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Impacts of anthropogenic noise on marine life: Publication patterns, new discoveries, and future directions in research and management



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ABSTRACT

Anthropogenic underwater noise is now recognized as a world-wide problem, and recent studies have shown a broad range of negative effects in a variety of taxa. Underwater noise from shipping is increasingly recognized as a significant and pervasive pollutant with the potential to impact marine ecosystems on a global scale. We reviewed six regional case studies as examples of recent research and management activities relating to ocean noise in a variety of taxonomic groups, locations, and approaches. However, as no six projects could ever cover all taxa, sites and noise sources, a brief bibliometric analysis places these case studies into the broader historical and topical context of the peer-reviewed ocean noise literature as a whole. The case studies highlighted emerging knowledge of impacts, including the ways that non-injurious effects can still accumulate at the population level, and detailed approaches to guide ocean noise management. They build a compelling case that a number of anthropogenic noise types can affect a variety of marine taxa. Meanwhile, the bibliometric analyses revealed an increasing diversity of ocean noise topics covered and journal outlets since the 1940s. This could be seen in terms of both the expansion of the literature from more physical interests to ecological impacts of noise, management and policy, and consideration of a widening range of taxa. However, if our scientific knowledge base is ever to get ahead of the curve of rapid industrialization of the ocean, we are going to have to identify naïve populations and relatively pristine seas, and construct mechanistic models, so that we can predict impacts before they occur, and guide effective mitigation for the most vulnerable populations.

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1. Introduction

Anthropogenic underwater noise is now recognized as a world-wide problem, and recent studies have shown a broad range of negative effects in a variety of taxa. Underwater noise from

shipping is increasingly recognized as a significant and pervasive pollutant with the potential to impact marine ecosystems on a global scale (Clark et al., 2009; Merchant et al., 2015; Williams et al., 2014b). Different noise sources such as seismic surveys have widespread regional effects, but a much greater local impact than shipping (Hildebrand, 2009). Pile driving for offshore construction, military activity, anti-predator devices, and pleasure crafts (with depth-and fish-finders) may also be significant local or regional sources of underwater noise (Tougaard et al., 2009; Wright, 2014). Marine renewable energy devices may produce lower noise levels than many other anthropogenic sources, but have the potential to cause long-term exposure to sessile marine organisms (Gill, 2005).

Regarding manmade ocean noise as a pollutant is a relatively recent development. Underwater noise was first posited as a potential threat to marine fauna fairly recently, in the context of long-range communication among baleen whales (Payne and Webb, 1971). Prior to that, underwater noise research was focused on military applications: hydrophones have been used to listen for sounds produced by submarines since World War I, and radiated noise from ships was identified as a nuisance in signal processing of active sonar in World War II (Lemon, 2004). Only in the last few decades has noise as a source of disturbance to marine life become a field of study (Simmonds et al., 2014).

At the 3rd International Marine Conservation Congress (14–18 August 2014, Glasgow, Scotland), we organized a symposium, originally entitled “Impacts of ship noise on marine life: Research and outreach on the Pacific Northwest coast.” The symposium consisted of six talks. During the planning phase, it became evident that there was a need to broaden the scope of the symposium geographically, beyond Pacific waters, and thematically, to include anthropogenic noise sources other than shipping activities. The final symposium was called “Impacts of ship noise on marine life: new discoveries in research.” The talks ultimately spanned organisms from crustaceans to the great whales, and described ongoing research and conservation efforts in both the Atlantic and the Pacific. During the symposium debriefing phase, the participants agreed that there was value, given the fast-moving nature of ocean noise research, in using these six projects as case studies to illustrate how various researchers and managers are approaching the study of ocean noise impact and mitigation. There was also recognition that no six projects could ever cover all taxa, sites and noise sources, so the participants agreed to conduct a follow-on bibliometric analysis to place the talks within the broader historical and topical context of the peer-reviewed ocean noise literature as a whole.

The primary objective of the paper is to describe six ongoing projects around the world that illustrate ways that researchers, managers, environmental educators and policy-makers are addressing the issue of ocean noise across various taxonomic groups and jurisdictions. Secondly, we placed these six case studies in a broader context by conducting a bibliometric analysis of published ocean noise literature. Through this, we aim to explore broad trends in research on ocean noise published in English since 1900. This component of our work highlights the exponential growth of research on ocean noise over the last century, tracks temporal patterns in topics covered by ocean noise researchers, and reveals the changing landscape of journals that publish research on this topic.

2. Methods

2.1. Case studies

Here, we showcase effects of noise in two species-specific case studies, one vertebrate and one invertebrate (i & ii). Next, by using the Strait of Georgia site in British Columbia (BC), Canada as an

example, we illustrate recent approaches to establishing baseline noise levels (iii) and creating noise models (iv). Finally we present potential noise management scenarios using empirical data and statistical models of ocean noise and marine mammals (v); and discuss current initiatives led by environmental non-governmental organizations (ENGOS) and various partnerships to bring ocean noise to the public attention (vi).

- i. Rapid recovery following noise exposure? The case of the threatened European eel (*Anguilla anguilla*) (presented by RB, on behalf of project collaborators JP, SDS, ANR);
- ii. The effect of ship noise on the behaviour and physiology of *Carcinus maenas* (presented by MAW, in collaboration with ANR, SDS);
- iii. Noise exposure from shipping in the Strait of Georgia, British Columbia (BC), Canada (presented by NDM in collaboration with DTD, PDO);
- iv. Key issues in spatiotemporal data and analysis of vessel movement patterns as an indicator of marine noise (presented by RC, on behalf of PDO, NS);
- v. Chronic ocean noise and critical whale habitats: mitigation through marine spatial planning or allowable harm limits to target populations (presented by RW, on behalf of project collaborators: EA, CWC, CE, PSH, LT);
- vi. Engaging diverse audiences to advance management solutions for underwater noise (presented by AJW, in collaboration with LKB).

2.2. Bibliometric analysis of ocean noise literature

Literature searches were conducted on 10 October 2014 by querying the ISI Web of Science database using the search terms listed in Table 1. This database was chosen because of its well-defined coverage and advanced search possibilities to facilitate extraction of summary statistics. The search was conducted for papers published in English only, so we consider this broadly illustrative but by no means complete. The terms were entered into the “Topic” field, and the option to omit conference proceedings was selected. This includes Science Citation Index Expanded (SCI-EXPANDED) –1900-present, Social Sciences Citation Index (SSCI) –1975-present, Arts & Humanities Citation Index (A&HCI) –1975-present. Although we searched from the beginning of the ISI database, the first papers using the search terms in Table 1 appeared in the 1940s. Subsequent temporal analyses are plotted beginning in 1940. Occurrences in the title, abstract, and all other fields in each record were returned, for a total of 576 unique papers (with some appearing in two or more searches), which constituted the basis for the analysis. After accounting for papers that returned more than one search term, full record (including abstracts when provided; N = 493) was downloaded and stored in a spreadsheet for analysis (see Supporting/Supplementary Information). This was done by saving search results to “Other file format, Tab-delimited (Win)”. Synonymous search terms (e.g., airgun noise and seismic survey noise) were then merged for better comparison of topic coverage.

The bibliographical data were visually assessed in various ways. Firstly, the unique papers with abstracts included were split into two categories: those that included any of the terms “impact,” “effect” or “conserv**” and those without. The rates of citation for each group as well as the total pool of records were then calculated and plotted. Citation rate was calculated by dividing the number of citations for a given paper in a given year and then further divided by the total number of papers (among those 493 papers downloaded in this analysis) published up until that year. The mean

Table 1

The list of search terms used in the ISI bibliometric analysis. Search terms were refined iteratively to omit literature in related but irrelevant fields (e.g. including 'anthropogenic' in 'sonar anthropogenic noise' removed irrelevant results on sonar signal processing). Where necessary, search terms were enclosed in quotation marks (e.g., "ocean noise") to omit large numbers of publications in unrelated fields.

Topic/search term	Final topic	No. Records	Comment
Airgun Noise	Airgun/Seismic Survey Noise	60	Noise levels from seismic survey airguns used in geophysical research or offshore oil and gas exploration
Marine Anthropogenic Noise Impact	Marine Anthropogenic Noise Impact	61	Biological or ecological impacts of human-generated noise sources
"Marine Noise"	Marine/Ocean/Underwater Noise	392	Ocean noise studies of ambient (natural) or anthropogenic sources
"Ocean Noise"	Marine/Ocean/Underwater Noise	–	See "Marine Noise" for number of records and comments
"Pile Driving" Noise	"Pile Driving" Noise	52	Noise generated from pile driving for construction of piers or windfarms etc
"Seismic Survey" Noise	Airgun/Seismic Survey Noise	–	See "Airgun Noise" for number of records and comments
"Shipping Noise"	"Shipping Noise"	50	Noise generated from large ships
Sonar Anthropogenic Noise	Sonar Anthropogenic Noise	30	Noise generated from sonar, either military or fish-finding sonar
"Underwater Noise"	Marine/Ocean/Underwater Noise	–	See "Ocean Noise" for number of records and comments
"Wind Farm" Noise	"Wind Farm" Noise	21	Noise associated with either construction or operation of windfarms, or both
Combined	Combined	576	Total number of unique scientific papers using any of these search terms (after duplicates removed)

of the resulting rate of citations per paper per year was then taken across all years since publishing to create one index for each paper. This calculation was done to avoid over-weighting more recent papers that may be cited more, due to there now being more papers addressing the topic. All publications since 2010 were discounted from this plot, as such papers will not have had a 'fair' opportunity to be cited frequently. Finally, a trendline was added to ease visual interpretation and is not intended to reflect a statistically significant regression. Rough taxonomic coverage was assessed in a similar manner, with the groupings being: Invertebrates ("crab," "clam," "mussel" or "invertebrate"); Marine Mammals ("dolphin," "whale," "porpoise," "cetacean," "seal," "sea lion," "pinniped" or "marine mammal"); Sea Turtles ("turtle"); Fish ("fish"); Multiple (with more than one taxonomic group mentioned); and None (none of the taxonomic search terms could be found).

Next, the differences in publication rates between the different topics, and the total number of unique papers combined, were assessed visually. This was done by plotting the raw count of papers in each topic by decade, as well as the proportion of papers published in each topic area (including those that contained >1 topic).

Finally, changes in the journals (or other ISI-listed sources) that published papers on the subject were assessed in terms of their 'market share'. The top 20 publishers were plotted for the 1940s to the 1980s, the 1990s to the 2000s, and 2010 and onward to reveal any changes between traditional venues to those associated with the expansion in the literature in the 1990s to those in use today.

3. Results

3.1. Case studies

i. *European eels: rapid recovery following exposure?* To date, studies investigating the impact of anthropogenic noise on individuals have focused on responses during the period of exposure itself. Given that noise is transitory, relative to many other anthropogenic pollutants, the question remains as to whether animals rapidly recover or continue to be affected once exposure stops. Recent work on the threatened European eel (*Anguilla anguilla*) has shown that acute playback of shipping noise recordings causes an increase in ventilation rate (indicating elevated stress) and a reduction in the likelihood of startle responses to a simulated ambush predator (suggesting impaired attention) (Simpson et al., 2014). To examine potential recovery or carry-over effects of noise exposure, we performed two follow-up experiments

using the same methodology and response variables, but focusing on the behaviour and physiology of eels in the immediate aftermath of noise cessation (i.e., in the first two minutes following exposure to noise). The results indicate that the effects of anthropogenic noise can be short-lived and potentially suggest that instant reduction in anthropogenic noise output may decrease direct detrimental effects of man-made noise (Bruintjes, unpublished data).

ii. *The effect of ship noise on the behaviour and physiology of *Carcinus maenas*.* Contrary to earlier conceptions, it has now been realised that marine invertebrates can be very sensitive to sound; however, whilst they represent a considerable portion of marine fauna and are essential components in ecosystem dynamics, how they are affected by anthropogenic noise has received scant attention. A series of carefully controlled experiments investigated how the playback of ship noise affects both the behaviour (foraging and anti-predator) and physiology (oxygen consumption) of the shore crab (*Carcinus maenas*) (Wale et al., 2013a, 2013b). Compared to exposure to playback of ambient harbour noise, ship-noise playback resulted in crabs becoming more distracted from food, taking longer to find shelter in response to a simulated predation event, and righting themselves more quickly when turned on their backs. Single exposure to playback of ship noise also led to significantly higher oxygen consumption (indicating a higher metabolic rate and potentially increased stress), with larger individuals affected more strongly. When repeatedly exposed to ship-noise playback, crabs continued to consume oxygen at an elevated level, providing no obvious evidence of habituation or tolerance. In combination, these results highlight that invertebrates, like vertebrates, may also be susceptible to the detrimental impacts of anthropogenic noise, and that such noise may elevate risks of starvation and predation.

iii. *Noise exposure from shipping in the Strait of Georgia.* In the Northeast Pacific, levels of underwater noise are rising as global trade and coastal development continue to expand. Marine fauna in this region, including several marine mammal and fish species, may be affected by communication masking and by behavioural, physiological, and developmental responses to this industrial activity. To enable management of these effects and to develop mitigation strategies, there is a need to assess current noise levels and the contribution of anthropogenic sources. This study focused on the Strait of Georgia, BC, a habitat for endangered killer whales (*Orcinus orca*) and their acoustically receptive prey

(Chinook salmon; *Oncorhynchus tshawytscha*). The Strait lies on the main shipping route into the Port of Vancouver, one of the busiest ports in North America. We combined acoustic data from the VENUS cabled ocean observatory (operated by Ocean Networks Canada) with AIS ship-tracking data using a recently developed technique (Merchant et al., 2014). The contribution of vessel passages to noise exposure was found to heighten median noise levels by 10–15 dB, and 91% of ship passages were attributable to AIS-tracked vessels. AIS-tracked vessels contributed effectively all of the noise exposure in the frequency range 0.02–1 kHz, a result which suggests that AIS-based noise mapping could be predictive of noise exposure in this habitat. Such maps (e.g., (Erbe et al., 2012, 2014)) would help to identify areas of greatest concern for the conservation of acoustically sensitive species, provided they can be adequately validated (Merchant et al., 2015).

- iv. *Vessel movement data*. There is increasing interest in modeling noise pollution in the marine environment from marine vessels. This is of acute concern in the southern Strait of Georgia: the area is important habitat for numerous marine mammal species, and is also frequented by high volumes of recreational and fishing boats, tugs, ferries, cruise ships, carriers, and tankers. Numbers of the latter two categories of vessels are expected to increase with proposed oil pipeline and terminal expansions. Fundamental to understanding marine vessel noise is an understanding of spatiotemporal patterns of vessel movements, typically represented as vessel density, as an indicator of noise. However, inadequate attention is often given to the source of vessel movement data, and the opportunities and limitations of integrating multiple sources to use in noise models. In addition, most attention in models is focused on large vessels more easily captured by satellite Automatic Identification System (S-AIS), to the exclusion of smaller vessels such as recreational and fishing boats. This study advances understanding of data and analytical considerations for using spatiotemporal patterns of vessel movement as an indicator of marine noise. The reliability and usability of S-AIS can be compromised by vessel position errors, spatial and temporal data gaps linked to satellite coverage, exclusion of small vessels and management of large volumes of data. To compensate for many of these issues a comprehensive marine vessel dataset is being compiled by integrating multiple sources, such as RADAR, shore-based AIS, and Long Range Identification, in addition to S-AIS. Ship position errors can be determined by comparing these different sources. In addition, positions of small vessels can be captured by regular low altitude air photography.
- v. *Chronic ocean noise and critical whale habitats: mitigation through marine spatial planning or allowable harm limits to target populations*. Pressing challenges in marine conservation and management include the need for research methods to quantify cumulative impacts of both lethal and sub-lethal stressors on impacted populations, and policy decisions about tolerable harm levels from human activities that degrade habitats (Erbe et al., 2014; Williams et al., 2014a, 2014c). Illustrated using marine mammal examples, we outline ways that ocean noise can affect individuals, populations and ecosystems. We discuss two ways to mitigate harmful effects: setting allowable harm limits at the level of the population; and marine spatial planning to identify priority areas for mitigation, or 'Quiet Marine Protected Areas' (Q-MPAs). We used the *US Marine Mammal Protection Act's* Potential Biological Removal equation (Wade, 1998) as a

placeholder definition of allowable harm and constructed matrix-based models to estimate the proportion of prey reduction required to exceed stated objectives for allowable harm. We identified populations for which a prey-demography link was available, and "reverse-engineered" limits for two marine mammal populations (humpback (*Megaptera novaeangliae*; (Robbins, 2007)) and killer whales (Ford et al., 2010; Ward et al., 2009)). From a marine spatial planning view, MPAs offer a powerful tool to separate valued ecosystem components from threatening processes, such as fishing. We illustrate two complementary approaches for area-based management of exposure to chronic anthropogenic noise (Erbe et al., 2014), and outline the numerous benefits, including maintaining ecological integrity inside Q-MPAs and resilience in the face of additional anthropogenic stressors.

- vi. *Engaging audiences to advance management solutions*. In 2011, WWF-Canada's Pacific office (Vancouver) began a multi-year project designed to advance management and understanding of underwater noise in Canada's Pacific. The project used a small team to make rapid progress around this complex emerging issue through using a strategic, targeted approach that involved a wide range of partners, from local to international levels. At the start of the project, outside the marine science community there was relatively little awareness about underwater noise as a conservation concern in coastal British Columbia, especially regarding vessel-generated noise. To build understanding, the project team engaged with diverse expert and non-expert audiences while simultaneously developing scientific knowledge and policy proposals for regulatory agencies. Projects were strategically chosen, including the identification of shipping noise hot-spots (Erbe et al., 2014); introducing noise management into marine spatial planning; working with the maritime industry to develop support for vessel noise reduction; and communicating to the public via social and mainstream media. Local successes fed into developing the expertise that led to invitations to participate in international processes, including helping draft International Maritime Organization Guidelines to Reduce Underwater Noise from Commercial Shipping, and collaborating with WWF-International to develop the report *Reducing Impacts of Noise from Human Activities on Cetaceans* (Wright, 2014). As an international NGO, WWF is well-placed to work at multiple levels and with multiple partners; other national- and international-level NGOs may be similarly placed to broker solutions to this complex issue.

3.2. Bibliometric analysis of published ocean noise research

Querying the ISI Web of Science database using the search terms in Table 1 returned 685 records, or 576 unique papers, which are summarized below. Journal records matching our keywords did not appear until the 1940s (our search began with the year 1900), although we are aware of pre-World War II research presented in unpublished reports. Accordingly, the period from 1900 to 1940 is not included in any of the graphics. The total number of papers has drastically increased since the beginning of the 1990s, with the truncated decade since 2010 still producing more papers on the subject of noise than any previous decade (Fig. 1). Our findings match what one would predict from the military origins of ocean acoustics (Lemon, 2004). At first consisting only of marine noise and its synonyms, more specific terminology began appearing in the underwater noise literature in the 1970s, starting with

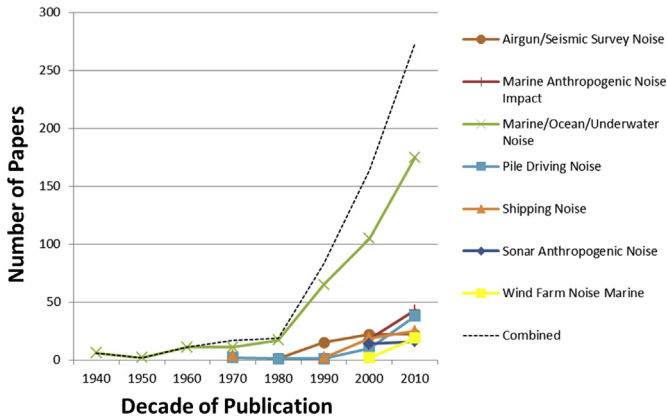


Fig. 1. The number of publications across underwater noise topic by decade.

“shipping noise”. Papers on noise from pile driving and wind turbines have particularly increased in the last 15 years. Although papers are becoming increasingly specialized over time with respect to specific sound sources, more than half of recently published papers still use the broadest search term (i.e., “Ocean noise”; Fig. 2).

With regard to taxonomic coverage, biology did not appear to be an important component of the literature until the 1990s and currently about 50% of papers refer to one or multiple taxonomic groups (Fig. 3). Nevertheless, marine mammals have driven the biological studies across decades. Studies on fish species have also increased substantially in the last couple of decades, followed by research on invertebrates (although invertebrates remain heavily underrepresented). The taxonomic group in our list with the least representation, sea turtles, remain under-studied, with only two abstracts solely mentioning them (n = 2). Despite the focus on the search term “noise,” papers with abstracts containing references to animal groups (and noise) are more prevalent in the literature since 2010 than those without mention of animals.

Finally, the venues in which our records were published have also changed over time (Fig. 4). While the *Journal of the Acoustical Society of America* (JASA) and, to a lesser extent, *Applied Acoustics*, remain important outlets today, their dominance is much reduced from the period from the 1940s–1980s. Noise-related literature began to appear in a range of other journals in the 1990s and 2000s, with *Acoustical Physics* (founded in 1955 and the only Russian academic journal in the field of acoustics) taking a sizeable share. Also in this period, *Marine Ecology Progress Series* (first published in

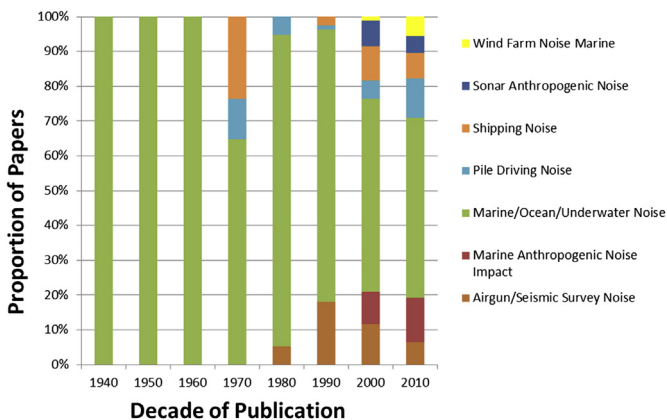


Fig. 2. The proportion of underwater noise publications across topic by decade.

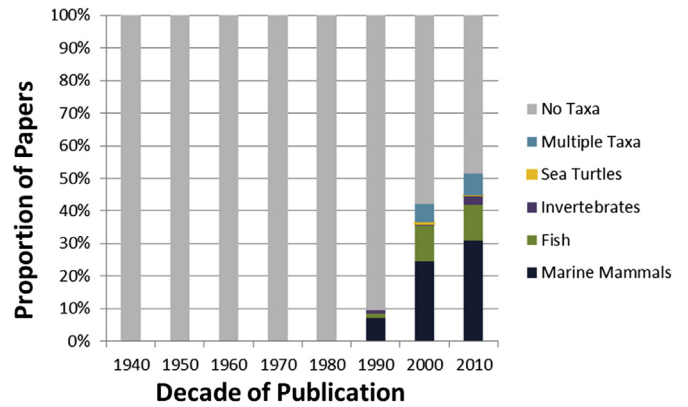


Fig. 3. The proportion of publications across taxa by decade.

1979) made a notable entrance in the field. However, since 2010 the diversity of journals publishing noise-related papers has flourished, with 18 out of the top 20 journals we identified already represented this decade. Perhaps noteworthy here is the rise of papers published in *Marine Pollution Bulletin* and *Environmental Research Letters*, suggesting a change in the focus of the published work from physical acoustics to more ecological impact-based studies. Perhaps the most sizeable entrance in this period, however, was that of the proceedings volume, *The Effects of Noise on Aquatic Life*. Finally, it must be acknowledged that JASA may be somewhat over-represented across all periods due to their tradition of publishing abstracts from presentations at their meetings that could later be republished in JASA (or elsewhere).

Using the mean number of citations per paper per year index it appears that there has been no strong trend in the citations of papers that cannot be attributed simply to the swelling of the literature (Fig. 5). However, the picture is less clear when the citation rates for papers with or without impact-related terminology (i.e., “effect”, “impact”, and “conserv*”, or E, I & C in Fig. 5) are considered. While it seems that there is an increasing tendency for papers with impact-related terminology to be cited, the citation rate for those without those terms appears relatively stable, or possibly decreasing. It must, however, be noted that this index provides inflated values for papers published and cited early in the series of records, and these ‘outliers’ may be producing the apparent trend that is slightly negative.

4. Discussion

The topic of anthropogenic ocean noise is a fast-moving, maturing scientific discipline. From its initially narrow focus on naval applications (Lemon, 2004) to the first, prescient suggestion that whales may be affected by ocean noise across very long distances (Payne and Webb, 1971), the literature has taken a more holistic view over time. This is evidenced by the journals publishing papers on the topic, the diversity of anthropogenic sound sources under consideration, citation rates, and taxonomic coverage. Overall, papers on physical acoustics that did not consider effects on any organisms outnumber those that investigated ecological impacts. But the proportion seems to have shifted since 2010, when slightly more than 50% of papers published considered effects on at least one taxonomic group, which might have resulted from our focus on the term “noise” rather than “sound”. Additionally, some journals (e.g. JASA), might have been over-represented due to a tradition of publishing abstracts from presentations at their meetings that might later be published in the same journal or elsewhere. When ecological effects were considered, marine

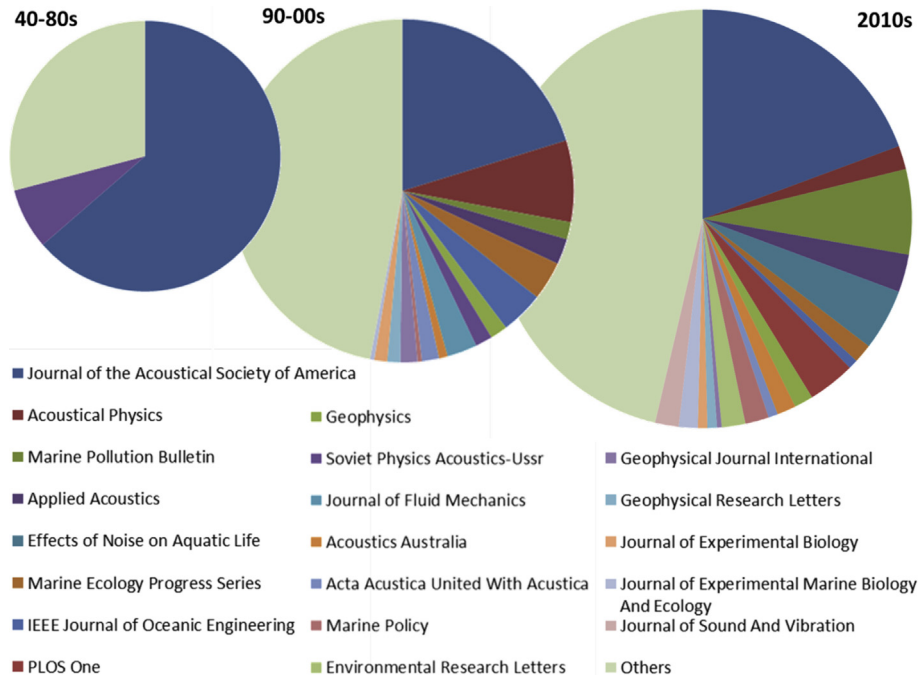


Fig. 4. Changing patterns in publication outlets on underwater noise (diameters not to scale). The number of publications in the groups are as follows: 1940–1980s, $n = 55$; 1990–2000s, $n = 247$; and 2010s, $n = 274$.

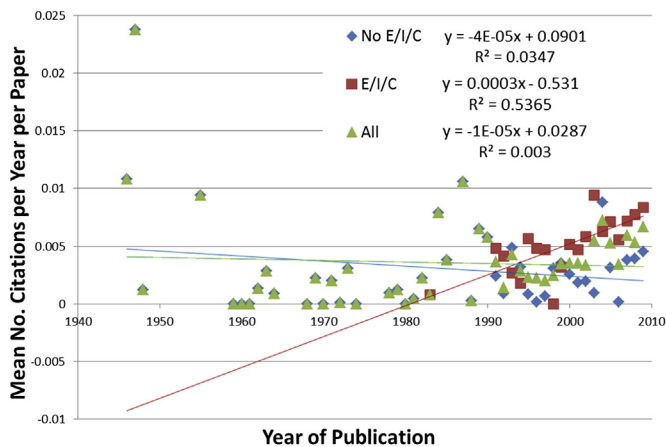


Fig. 5. Mean number of citations for each year since publication, as a proportion of the number of papers in our search output by that year, plotted for each paper against the year it was published. No E/I/C = search without search terms “effect”, “impact”, “conserv”; E/I/C = search terms “effect”, “impact”, “conserv” and All = all papers pooled. Trendlines are visual aids only and are not intended to reflect a statistically significant regression.

mammals were the most frequently considered group (Fig. 3). This is unsurprising, given the high profile of cases when beaked whales (Family Ziphiidae) are exposed to anthropogenic sonar (Jepson et al., 2003; Nowacek et al., 2007). We expected invertebrates to be the biggest taxonomic knowledge gap, but marine turtles seem to be similarly under-represented. That said, given the vastly larger number of invertebrate species than marine turtle species, it could be said that invertebrate species are still the most poorly studied group in relative terms, rather than absolute number of publications.

These broad patterns were reflected well in the case studies presented at the IMCC3 symposium on ocean noise. Three of the case studies (iii, iv, v) had a strong element of physical acoustics and

soundfield modelling. When focal study animals were discussed, most considered marine mammals (iii, iv, v, vi). Two of the talks considered fish (i, iii), and only one focused on invertebrates (ii). No marine turtle projects were presented. Perhaps reflecting the increasing diversification of the field over time (Figs. 1, 2 and 4) and the conservation focus of the conference, many talks asked specific questions to inform management. For example, topics covered included: effects of chronic ocean noise on endangered species (v); recovery time after mitigation (iv); and interdisciplinary studies that integrate noise impacts as mediated by physiology and size dependency (ii; (Wale et al., 2013a, 2013b)). One failing in our selection of case studies to highlight was a fairly narrow geographic focus, namely drawing from studies conducted in developed countries in the northern hemisphere.

The case studies build a compelling case that a number of anthropogenic noise types can affect a variety of marine taxa. What is needed next is a conversation with policy makers about severity of effects from noise of varying type, frequency, intensity and duration to facilitate the setting of quantitative allowable harm limits, and viable approaches to provide these. Such limits could be set at the level of habitat, individuals, populations or ecosystems.

Traditionally, the predominant outlet for publishing marine noise research has been specialized journals in acoustics, physics and engineering. These are not particularly accessible to those in applied ecology or studying environmental impacts, let alone being accessible to decision makers and planners. However, this is changing (Fig. 4). Several biologically-focused journals have become regular outlets for noise-related research. Additionally, the science-policy journal *Marine Pollution Bulletin* has become the third largest publisher overall of noise-related papers as revealed by our search; this is due to manuscripts published since the beginning of 2010. Although not revealed in our analysis as a highly-cited area of research, law and policy journals are also beginning to publish papers on underwater noise (e.g., (Weilgart, 2007)); because these publications are aimed at an audience with a background in law or policy, they are arguably more accessible to decision makers than those that focus on physical acoustics.

This is a highly technical subject, and any management advice must be driven by evidence from rigorous scientific studies led by those with relevant expertise. That said, there will be no effective conservation or mitigation if acousticians talk only to themselves. In one case study (vi) on engaging diverse audiences, it emerged that it was fruitful to bring together largely non-technical audiences of managers, scientists, NGOs, policymakers and stakeholders (importantly, including various maritime industries) to identify priority topics for research, communicate results, and explore opportunities for solutions and incentives for mitigation. The topics related to underwater noise are technical in nature and at least some of the solutions require the multifaceted approach that an interdisciplinary group provides. One such interdisciplinary group has assembled to collaborate on a new ship-source noise modelling project in Canada led by one co-author (RC) and involving other co-authors (NDM, RW, DTD, and PDO). This project will pick up where case studies iii, iv and vi left off. In the next phase, First Nations, government, industry, environmental non-governmental organizations and coastal communities have been integrated into the project at the outset to ensure that the analyses will specifically address the needs of varied end users with respect to monitoring and mitigating impacts of underwater noise. The fact that underwater noise threatens a charismatic group of animals (marine mammals) has also helped to engage these diverse audiences and generate public interest in finding solutions.

4.1. Our perspective: synthesis & future directions

The case studies show that non-injurious effects can still accumulate to have population-level impacts mediated through physiological impacts and probably other mechanisms. We still lack information on hearing abilities (audiograms) of many acoustically active species that we suspect should be sensitive to anthropogenic noise (Erbe et al., 2014). Additionally, most audiograms have been created using sound pressure; however, many fish and invertebrate species instead detect sound using particle motion (Popper and Fay, 2011), so there is still fundamental work to be done. But we should view these relatively tractable audiogram studies not as an endpoint, but rather as the next step needed to move beyond predicting effects on behaviour of individuals. Management and mitigation need to begin moving beyond a near-exclusive focus on high-level, 'injurious' noise exposures, and start taking various population-level effects into account. Such studies are well underway for terrestrial avian communities (Francis et al., 2009) and some marine mammal populations (New et al., 2013). For other populations, taxa and ecosystem-level effects, we believe that it is time to start studying them so that we can provide effective advice to managers.

Conducting studies at the population, community or ecosystem level will be challenging, but not impossible (Boyd et al., 2011). We can predict population consequences for some species by, for example, focusing research efforts on potentially critical early life stages (e.g., egg and larval phase (Bruintjes and Radford, 2014; Debusschere et al., 2014; Nedelec et al., 2014; Wysocki et al., 2007)) or antipredator behaviour ((Pirota et al., 2015; Simpson et al., 2014)). We will never have studies on sensitivity of all combinations of species, noise and context, but filling in key taxonomic gaps will allow us to make predictions through comparative studies or mechanistic models that allow us to generalize so that we can predict potential impacts in cases where we have few or no data. A mechanistic, integrative approach (e.g., (Kight and Swaddle, 2011)) considers not only behavioural responses, but also their physiological and genetic bases. Constructing such models will benefit from combining field and laboratory studies to make predictions about scenarios that are (logistically) impossible or difficult to

obtain in the field (Graham and Cooke, 2008; Popper and Hastings, 2009; Slabbekoorn, 2014). We need to identify tractable study sites, species and scenarios to collect sufficient replication to understand response variation between species, individuals, context, situations and through time (Bruintjes and Radford, 2013; Radford et al., 2015). To predict population-level effects from individual responses will require data on energetic demands, energetic cost of disturbance, predator-prey dynamics and their sensitivity to noise, and knowledge of the ratio of prey requirements to availability in the environment (New et al., 2013; Williams et al., 2011, 2006; Williams and Noren, 2009).

A combination of urbanization, human population growth, climate change, and economic growth is causing the world ocean to become an increasingly noisy place (McDonald et al., 2008; Moore et al., 2012). The field of ocean noise research is growing rapidly, but it is doing so while the ocean acoustic environment is becoming degraded (Hatch et al., 2012). If our scientific knowledge base is ever to get ahead of the curve of rapid industrialization of the ocean, we are going to have to identify naïve populations and relatively pristine seas, (e.g., areas predicted to have comparatively little human impact (Halpern et al., 2008), or cetaceans in the Arctic or Antarctic living in habitats that are not yet used by the oil and shipping industries (Moore et al., 2012)) so that we can anticipate impacts before they occur, and guide effective mitigation for these potentially vulnerable populations. An alternative would be to choose precautionary measures for the quietest sites, such that they become, at best, acoustic refuges, or at worst, experimental control sites to improve our understanding of the ecological cost of ensouffication of the world ocean.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.ocecoaman.2015.05.021>.

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