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Review

A critical review of the potential impacts of marine seismic surveys on fish & invertebrates

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ABSTRACT

Marine seismic surveys produce high intensity, low-frequency impulsive sounds at regular intervals, with most sound produced between 10 and 300 Hz. Offshore seismic surveys have long been considered to be disruptive to fisheries, but there are few ecological studies that target commercially important species, particularly invertebrates. This review aims to summarise scientific studies investigating the impacts of low-frequency sound on marine fish and invertebrates, as well as to critically evaluate how such studies may apply to field populations exposed to seismic operations. We focus on marine seismic surveys due to their associated unique sound properties (i.e. acute, low-frequency, mobile source locations), as well as fish and invertebrates due to the commercial value of many species in these groups. The main challenges of seismic impact research are the translation of laboratory results to field populations over a range of sound exposure scenarios and the lack of sound exposure standardisation which hinders the identification of response thresholds. An integrated multidisciplinary approach to manipulative and *in situ* studies is the most effective way to establish impact thresholds in the context of realistic exposure levels, but if that is not practical the limitations of each approach must be carefully considered.

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1. Introduction

The extent to which anthropogenic noise in the world's oceans impacts marine fauna is a subject of growing concern (Slabbekoorn et al., 2010; Azzellino et al., 2011; Williams et al., 2015). Sources of marine anthropogenic noise include high-intensity acute sounds produced by activities such as military exercises (Dolman et al., 2009), oil and gas exploration (McCauley et al., 2000) and pile driving (Bailey et al., 2010), as well as lower-level chronic noise generated by commercial shipping and recreational and commercial fishing vessels (Codarin et al., 2009; Malakoff, 2010). Many marine animals, from small invertebrates to large cetaceans, make extensive use of underwater sounds for important biological activities such as intraspecific communication, predator avoidance, navigation, larval orientation, foraging and reproduction (Montgomery et al., 2006; Vermeij et al., 2010; Mooney et al., 2012b). The ability to detect low-frequency sound in particular may have evolved in fish, cephalopods, and other mobile marine invertebrates to avoid predators (Mooney et al., 2010). Anthropogenic noise can interfere with the ability of an animal to detect and/or use its 'acoustic' or 'auditory' scene and potentially decrease its fitness and chance of survival (Popper and Hastings, 2009). Potential effects of anthropogenic sound sources on marine animals range from disturbance that may lead to displacement from feeding or breeding areas, to auditory damage, tissue trauma and mortality (Popper and Hawkins, 2012). Alternatively, some marine species may experience no effect of exposure to intense sources, particularly if the received frequency does not exceed hearing thresholds (Popper and Hastings, 2009). The area over which anthropogenic noise may adversely impact marine species depends upon multiple factors including the extent of sound propagation underwater, its frequency characteristics and duration, its distribution relative to the location of organisms, and the absolute sensitivity and range of spectral hearing among species (Slabbekoorn et al., 2010; Popper and Hawkins, 2012).

Marine seismic surveys typically involve the use of airgun arrays that are towed behind vessels and produce high intensity, low-frequency impulsive sounds at regular intervals. There are two common seismic survey configurations: 2-D seismic surveys involve a ship towing a single airgun array and a single streamer of hydrophones to provide a two-dimensional image of the subsea geology, and 3-D seismic surveys involve a ship towing two airgun arrays with ten or more parallel streamers to provide data which are processed to create a complete three-dimensional image of the subsea geology. Optimum frequency range for a particular array is a trade-off between resolution and depth of penetration. These sounds are directed down towards the substrate and are used to generate detailed images of the seafloor and its underlying geological formations (McCauley et al., 2000; Gausland, 2003). The predominant frequency range of seismic airgun emissions is within the detectable hearing range of most fishes and elasmobranchs (Popper et al., 2003b; Popper and Fay, 2011; Ladich and Fay, 2013) and can also elicit a neurological response in cephalopods (Mooney et al., 2010) and decapods (Lovell et al., 2005).

Although offshore seismic surveys have long been considered to be disruptive to fisheries (McCauley et al., 2000; Engås and Løkkeborg, 2002), most studies on the effects of noise focus on cetaceans (reviewed by Gordon et al. (2003)), while comparatively few studies target commercially important species (Williams et al., 2015), particularly invertebrates. Furthermore, much information on the effects of seismic operations on marine life is derived from 'gray' literature or anecdotal reports which may lack appropriate experimental design or fail to adequately describe it (Hawkins et al., 2015). There have been concerns from various fishing industry groups that seismic operations negatively affect catch rates within a given area (e.g. snow crabs in northwestern Canada (Christian et al., 2004), rock lobsters and commercial scallops in southeastern Australia (Parry and Gason, 2006; Harrington et al., 2010)). Efforts are being made to improve relationships between fisheries and petroleum industries regarding improved regulation of seismic surveys (Knuckey et al., 2016), as well as to develop a coordinated global plan to address noise impacts (Nowacek et al., 2015), but the lack of robust studies and clear interpretations may hinder such efforts. Several countries have adopted precautionary principles in their approvals process for seismic survey activities based on potential impacts to fish and invertebrates (e.g. St Lawrence Seaway in Brêthes et al., 2004; Canada in Department of Fisheries and Oceans (DFO), 2004; Norway in Dalen et al., 2007). These policies restrict the timing, location, and duration of seismic exploration and can often be a source of conflict between various stakeholders (Lewandowski, 2015). As such, there is an urgent need to conduct a critical review of the associated science and identify knowledge gaps so that such precautionary policies can be developed or further refined according to the best information on species-specific responses to known exposure levels of low-frequency sound (Parsons et al., 2009; Prideaux and Prideaux, 2016).

Previous reviews on aquatic noise impacts have focussed on particular taxa, including cetaceans (Gordon et al., 2003; Erbe et al., 2016), turtles (Nelms et al., 2016) and fish (Popper and Hastings, 2009; Radford et al., 2014), or often in the context of general noise pollution (Popper and Hastings, 2009; Slabbekoorn et al., 2010). Hawkins et al. (2015) identified knowledge gaps in our understanding of noise effects on fish and invertebrates and provided valuable recommendations for priority research, but a comprehensive review of existing studies was outside their scope. Only McCauley et al. (2000) has critically reviewed a broad range of taxa specifically related to seismic sound impacts. The number of experimental studies has considerably increased since that review, and we therefore provide an updated, critical synthesis of the effects of seismic surveys on marine fish and invertebrates.

This review aims to summarise scientific studies which investigate the impacts of low-frequency sound on marine fish and invertebrates, as well as to critically evaluate how such studies may apply to field populations exposed to noise from seismic surveys. We also provide recommendations for future research investigating the potential impacts of seismic surveys on marine biota. For the purposes of this study, we define seismic operations as those using airguns, and we target peer-reviewed studies that focus on impulsive low-frequency sound (<300 Hz), which is distinct to marine seismic surveys and a few other activities (e.g. pile driving). Due to the limited number of marine environmental impact studies involving airguns (particularly for invertebrates), we occasionally draw on studies using other sound sources such as laboratory playback, pile driving or ship noise (continuous low frequency), as well as studies that examine the impacts of low-frequency sound on some freshwater and estuarine fish species, to highlight potential responses and areas of future research.

This paper is organised into five additional sections: Sections 2 and 3 briefly summarise the acoustic properties of marine seismic sound and sound detection in fish and invertebrates, respectively. Section 4 reviews the impacts of seismic surveys on marine invertebrates and fish, including a knowledge gap analysis. When quantifying the impact of any anthropogenic activity, an understanding of the

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