confrontation with major social or environmental changes.

In identifying forth-coming issues (Rudd, 2014; Sutherland et al., 2014) horizon scanning encourages scientists to focus on emerging topics, and policy makers and managers to prepare to address these topics and their implications should they arise. In this way, the outputs from horizon scanning activities also can be used to influence policy. Therefore, perhaps the greatest value of conducting horizon scanning exercises such as this is to stimulate and support actions that will prevent plausible threats from materializing, or if they already exist, manage them before significant impacts occur. In the case of marine noise pollution from vessels, this involves identifying the knowledge that is currently lacking, but is necessary to better inform and guide policy and management of chronic noise produced from these vessels.

METHODOLOGY

Identifying Priority Research Questions

Forty participants took part in this horizon scanning workshop, including scientists and experts in disciplines relevant to marine noise (e.g., environmental none-governmental organizations, coastal planners, naval operators, and shipping representatives) who are collectively affiliated with organizations that have diverse research and management mandates. These individuals, see **Table 1**, were all brought together through their direct involvement or association with one of three marine noise related research projects that are occurring across Canada and sponsored by Marine Environmental Observation Prediction and Response (MEOPAR), a Network Center of Excellence (NCE) in Canada.

The methods used in this horizon scan aimed to provide the participants with an inclusive, transparent, and structured communication process. It took the form of a modified Delphi; a technique developed for systematic forecasting (Rowe and Wright, 1999). Delphi are generally considered to have four key features: anonymity, iteration, controlled feedback, and the statistical aggregation of group responses. Anonymity is achieved through the use of a questionnaire that allows individuals to express their opinions privately without social pressure. Additionally, with the iteration of the questionnaire over multiple rounds, respondents are given the chance to change their opinion with the benefit of group discussion and without any judgment. The structure of this technique aims to enable and encourage all the positive attributes of interacting group discussions such as a wider knowledge base and creative synthesis while anticipating negative aspects such as personal or political conflicts.

We used this Delphi framework for ranking a series of questions in terms of their research priority, see **Figure 1**. Between each round of the questionnaire, feedback was provided in which the group is informed of the opinions of their colleagues anonymously. Feedback was provided in the form of a simple statistical summary, a mode value of the rank scores submitted after each run by each participant.

Each of the three projects contributed what its core team of researchers considered to be 10 priority research questions for the future based upon their projects findings. These questions were then compiled by the authors and distributed via an online questionnaire (1st round of the Delphi) prior to the participants arriving at the workshop, see **Figure 1**. The questions presented in the first round can be viewed in **Table 2**. Participants were asked to score each of the 30 research questions from 1 (well-known or poorly known but unlikely to have any serious impact should it not be answered) to 5 (poorly known but likely to have a significant impact if answered). The mode was determined among participants for each question.

After analyzing each of the questions from the first round of results as a group, participants were asked to complete the questionnaire again for a second time (2nd round of Delphi). The 10 priority research questions identified with the highest mode scores after this second round were retained for further discussion and analysis in a third and final questionnaire (i.e., the horizon scan). This time, participants were asked to consider each of the priority questions in terms of:

1. "What is the current state of knowledge of this question?" ranging from limited knowledge to full knowledge
2. "How important is it to answer this question?" ranging from low to high
3. "What financial resources are needed to answer the question?" low, medium or high
4. "What is the time scale over which it can realistically be answered?" short, medium, or long term

Participants independently and confidentially scored each of these factors and average scores were then calculated. Average

TABLE 1 | Information related to the backgrounds of workshop participant.

Current position	No. participants	Examples of relevant areas of expertise	Years of experience per individual
Professor	6	Marine Biology, Biochemistry, Marine Mammal Biology, Icthyology, Economics, Geography, Ecology, Marine Planning and Management, Geovisualisation	20–35
Researcher	15	Physical Oceanography, Marine Biology, Marine Mammal Biology, Ecology, Marine Engineering, Acoustics, Marine Management, Geography, Marine Policy	5–20
Post doc fellow	5	Environmental Modelling, Marine Biology, Physical Oceanography, Mammal Biology, Ecology, Marine Engineering, Marine Planning and Management, Marine Policy	8–20
PhD student	3	Marine Biology, Acoustics, Marine Mammal Biology, Ecology	5–10
Masters student	1	Geovisualisation, Marine Mammal Biology, Marine Planning and Management	1–5
Government organization	5	Marine Biology, Ecology, Acoustics, Marine Planning and Management, Marine Policy, Marine Engineering	1–5
Non-government organization	5	Marine Biology, Ecology, Geography, Marine Policy, Marine Mammal Biology, Maritime Industry, Marine Planning and Management,	5–30

scores were then visualized using radar diagrams to compare this multi-criteria ranking among questions.

Priority Ranking Consistency with Current Scientific Literature

Following the workshop, the authors conducted an extensive search of peer reviewed journal articles since 1999/2000, in order to place the priority research questions identified in the workshop within a broader global research context. Literature searches were conducted by querying several web-based science journal databases including Science Direct and Google Scholar. These were chosen due to the broad, international range of multidisciplinary journals they provide access to. This was deemed prudent given the diversity of research currently being undertaken in a range of disciplines including engineering, physics, biology, and economics.

Search terms (derived from key words in the priority research questions identified by the workshop) included: marine noise, marine mammals, policy, management, noise pollution, ocean noise, shipping/vessel noise, and underwater noise. Occurrence of these words in the title, abstract or article were returned, and compiled for review. We empathize here that this search is bibliometric in nature and not an exhaustive review, and that our search terms come exclusively from key questions identified in the horizon scan exercise. For a more fulsome review of the scientific literature on marine noise pollution we refer the reader to Williams et al. (2015b). Searches involving variable combinations of the search terms noted previously, resulted in a total of 84 uniquely identified scientific journal papers that were further assessed for relevancy. It should also be noted that this search was only conducted for journal papers that were published in English in the past 15 years, therefore while the search was comprehensive and concluded in 84 papers being examined, it was by no means considered complete.

The journal papers were assessed in two different ways, the first in relation to the questions identified during the horizon scan. The authors noted when researchers were directly identifying questions similar to those identified in the workshop, or simply suggesting similar questions as a focus of future work. Secondly, if researchers were considering or contributing to the questions indirectly, authors noted whether or not they did so through citation of other associated literature or through the collection of their own data.

RESULTS

The 10 questions identified with the highest scores are presented here. The order they are presented in does not reflect their mean score, but related questions have been grouped together into four groups: (1) management and policy questions; (2) marine mammal biology; (3) marine mammal behavior questions; and (4) marine vessel questions.

Priority Management and Policy Questions

Three of the questions identified as being high research priorities were heavily related to marine policy and management issues (**Figure 2**). When asked to consider each of these questions separately in round 3, workshop respondents felt that all three would require a similar amount of time and financial investment to achieve. There was also a general consensus that the answers to all three questions are very much needed, and particularly so question 3, which considers the designation of thresholds to inform policy. All three questions were deemed to be a high priority and do not appear to be especially costly to achieve. However, at this stage participants felt that the current state of knowledge was insufficient to begin addressing any of these three research questions. Subsequent sections raised questions that address fundamental knowledge that can fill in the gaps needed to inform management and policy.

(1) How important is it to identify and maintain acoustic refugia?

Underwater noise pollution is a problem in areas inhabited by acoustically sensitive marine fauna. Sound is a particularly significant aspect of marine mammal ecology, it functions as a primary communication channel to group cohesion and reproductive success. Therefore, constant input of artificial sound may have implications for these species and, consequently, to

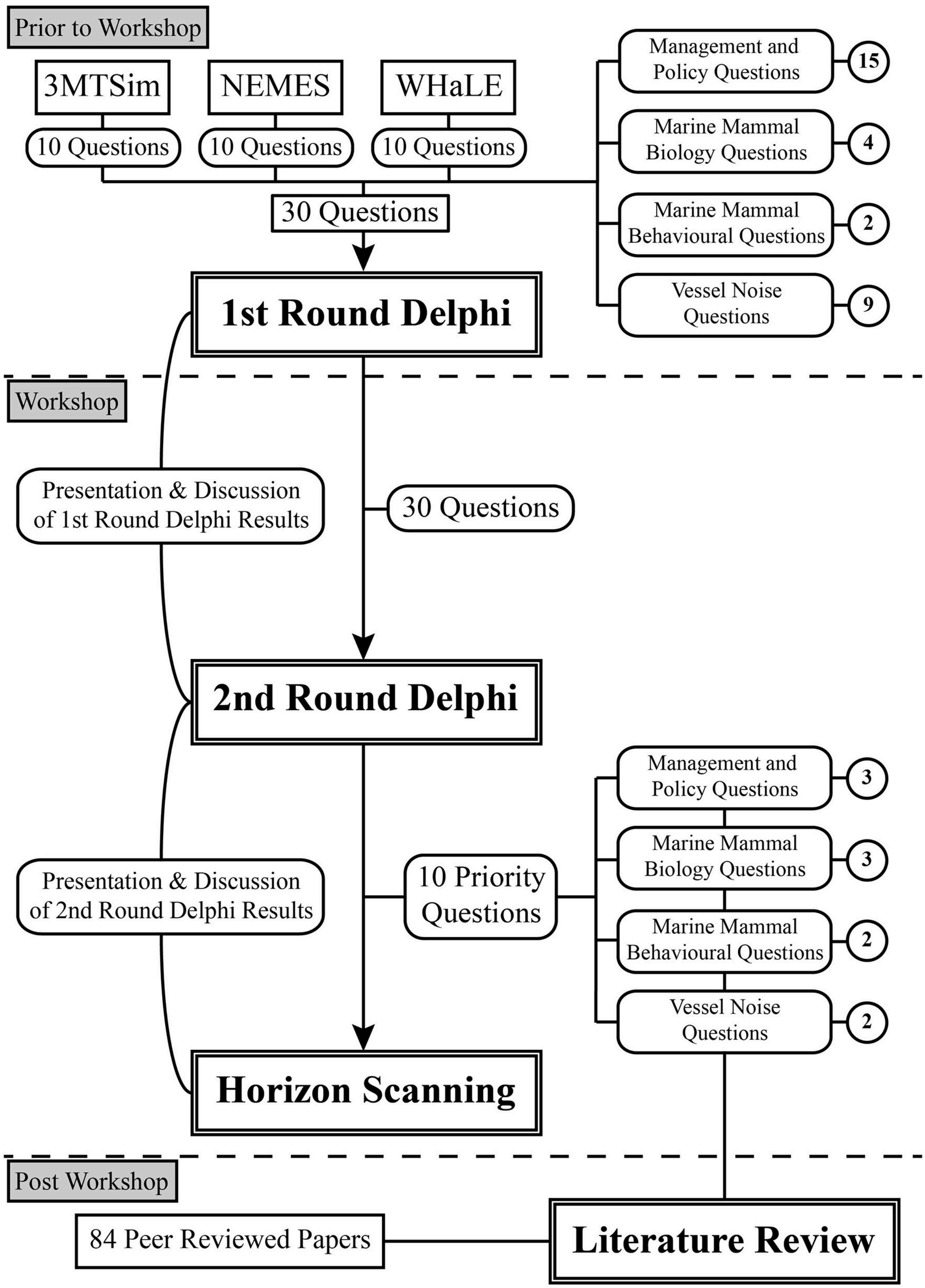

FIGURE 1 | Workflow diagram depicting the various steps of the methodology.

TABLE 2 | Compiled questions from the three MEOPAR research projects that were presented to participants in the 1st round of the Delphi questionnaire.

	Question
1	How can marine noise be effectively integrated into policy for MPA's?
2	What are the public, industry, and government perceptions of the prevalence and impacts of noise from vessels in the marine environment?
3	What is the relevant contribution of different vessel types to noise in the marine environment?
4	Can specific frequencies (e.g., mating calls, echolocation) be associated with different behaviors amongst different marine mammal species?
5	Does vessel risk mitigation efforts differentiate between endangered and non-endangered whale species? Are mariners more willing to only respond for endangered species?
6	To what extent and how will climate change effect the management of marine noise in the future?
7	How important is it to identify and maintain "acoustic refugia"?
8	What actions can be taken to minimize the harmful effects of acute noise events on marine mammals when utilizing equipment such as air-guns or sonar?
9	How can we incorporate marine noise into cumulative impact assessment and to what extent do we understand the relationship between noise and other actors within the assessment?
10	How reliable is AIS as a source of data for marine vessel distribution, intensity, and speed?
11	Is it possible to track the location of marine mammals and convey that information to vessels in real-time to enable dynamic noise management protocols?
12	How can noise from vessels and other expanding industries such as marine renewable energy be mitigated through marine spatial planning?
13	How do the public, industry, and government perceptions of marine noise compare to other threats to the marine environment?
14	What are the operational standards and protocols required for ships to respond to alerts in order to reduce vessel risks to whales?
15	What attributes of marine vessels are the most effective indicator of marine noise?
16	What are the tradeoffs in noise exposure between reducing vessel speed (longer temporal exposure) or increasing vessel speed (shorter temporal exposure) through regions with vulnerable species/habitat?
17	What is the greatest level of noise that can be sustained without critical harm to marine mammal species?
18	What can be done to ensure self-regulation of marine noise by industries such as ports, passenger vessels/tourism vessels, shipping, and oil and gas?
19	To what extent is marine vessel distribution and intensity a proxy for noise exposure?
20	What level of error is acceptable when using a noise prediction model to measure underwater noise exposure to marine mammals?
21	Is it possible to identify global spatial and temporal trends in ambient marine noise?
22	How can geovisualizing a marine environment contribute to a better understanding of the exposure and impacts of noise?
23	What are the spatiotemporal occurrences of marine mammal species in Canadian waters and how and at what spatial and temporal scales do environmental factors influence their occurrences?
24	How important is it to measure the contribution of small recreational vessels to marine noise in key areas?
25	What technological advances would be required to achieve real time monitoring of vessels and marine mammals?
26	How important is it to identify the relationship between marine noise and other stressors on the marine environment?
27	What resources can be used to estimate and potentially mitigate the noise from new and developing industries?
28	What behavior responses can we expect amongst marine mammals if critical levels of noise are reached for a species?
29	How important is it to identify acoustic thresholds to be integrated within and inform marine policy?
30	What are the relationships between marine mammal behavior and acute and chronic noise exposure?

overall ecosystem health as they often hold important ecological roles, such as apex predators. While there are many parts of the sea subject to constant anthropogenic sound, there are also areas that are relatively quiet.

Areas that are important habitats for noise sensitive species and where background anthropogenic noise levels are also relatively low have been labeled as "acoustic refugia" by several scientists and managers. There is a need to identify and maintain these areas for a number of reasons other than simply protecting the noise sensitive species that live in them. For one, managing and protecting an area that is already quiet rather than trying to restore quiet in an area that is already noisy is likely to be far less challenging (Williams et al., 2015a). Failing to identify and manage human activities in areas that are both biologically important habitats for noise vulnerable species and still quiet, so as to maintain these refugia as "sanctuaries," could ultimately result in such acoustic havens disappearing altogether. Nonetheless, it has been shown that there is considerable potential for area-based management to reduce exposure of marine animals to both acute and chronic anthropogenic noise. Williams et al. (2015a) have begun to explore this concept further through the identification of habitats in British Columbian waters that are both important to marine mammal species and also currently receiving low levels of noise from shipping.

Identification of refugia themselves is not without difficulty, and as discussed later in question 6, assessments of cetacean distribution and other highly mobile species that are impacted by noise is still very much an ongoing process. It has also been shown that obtaining ambient noise levels can be challenging given that they can vary considerably within an area depending on the season and propagation conditions (Zakarauskas et al., 1990). However, once it is established that an area includes important habitat and is quiet, this in itself can be used as a pre-existing argument for putting management and or mitigation measures in place.

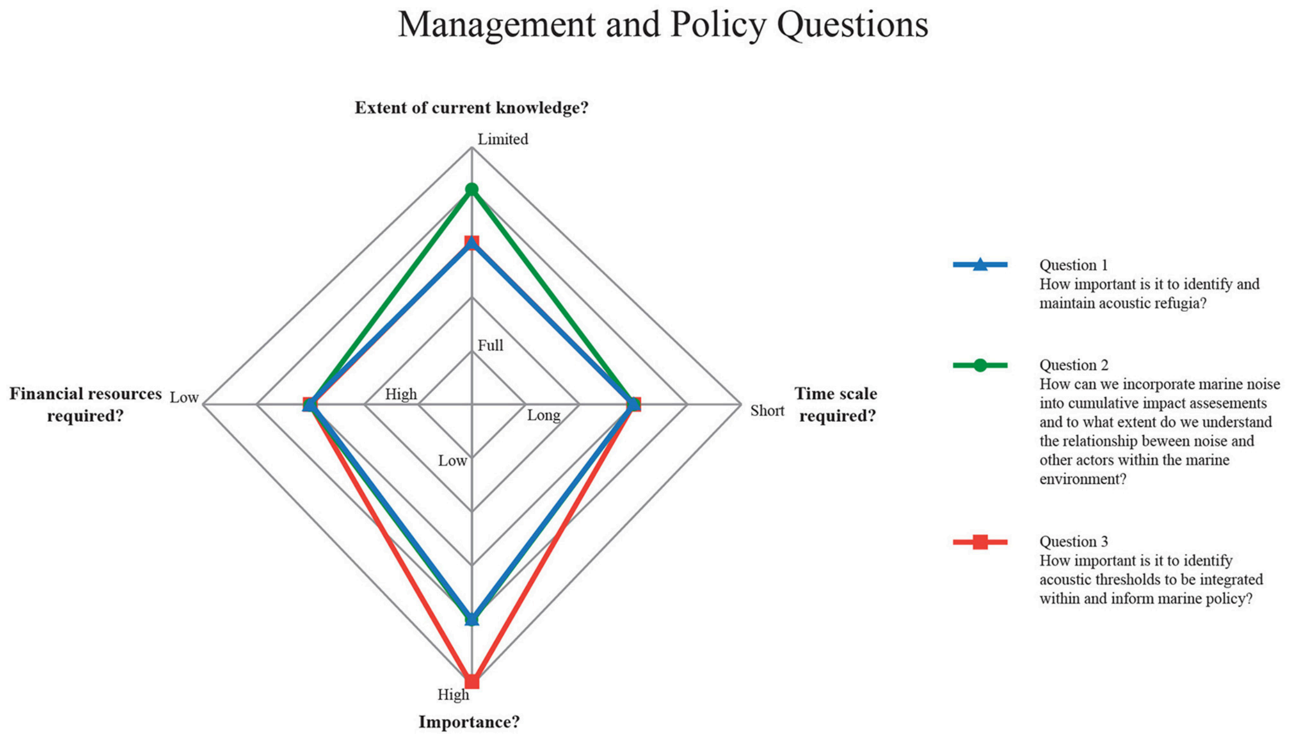

FIGURE 2 | Radar diagram showing the workshop respondents' mean score rounded up to the nearest rank value in "round 3—horizon scanning" questionnaire for those priority research questions related to policy and management.

It should also be noted that management measures for maintaining the acoustic integrity of such areas once identified are still in their infancy. For example, Marine Protected Areas (MPAs) while often the "go to" example of a spatial management tool, may only prove effective in a limited number of circumstances for resident coastal populations of cetaceans and be completely impractical for migratory species of baleen whales. Therefore, further consideration should also be given to managing these areas once identified both in a spatial and temporal context (vessels and activities permitted within different zones at different times) and for specific noise levels (low, medium, and high frequency thresholds). To do this would require both acoustic baselines and thresholds (see question 3) along with sufficient, quality data on important cetacean habitats. There is also a need to evaluate contributions of small vessel traffic to anthropogenic noise, which is currently understudied.

(2) How can we incorporate marine noise into cumulative impact assessments and to what extent do we understand the relationship between noise and other actors within the assessment?

Efforts are on-going to quantify the cumulative impact that human actions and activities have on marine habitats and species. Assessing the cumulative impact to a species or population is a fundamental decision making tool that employs a scientific understanding of how human activities place species, habitats and the wider ecosystem under stress. While the impacts of noise are now widely acknowledged within Environmental Impact Assessments (EIA) their inclusion within the development of cumulative assessments is not as advanced (Hatch and Fristrup, 2009).

The inclusion of noise within such an assessment is highly complex, not least because the cumulative effects of noise can be considered potentially in three complementary frameworks:

(i) Accumulation of noise levels from multiple sources of the same type of activity can combine to produce a larger noise-related impact than would occur from each source individually.
(ii) A single noise source can also be a source of other stressors included in a cumulative impact assessment such as oil pollution, introduction of invasive species, chemical contaminants, and risk of ship strike.
(iii) Multiple noise producing activities and their associated multiple stressors can result in cumulative effects which are very difficult to assess and measure. Activities such as shipping, oil and gas exploration, fishing and renewable energy developments may all exist in an area and together combine to result in an accumulation of other stressors (see ii above) including noise.

Assessing the cumulative impact (with the inclusion of noise) to a species, population, community, and/or ecosystems would aid decision making. However, to develop such an assessment we need to develop a stronger scientific understanding of how human activities (that generate noise), interact with and place species, habitats, and the wider ecosystem under stress. Policy makers, regulators, and managers all face the challenge of trying to mitigate and manage accumulating and interacting impacts with very little substantiated scientific assistance. Therefore, there is a need for further research on appropriate noise baselines for examining changes in risk.

(3) How important is it to identify acoustic thresholds to be integrated within and inform marine policy?

We defined acoustic threshold as the level of sound above which an individual is predicted to experience changes in their hearing capabilities (either temporarily or permanently). This will affect their behavior with potential for affecting individual fitness (there should be some endpoint that characterizes the outcome that we should be concerned about). Different defined thresholds have been set by organizations such as NOAA (Horowitz and Jasny, 2007; Hatch et al., 2016) and the European Union (Merchant et al., 2014; Maccarrone et al., 2015) for acute and incidental exposure to anthropogenic noise sources. However, in many instances data gaps still severely restrict the derivation of noise exposure thresholds and in some cases explicit threshold values for certain effects are not scientifically defensible with little or no supporting data. If information is available about noise thresholds for specific marine species this would allow regulatory agencies to develop better informed policy when it comes to permitting or prohibiting activities that introduce marine noise to that species habitat. In addition this would aid in ensuring compliance with associated conservation legislation and other associated conservation mandates. For example, in Canada the government, is mandated to protect the critical habitat of Southern Resident Killer Whales under the Species at Risk Act (SARA) a component of which is protecting them from threats in their underwater acoustic environment.

Despite significant progress, the challenge of protecting marine life from underwater noise is still a complicated and unresolved process. For the most part it is still not known what levels of noise exposure (volume, frequency, or exposure time), is safe for different species. Additionally, not enough is known about the potential effects of noise on the behavior or ecology of marine mammals that carry individual fitness or population level consequences to set any standards or apply any exposure limits with confidence.

Priority Mammal Biology Questions

The three questions identified that all relate in some way to the biological impacts on marine mammals from noise (Q4, Q5, and Q6) all showed similar trends in the horizon scanning questionnaire. All three questions were deemed to be costly and require a substantial amount of time to answer (**Figure 3**). While they are all "need to know" questions, number 5, related to identifying acoustic threshold noise levels was considered to be the most important.

(4) Can specific frequencies be associated with specific behaviors (e.g., mating calls, echolocation clicks) amongst different marine mammal species?

There is a significant amount of evidence to suggest that noise over a variety of frequencies has an effect on the ability of marine mammals to communicate, navigate, forage, and engage in social behaviors. In general vocalizations can differ in a multitude of ways such as frequency, amplitude, call rate, and duration, and these parameters can vary among species depending on the behavior being carried out. For example, blue whales (*Balaenoptera musculus*) produce distinctive low frequency (<100 Hz) sounds called D calls, that are associated with foraging behavior (Melcón et al., 2012). Fish eating killer whales (*Orcinus orca*) on the other hand are known to produce echolocation clicks that have a 40,000 Hz bandwidth with a mean center frequency of 50,000 Hz while their social whistles range between 2 and 16,000 Hz (Veirs et al., 2016).

When the frequencies of mammal vocalizations and anthropogenic noise overlap it will undoubtedly impact their ability to carry out the specific behavior associated with that particular sound production through a process called masking. Erbe et al. (2016a) explain masking as the process whereby an individual's threshold, measured in decibels (dB), for detecting a sound is raised by another sound (the masking sound). Understanding and differentiating the functioning frequencies of species calls provides us with a tool to better understand the masking capabilities of noise produced by different activities. This in turn could potentially allow for management and mitigation measures to be more targeted and effective, e.g., calf and mother communication calls are known to be extremely important in certain species such as beluga in specific months of the year. Therefore, providing seasonal measures to reduce the intensity of that particular noise frequency could be seen as a more feasible option than simply imposing a blanket ban on noise producing activities.

Work has already been undertaken to identify specific frequencies that can be associated with distinct behaviors in several species of marine mammal partly to determine the potential impact of noise in the same frequency band (Croll et al., 2001; Clark et al., 2010; Wieland et al., 2010; Papale et al., 2015; Samarra et al., 2015; Gospić and Picciulin, 2016). It should be noted, however, that the impact of non-overlapping noise, i.e., noise occurring in frequency bands not utilized by the individual for their own transmissions, has received less attention.

(5) What is the greatest level of noise that can be sustained without significant harm to marine mammal species?

For many years research on acoustic impacts of noise on marine mammals focused on direct and typically physical impacts to cetaceans, usually from acute exposure (Williams et al., 2014a). Emphasis was also placed on the introduction of sounds within the frequency ranges that certain cetacean species are known to vocalize. However, our knowledge about ambient noise, the sound field against which signals must be detected, is still incomplete. Given that ambient noise has been increasing over the decades mainly due to shipping, and by as much as 12 dB in some areas (Hildebrand, 2009), ambient noise is now considered a major component of the total noise received by individuals.

Often the associated impact from acute types of noise exposure will directly affect the specific individual or a group of animals, the larger population, or species level impact is not

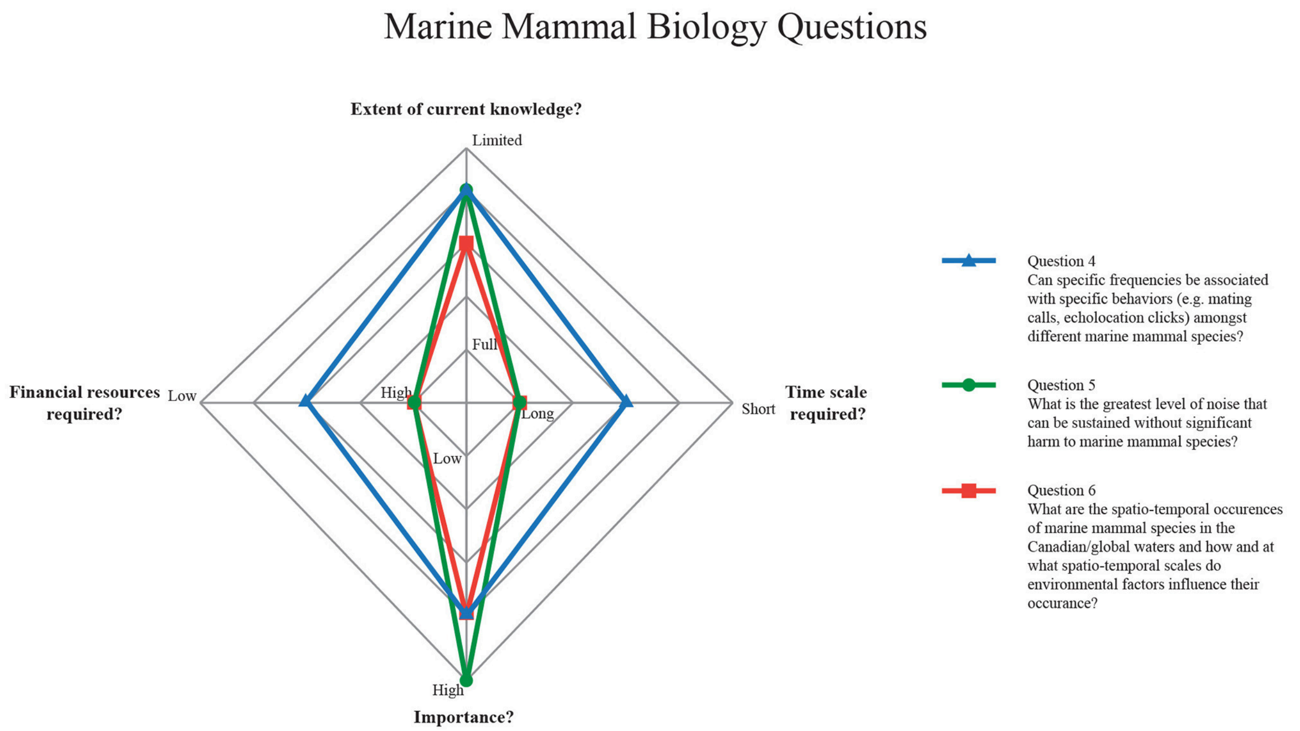

FIGURE 3 | Radar diagram showing the workshop respondents mean score rounded up to the nearest rank value in "round 3—horizon scanning" questionnaire for those priority research questions related to biological aspects of marine mammals.

as easy to quantify or assess. The focus of concern has now expanded to include a wider range of potential effects that include exposure to increasing chronic noise and sounds outside the specific frequency bands used by marine mammals. There is some evidence that research is starting to address the complexity of assessing the consequences of noise exposure. Recent work on several species of cetaceans has resulted in the reassessment of values related to hearing functions previously proposed for several species. Such developments have complicated associated guidance for masking and the onset of temporary and permanent threshold shifts.

It is important to note that basic hearing data, such as audiograms and thresholds are of poor quality or missing for many species of marine mammals and in the case of baleen whales, all species. Therefore, efforts must continue to provide better and more foundational hearing data to allow for modeling of potential noise affects across populations.

(6) What are the spatio-temporal occurrences of marine mammal species in Canadian/global waters and how and at what spatio-temporal scales do environmental factors influence their occurrence?

Marine mammal species are a diverse group, and as such their patterns of distribution and movement are hugely variable. Many factors can influence the distribution of marine mammals from habitat features such as bathymetry and temperature to the abundance of prey/predators and presence of human activities. There is a varying amount of data on cetacean distribution that is dependent on the species or individual population. Spatial data on human activities in general is a lot more complete and accessible for the most part, however associated modeled noise information from activities is not always available. Several studies have now attempted to integrate information on marine mammal distribution and the noise levels likely to exist from noise generating activities. Such work allows regulators to estimate the number of animals that are likely to exceed a noise "dose" greater than the threshold derived for that species. However, it is important to note that the presence of an individual in the same place and time as a noise does not guarantee that it will be affected, simply that such spatial and temporal overlaps are a necessary precursor to risk.

Through the use of better and more robust spatial data, and through consideration of the problem spatially, management, and planning tools can potentially be introduced to accurately separate species at risk from noise generating activities.

In order to minimize the threat of anthropogenic noise, managers, and policy makers need a comprehensive understanding of the geographical and seasonal distribution of marine mammal populations. Large-scale studies on the spatial, temporal and spectral extent at which these highly mobile species live their lives would allow us to evaluate the degree of influences changes in their acoustic environment truly have on a population.

Priority Marine Mammal Behavior Questions

Questions 7 and 8 related directly to impacts on marine mammal behavior from noise. Whilst the participants recognized the crucial nature of answering these questions they identified the associated cost and time required to gain answers as being significant (see **Figure 4**).

(7) What behavioral responses can we expect amongst marine mammals if acoustic threshold levels of noise are reached for a species?

Behavioral responses to anthropogenic noise such as changes in call frequency and reduction in vocalizations, have the potential to impact marine mammal activity budgets, physiology, communication, and habitat use. Several studies on different species have begun to explore these responses using behavioral attributes such as changes in site tenacity, dive patterns, swimming speed, orientation of travel, group cohesion and dive synchronicity to indicate possible disturbances or stress (Wright et al., 2007).

Research on beaked whales for instance has found that broadband ship noise elicited significant behavioral changes in their natural foraging behavior (Pirotta et al., 2012). Some studies have even noted vocal behavioral responses to anthropogenic noise, for example a study on blue whales found that they were likely to increase the frequency that they emitted calls in the presence of ships, conversely they stop calling in the presence of mid-frequency active sonar (Melcón et al., 2012). There can be considerable variation in the reaction of marine mammals to noise depending on factors such as species, individual, age, sex, and the individual's behavioral state. It is likely due to the variability of all these different factors that many studies report conflicting results. The problem with many example studies of behavioral response to noise is that many of the more rigorous behavioral studies rarely report detailed information on the acoustic stimulus and the acoustic studies rarely have a sufficient sample size for inferring behavioral responses.

(8) What are the relationships between marine mammal behavior and acute and chronic noise exposure?

Marine mammals are particularly susceptible to the negative effects of anthropogenic noise if the exposure(s) cause behavioral or physical changes or impede the process of conveying or acquiring information acoustically. As highlighted previously, the level of noise exposure that is safe for different species of marine mammals is still unknown. What is known is that exposure to acute, intense noise events can ultimately result in both lethal and sub-lethal injuries, stranding events, permanent threshold shifts, and very often death (Firestone and Jarvis, 2007; Weilgart, 2007; Wright et al., 2007).

It is only in recent years that studies have begun to address lower-level and chronic noise pollution (Williams et al., 2014b). Calculating cumulative and long-term impacts to populations is even more difficult than trying to determine acute impacts to individuals. Behavioral changes for example, are more likely to be a response to chronic rather than acute noise, with prolonged exposure leading to cumulative behavioral disruption and very likely long term stress effect. Energetic deficiencies from such behavior have the potential to lead to impacts on an individual's survival, reproductive capability and ultimately population decline.

Accurate measurements of received noise level are often difficult to obtain and this coupled with what can be subtle short-term behavioral changes relative to the received sound levels make defining a "cause-effect" relationship difficult. Determining if a whales hearing has been compromised, if they can no longer detect predators effectively, or maintain a connection with their offspring, or when a change in song pattern or dive time indicates stress and ultimately effects that animals overall fitness is an ongoing challenge.

Priority Vessel Questions

Two of the questions identified through the workshop Delphi relate directly to vessel noise (question 9 and 10). When assessed by participants in the third round these were deemed to be the most progressed of all the priority questions identified in terms of what is already known (see **Figure 5**). In terms of the time required to answer them it would appear that question 9 is the most feasible question to answer in the short-term, while 10 will require a longer commitment and consideration.

(9) What attributes of marine vessels are the most effective indicators of marine noise?

Tonal noises associated with propeller movement and in particular noise produced by cavitation on the blades, are typically considered to be the dominant sound when assessing the environmental impact of ship source noise, and this impact, which varies depending on ship class, operating conditions and speed (Lidtke et al., 2016). Additional fouling or damage to propellers while altering the noise produced by the vessel is unlikely to result in any acoustic differences that would not already be associated with that particular class of vessel. Noises associated with hull vibration and on-board ship machinery are thought to be less significant in terms of marine life impact (Lidtke et al., 2016). Noise sources such as broadband cavitation will become even more significant when a ship is operating in "off-design" conditions, for example when maneuvering in shallow coastal waters.

Different noise signatures from vessels can be related to vessel type and operational differences, including engine type, load of vessel, propeller type, blade number, or hull design. The metrics of ship noise including source level and spectral characteristics have already been collected for several classes of vessel including container ships and tankers (Veirs et al., 2016). Differences in dominant frequencies emitted have been found to relate to vessel-type, however, the cause of differences are not always known (Santos-Domínguez et al., 2016). This is particularly important for ambient noise modeling and acoustic impact assessments and therefore should be a priority for future studies.

There is already a considerable amount known about the noise levels that are produced by different vessels based on both their physical and behavioral attributes (Veirs et al., 2016). Further work on more modern vessels with new engine and

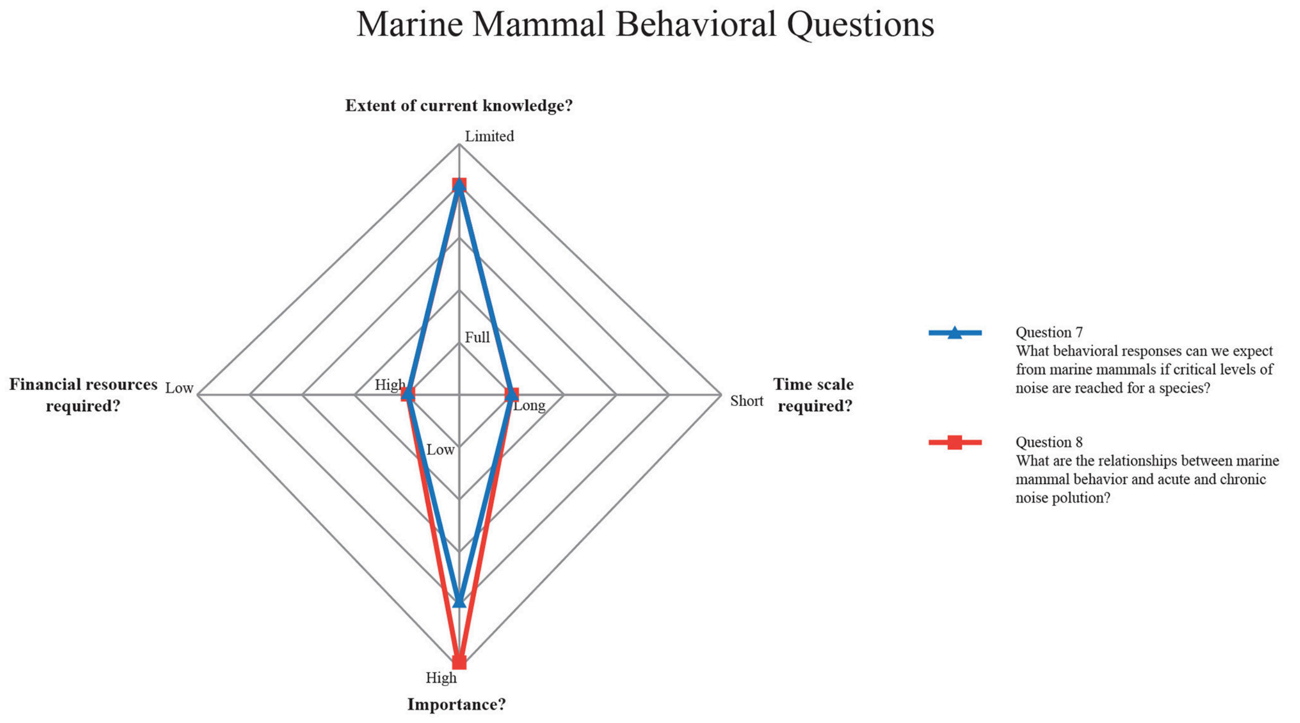

FIGURE 4 | Radar diagram showing the workshop respondents mean score rounded up to the nearest rank value in "round 3—horizon scanning" questionnaire for those priority research questions related to behavioral aspects of marine mammals.

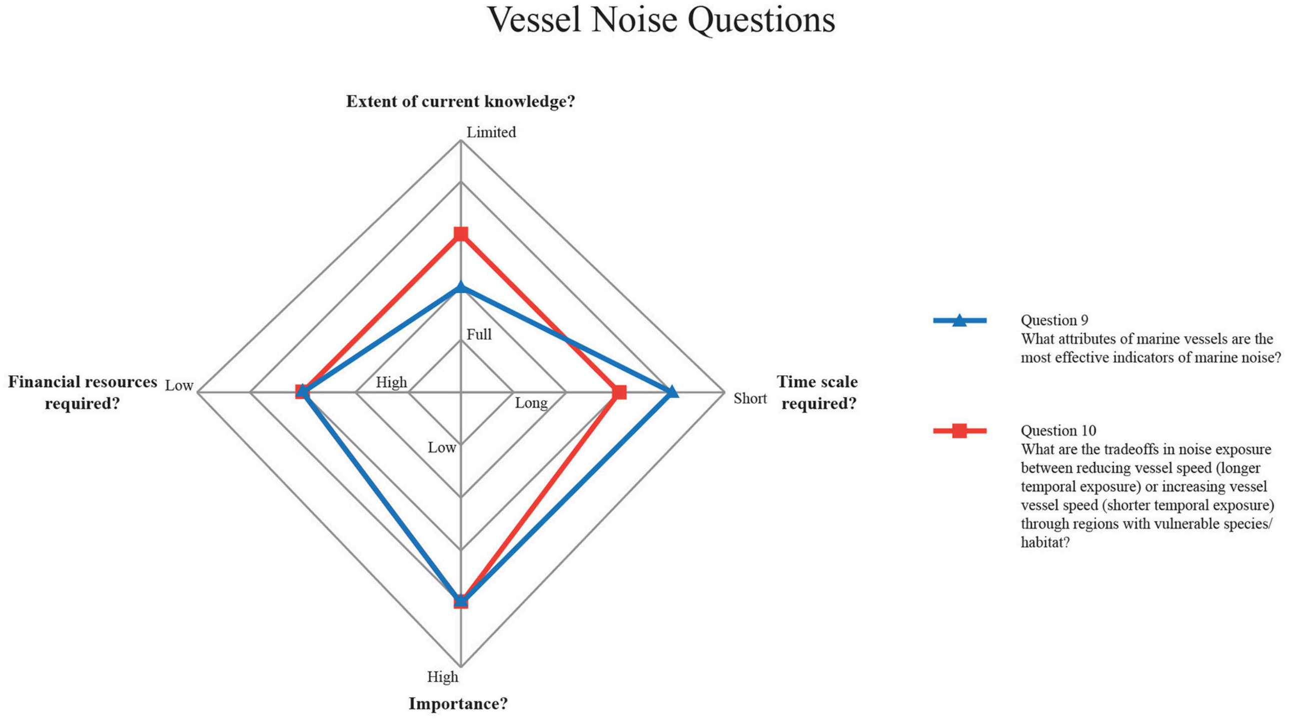

FIGURE 5 | Radar diagram showing the workshop respondents mean score rounded up to the nearest rank value in "round 3—horizon scanning" questionnaire for those priority research questions directly related to vessel noise.

propeller designs and configurations alongside building on current knowledge to derive statistical relationships between noise generated and vessel characteristics, operating parameters and oceanographic features still needs to be carried out.

(10) What are the tradeoffs in noise exposure between reducing vessel speed (longer temporal exposure) or increasing vessel speed (shorter temporal exposure) through regions with vulnerable species/habitat?

Prioritizing and implementing management/mitigation strategies in acoustically sensitive areas should be a key focus of future work. However, in order to ensure mitigation measures are truly effective we need to be able to quantify and assess the tradeoffs between different management scenarios. In the case of shipping, it is well-known that broadband cavitation noise is a major if not the primary source of sound generated by fast moving vessels and that it often increases directly with an increase in speed (Aguilar-Soto et al., 2006).

Future work should also include scenarios that consider additional covariates to speed, such as size and draft. Furthermore, from years of observations it is already known that there is great temporal variability in the amount of noise radiated by vessels. Such variations in amplitude should also be explored further as extremely noisy "outlier" vessels may represent extreme masking cases. Thus, these outlier cases should be considered when trying to govern variables such as speed, vessel class and load.

Developing scenario-building techniques to measure vessel noise exposure within vulnerable habitats or for sensitive species is a necessary step toward understanding how dynamic acoustic activities can effect an area. Methods using AIS data to analyze the spatial distribution of ships and their associated noise contribution are now being explored. Ultimately the results from such work could be used to inform and help prioritize mitigation and management strategies in acoustically vulnerable locations.

Priority Questions in Published Literature

As noted in a recent literature review by Williams et al. (2014b), there has been a significant increase in the range of anthropogenic noise topics being covered in journal publications over the last few decades in particular. The literature search undertaken as part of this study focused on only two of these specific topics: marine mammals and vessels. However, the articles we assessed in general also agreed with another of the Williams et al. (2014b) findings in that the majority of the papers concentrated on ecological impacts, management, and policy rather than physical interests. For example, Maccarrone et al. (2015) and Farcas et al. (2016), both considered best practices for assessing marine noise, while studies such as those carried out by Pine et al. (2016) and Houghton et al. (2015) consider the direct ecological impacts of anthropogenic noise producing activities on specific species and in particular areas. Although some journals such as Marine Mammal Science or JASA may have been more strongly represented than others in our literature search, this could perhaps largely be attributed to the key words used during our search.

A total of 84 journal papers were included in this assessment. Several papers, although identified in the word search, proved to have no content related to these priority questions and therefore were not included within this final count.

Papers were assessed based on: (a) if the question (or similarly worded question) was directly referred to in the paper either as a question being addressed by the paper or as a question being proposed as future work due to information still lacking; and (b) if the paper was providing evidence toward answering the question. This could have been via the research described in the paper, specific values referenced or through references cited in the paper (e.g., studies citing behavioral responses of a particular species when exposed to a specific vessel type or frequency would relate to answering questions 7 or 8).

The journal articles contents were assessed primarily with the specific research questions in mind. Some articles made clear and significant advancements to our most basic level of knowledge, which the horizon scan identified as still often lacking in order to answer many of the priority questions. For example, Veirs et al. (2016) recently published on their work collecting underwater sound pressure levels for over 1,500 unique vessels. This is the first study of its kind to present source spectra for different vessel classes and while it potentially provides crucial pieces of the puzzle for answering questions 9 and 10 (related to vessel noise), it will also contribute background information ultimately required to answer questions 1, 2, and 3 (management and policy). In contrast, other papers such as Hooker and Gerber (2004), did not appear to contribute as much to the specific topics that our horizon scan focused on, rather it eluded to them as part of their wider discussion about managing ecological reserves for larger animals such as marine mammals.

The number of papers that had any related content to each of the questions were tallied and summarized in **Table 3**. The number of papers that specifically referenced each of the questions is annotated in the second column and those that provided some form of evidence for answering the question in column 3. Note that the number of papers that provided evidence or reference the questions did not always add up to the number of papers presented in the related content column. This is because some papers referenced the question and provided additional evidence to support the answering of the question and so were counted in both columns 2 and 3, however the paper itself was only counted once as having provided related content.

It was deemed important to carry out this literature search as an accompaniment to the horizon scanning activity as we had already identified a certain amount of bias amongst our participants (being notably from biological backgrounds and solely presenting a North American demographic). Therefore, through assessing the wider literature we were able to compare the findings and discussions from a small group of individual experts with those from the wider field of study. Perhaps unsurprisingly, we found them to be largely in agreement with one another once we considered the content of the articles, the workshop discussion, and rationale behind scoring of questions.

TABLE 3 | A note of the number of papers identified in the review that highlighted the importance of the each of the horizon scanning priority research questions.

Priority research question	No. papers with related content	No. papers referencing question	No. papers providing supporting evidence	Papers referenced
1	16	14	2	Nowacek et al., 2003; Hooker and Gerber, 2004; Firestone and Jarvis, 2007; Haren, 2007; Weilgart, 2007; Tyack, 2008; Codarin et al., 2009; Hatch and Fristrup, 2009; Wright et al., 2011; Simmonds et al., 2014; Williams et al., 2014a; Bas et al., 2015; Williams et al., 2015a; Erbe et al., 2016b; Hatch et al., 2016; Pine et al., 2016
2	13	10	4	Lesage et al., 1999; Buckstaff, 2004; Wright et al., 2007; Hatch and Fristrup, 2009; Jensen et al., 2009; Ellison et al., 2011; Merchant et al., 2012b; Williams et al., 2014a; Maccarrone et al., 2015; Brooker and Humphrey, 2016; Erbe et al., 2016b; Farcas et al., 2016; Prins et al., 2016
3	13	11	3	Nowacek et al., 2001; Johnson and Tyack, 2003; Firestone and Jarvis, 2007; Horowitz and Jasny, 2007; Weilgart, 2007; Hatch and Fristrup, 2009; Holt et al., 2009; Wieland et al., 2010; Williams et al., 2014a; Erbe et al., 2016a; Farcas et al., 2016; Fleishman et al., 2016; Garrett et al., 2016; Pine et al., 2016
4	21	10	13	Croll et al., 2001; Nowacek et al., 2003; Buckstaff, 2004; Simard et al., 2006; McDonald et al., 2008; Simard et al., 2008; Tyack, 2008; Codarin et al., 2009; Hildebrand, 2009; Clark et al., 2010; Wieland et al., 2010; Castellote et al., 2012; Gervaise et al., 2012; Melcón et al., 2012; Papale et al., 2015; Samarra et al., 2015; Erbe et al., 2016a; Gospić and Picciulin, 2016; Hatch et al., 2016; Kaplan and Solomon, 2016; Veirs et al., 2016
5	12	11	2	Erbe, 2002; Nachtigall et al., 2004; Horowitz and Jasny, 2007; Holt et al., 2009; Jensen et al., 2009; Parsons et al., 2009; Castellote et al., 2012; Simmonds et al., 2014; Williams et al., 2014b; Maccarrone et al., 2015; Wright, 2015; Erbe et al., 2016a
6	16	12	5	Morton and Symonds, 2002; Simard et al., 2006, 2008; Clark et al., 2010; Simard et al., 2010; Mikis-Olds and Wagner, 2011; Castellote et al., 2012; Rolland et al., 2012; Ford et al., 2013; Bas et al., 2015; Papale et al., 2015; Williams et al., 2015b; Brooker and Humphrey, 2016; Erbe et al., 2016b; Kaplan and Solomon, 2016; Pyć et al., 2016; Salisbury et al., 2016
7	38	12	33	Lesage et al., 1999; Nowacek et al., 2001; Morton and Symonds, 2002; Johnson and Tyack, 2003; Buckstaff, 2004; Aguilar-Soto et al., 2006; Firestone and Jarvis, 2007; Mikis-Olds et al., 2007; Weilgart, 2007; Wright et al., 2007; Hatch et al., 2008; Simard et al., 2008; Tyack, 2008; Hatch and Fristrup, 2009; Holt et al., 2009; Jensen et al., 2009; Wartzok, 2009; Wade et al., 2010; Mikis-Olds and Wagner, 2011; Wright et al., 2011; Melcón et al., 2012; Merchant et al., 2012a; Pirotta et al., 2012; Rolland et al., 2012; Luis et al., 2014; Merchant et al., 2014; Williams et al., 2014a,b; Bas et al., 2015; Codarin and Picciukin, 2015; Houghton et al., 2015; Papale et al., 2015; Dunlop, 2016; Erbe et al., 2016a; Fleishman et al., 2016; Kaplan and Solomon, 2016; Todd, 2016; Veirs et al., 2016
8	34	11	29	Lesage et al., 1999; Croll et al., 2001; Johnson and Tyack, 2003; Buckstaff, 2004; Simard et al., 2006; Horowitz and Jasny, 2007; Mikis-Olds et al., 2007; Weilgart, 2007; Wright et al., 2007; Tyack, 2008; Codarin et al., 2009; Holt et al., 2009; Jensen et al., 2009; Wartzok, 2009; Ellison et al., 2011; Wright et al., 2011; Castellote et al., 2012; Gervaise et al., 2012; Melcón et al., 2012; Merchant et al., 2012a; Pirotta et al., 2012; Luis et al., 2014; Merchant et al., 2014; Williams et al., 2014a,b; Bas et al., 2015; Houghton et al., 2015; Papale et al., 2015; Aktas et al., 2016; Erbe et al., 2016a; Fleishman et al., 2016; Gospić and Picciulin, 2016; Pine et al., 2016; Todd, 2016; Veirs et al., 2016

(Continued)

TABLE 3 | Continued

Priority research question	No. papers with related content	No. papers referencing question	No. papers providing supporting evidence	Papers referenced
9	16	9	9	Hildebrand, 2009; Jensen et al., 2009; Bassett et al., 2012; McKenna et al., 2012; Pirotta et al., 2012; Bittencourt et al., 2014; Kaplan and Mooney, 2015; Williams et al., 2015b; Coomber et al., 2016; Garrett et al., 2016; Lidtke et al., 2016; Prins et al., 2016; Santos-Domínguez et al., 2016; Tani et al., 2016; Veirs et al., 2016; Wittekind and Schuster, 2016
10	6	2	4	Aguilar-Soto et al., 2006; Mikis-Olds et al., 2007; Jensen et al., 2009; Gervaise et al., 2012; Merchant et al., 2012b; Veirs et al., 2016

DISCUSSION

The subject of marine anthropogenic noise is a rapidly developing area of scientific research as evidenced in a recent publication by Williams et al. (2015b). This paper identifies 10 priority research questions that relate to marine noise, mammals and vessels. Furthermore, it ranks them in terms of cost, time, knowledge needed and the importance of answering the question so as to identify "low hanging fruit" to be targeted by researchers.

In terms of identifying a low hanging fruit to tackle first, question 9 (the attributes of marine vessels that are the most effective indicators of marine noise) would appear to be a good choice. Workshop participants felt that it required minimal time to answer and given what we already know on this matter, the associated costs would not appear to be significant in comparison to the amount that would be gained by answering this question (see **Figure 5**).

The results also allowed for consideration of each question individually and in relation to one another. Several questions were identified as being pre-requisites for answering other questions. For example, question 5 (identifying the greatest level of noise that will not cause significant harm), would need to be addressed prior to answering question 3 (Importance of identifying acoustic thresholds to inform policy). Likewise question 4 (can specific frequencies be associated with specific behaviors) would need to be ascertained before you could evaluate associated behavioral changes in question 7 (behavioral responses amongst marine mammals if acoustic threshold levels of noise are reached for a species) and question 8 (the relationships between marine mammal behavior and acute and chronic noise exposure).

The results from our Delphi horizon scanning exercise were largely consistent with the broader marine vessel noise literature we examined. However, there were two areas where the results from the horizon scan and the wider literature search differ.

Despite the number of papers related to marine mammal behavior affected by noise, workshop participants suggested that little is still known in relation to answering these two questions (questions 7 and 8). This is particularly striking considering the majority of the papers provided evidence supporting these questions. It is likely that the major reason for this apparent inconsistency results from the intrinsic complexity of the questions themselves and the variability inherent in the systems studied (i.e., individuals, populations, species, and their habitats). As explained in both the literature and in workshop discussions, proving a cause-effect relationship in behavioral studies is very challenging, and would be costly and time consuming to resolve. In other words, although a considerable number of publications exist, it is still considered relatively few in terms of the scale of work required to answer these questions.

When comparing the results of the Horizon Scanning and the literature search, particularly in relation to the marine mammal behavior questions (7 and 8) the content of the articles proved particularly illuminating. As discussed, the findings shown in **Table 3** appeared to be at odds with the findings of the Horizon scan, see **Figure 4**. However, when we considered the content of the articles identified, it was notable that although there were a significant number of publications the research effort appears to center around only a few species: for example, killer whales (Erbe, 2002; Morton and Symonds, 2002; Holt et al., 2009; Wieland et al., 2010; Williams et al., 2014b; Samarra et al., 2015; Houghton et al., 2015; Veirs et al., 2016) and bottlenose dolphins (Nowacek et al., 2001; Buckstaff, 2004; Nachtigall et al., 2004; Luis et al., 2014; Bas et al., 2015; Gospić and Picciulin, 2016). Perhaps un-coincidentally these are also two species that we have more knowledge pertaining to their hearing capabilities due to research conducted on captive animals. Other species, such as beluga (Lesage et al., 1999; Simard et al., 2010; Gervaise et al., 2012) and north Atlantic right whales (Nowacek et al., 2003; Clark et al., 2010; Rolland et al., 2012) received three or four publication each, but this is likely attributable to certain specific population being listed as critically endangered and therefore a focus of more intensive research efforts and associated funding. The majority of the other species acknowledged in the searched articles, [including: blue (Melcón et al., 2012), fin (Castellote et al., 2012), cuviers (Aguilar-Soto et al., 2006), and humpback (Dunlop, 2016) whales] only had one or two articles published on their specific behavioral responses to noise. This information was useful when trying to interpret the result of the horizon scanning in relation to the literature and it is also an example of why it was important to carry out this exploration of published literature.

The second inconsistency between the horizon scan and literature involves question 9 and question 10 (tradeoffs in noise exposure between reducing vessel or increasing vessel speed through regions with vulnerable species/habitats) as workshop participants considered these questions to rank highly in terms of current knowledge, yet they were not the focus of many studies in the literature. This difference could perhaps be attributed to the types of journals that were searched or the fact that vessel operational values and data are published and available through manufacturers and sources other than academic literature.

Horizon scanning exercises emerge from the knowledge and viewpoints of the participants involved and, therefore, it is important, as much as possible, to bring together individuals who reflect both the geographical and disciplinary diversity of the marine acoustic community. We recognized in this horizon scan that the demographic of our participant was slightly limited as they all stemmed from their association to three projects in Canada. For this reason we also conducted a search of international literature in attempt to place our findings within a broader, global context.

When we considered the backgrounds of the participants at the workshop (see **Table 1**), collectively they have a considerable amount of expertise related to the subject area. However, the number of participants from different disciplines was not evenly represented with the majority of individuals having their specialization rooted in some field of biology. This said, when we consider the original list of questions submitted by the three research teams (see **Table 2** and **Figure 1**), the majority of questions were considered to be either policy or management based. Interestingly those questions with a strong biological (marine mammal) component, remained in the top 10 for the most part, despite being the fewest entering round one. This could have been attributed to the composition of the workshop participants, or the fact they were "championed" in the workshop discussions by strong, influential individuals. However, it could also be more simply because of a logical, step-wise progression approach to dealing with marine noise. For example; if we don't know how the recipients are being effected, how to measure or quantify these effects, ascertain exposure levels for recipients or set thresholds beyond which they will be negatively impacted, then we cannot answer any subsequent questions related to vessel design and management measures.

A common point of discussion during our workshop was that of emerging issues. In general, issues move from new to emerging to widely known to acted upon (Sutherland et al., 2014). Horizon scanning, by definition, is the search for those issues that are new and emerging, not those that are widely known or being acted upon. While some issues identified by this scan were clearly emerging, the majority of them are longstanding. However, new issues can emerge from more general issues that are widely known. For example, research developing acoustic models derived from shipping data are now beginning to acknowledge that in some locations small boats and not larger ships are contributing more to increases in ambient noise (Erbe et al., 2012; Merchant et al., 2014). In this example, a new question arises: "how can small boat data be collected in order to better inform modeling predictions?"

Another dominant area of discussion amongst the workshop participants was the lack of evidence and level of certainty that could be associated with the issues at hand. For example, the geographic distribution of many cetacean species is often unknown or poorly documented and therefore the full extent of noise exposure is often unknown. Therefore, the true effect of noise at population or species level is not only uncertain but will likely remain so for some time yet.

In order to adequately address the above mentioned priority research questions for marine vessel research, effective long-term data collection and monitoring of both vessel traffic and marine mammal populations and communities are going to be required. In addition to the acquisition of information on a regular basis, maps of biologically relevant information such as habitats, and marine mammal distributions, as well as potential noise sources such as vessel traffic will need to be produced in order to better understand the spatial ecology and management scenarios. This information requires data to be integrated from various sources (e.g., hydrophones, aerial surveys, land, and satellite AIS) to give an accurate as possible picture of large scale patterns and spatio-temporal trends.

Exercises like horizon scanning are not intended to divert attention away from present-day issues but rather complement ongoing research and decision-making, inform and implement strategic planning and management, as well as guide long term research investments. Scanning research topics yields a product in the form of a defined research agenda. But perhaps most importantly horizon scanning can be used to encourage researchers, policy makers and practitioners to integrate in joint information sharing and synergistic gap analysis; a process through which participants with potentially diverse interests and backgrounds collaboratively identify, define, and answer scientific questions and address challenges that hinder development of effective policies.

The results from this horizon scanning exercise present the views of scientists, NGOs and government officials working on a wide range of marine noise related projects across Canada. In the future it would be valuable to repeat this exercise every 3 or 5 years with additional groups of stakeholders, economists and policy makers. This would allow for us to compare the level of agreement between the priorities identified by these different groups as well as track progress and identify how priorities change over time.

Scientists are among the best placed individuals to understand the true scope of the research challenges to be faced, to highlight new emerging issues related to vessel noise and to help identify technologies, management tools and governance systems that can help to mitigate the impacts of anthropogenic noise. The results from this exercise highlighted the priorities of scientists from across Canada and aims to provide insights as to how research scanning results can be synthesized and used to identify key questions that, if answered will enable us to prevent further degradation of marine acoustic environments or at least mitigate impacts.

AUTHOR CONTRIBUTIONS

LM: Substantial contribution to the concept, design, data acquisition and drafting of this paper. LS: Substantial contribution to data acquisition and analysis and presentation of data. NS: Substantial contribution to interpretation of data and contributed to drafting of paper and editing. PO: Substantial contribution to interpretation of data and contributed to drafting of paper and editing. RC: Substantial contribution to interpretation of data and contributed to drafting of paper and editing.

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