Marine Bioacoustics: The Importance of Sound in the Marine Environment

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Abstract

Our understanding of underwater bioacoustics has increased markedly over the last half-century and evidence for the impacts of sound on marine life is overwhelming. Since the 1960's, background sound levels below 100 Hz has increased by approximately 15 dB in the deep sea. Moreover, anthropogenic sound is estimated to double in intensity every decade in coastal waters in some regions of the world. Currently, regulatory bodies in New Zealand require emitted sound levels from any marine development project be assessed in order to predict the degree of impact on marine life. This process is critical for sustainability and conservation, and there is an urgent need to better understand the impacts of anthropogenic sound on fish and crustaceans. Here, the variety of underwater sounds of biological origin around New Zealand and the potential impacts of anthropogenic sound on fishes and crustaceans is discussed.

Simple Physics: Underwater Sound Propagation

Sound is transmitted through water as longitudinal waves, also called compression waves. These waves consist of alternating pressure deviations from the equilibrium state, which cause localised regions of compression and rarefaction, and corresponding oscillation of the water molecules [1,2]. The frequency of sound relates to the number of repeating compressions, or waves, per second which in term determines the wavelength of the sound; the longer the wavelength, the lower the frequency (f) (i.e., $f = \lambda/c$, where λ is the wavelength and c is the speed of sound in water (1500 m s^{-1})). Attenuation is the loss of sound energy, or sound intensity, as it passes through a medium. In seawater lower sound frequencies have lower attenuation over a given distance compared to higher frequencies. For example, a 500 Hz sound wave only loses 1 dB of intensity over a distance of 100 km of transmission in seawater, which is much less than frequencies above 500 Hz [3,4,5]. The audibility of sound at a given distance from the source is a factor of not only the level of the sound, but also the transmission properties of the local environment which are determined by scattering (reflections) and attenuation (absorption) [6]. The propagation of sound in shallow water is different than in deep water because it has greater interaction with the sea surface and seafloor. Therefore, the depth of water column, sea state and seafloor composition can greatly influence the propagation of sound in the sea, especially in shallow coastal waters.

Under the waves is a noisy environment

A wide range of sounds characterise underwater environments that are generated by biological (biotic) and physical (abiotic) sources [7,8]. A large majority of abiotic sounds underwater are due to the effect of wind interacting with the sea surface and waves, producing sound with dominant frequencies in the 10 – 1000 Hz range [8,9]. Biotic sounds are mainly attributed to soniferous animals engaged in reproductive and social behaviours, territorial defences and echolocation as well as incidental sound resulting from feeding activity and movement [8,9,10]. These sounds are produced over a wide range of frequencies from below 20 Hz in fin and blue whales [11,12] to 200 kHz in dolphins and shrimps [13,14].

Temporal and spatial variation in the underwater sound environment

Several studies have shown patterns of periodic increases in the intensity of underwater biotic sound from coastal reefs which are referred to as dawn and evening choruses [9,15,16]. During any chorus, the overall power level for the frequency band 0.7 – 2 kHz can increase by as much as 20dB re 1 $\mu Pa^2 Hz^{-1}$ which is due to the increased crepuscular activity of many reef inhabitants [9]. Furthermore, there can be variation within individual choruses which coincide with the lunar cycle [9]. For example, snapping shrimp showed significant lunar, diurnal and seasonal periodicity in their sound production, which accounted for the increases in the sound levels recorded in different habitats in the evening [8].

Nearshore environments may also be characterised by different underwater sounds. Marked differences have been found between the sounds emitted from three localised coastal habitats; a macroalgal-dominated reef, a

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sea urchin-dominated reef, and a sandy beach [8]. Overall, the urchin-dominated reef produced significantly more intense sound in biologically relevant frequencies (800 – 2500 Hz) compared to the macroalgal-dominated and sandy beach habitats [8]. There were also many differences in the sound among the habitats with the time of day the recordings were taken, showing that not only temporal compositions vary, but also the spectral composition between habitats.

The role of acoustics in the lives of crustaceans and fishes

Sound underwater has lower attenuation than in air meaning sound travels further underwater [17]. Light as an orientation cue for fish and crab larvae is only effective while it is detectable and it is therefore greatly limited due to its high attenuation in coastal waters. Chemical cues in aquatic environments are also limited by their detection distance. Therefore, underwater sound is considered as the principal cue for long-distance orientation from the open ocean to a desired settlement coastal habitat for fish and crab larvae [18,19]. Thus, it is not surprising crustaceans and fishes have evolved hearing mechanisms that allow for the detection and cognition of underwater sound.

Our understanding of the detection of acoustic stimuli by pre-settlement crustacean and fish larvae has slowly improved over the last 20 years. The planktonic larvae of fish and brachyuran crustaceans must find a suitable reef habitat if they are to settle and grow [8,9,18,20,21,22,23]. There is increasing evidence that underwater sound cues are used by the larvae of fishes and crustaceans to orient themselves towards reef habitats and settle once they arrive at the source [8,16,18,20,21,22,23,24,25]. Underwater sound is thought to act as an important cue for settlement-stage larvae because it can travel long distances with minimal attenuation, whilst also conveying information regarding the quality of and direction to habitats [18,20,21,26,27].

Jeffs et al. (2003) [27] demonstrated first hand that larval crustaceans may orient toward underwater reef sounds by using light traps coupled with an artificial source of natural ambient sound. The results showed significantly greater numbers of larvae in light traps coupled with sound compared to silent traps, although this effect was only observed during particular moon phases and no effect was seen near full or new moons when tidal currents would be strongest. Other scientists have also reported strong evidence for the attraction of larvae to reef sound in five common New Zealand coastal crab species (Plagusia chabrus, Notomithrax ursus, Cyclograpsus lavauxi, Hemigrapsus edwardsii and Pagurus spp.) (Radford et al. 2007).

Underwater sound has also been found to act as a settlement cue in both temperate (Hemigrapsus sexdentatus, Cyclograpsus lavauxi, Macrophthalmus hirtipes) and tropical (Grapsidae spp.) crab species [23]. Larvae subjected to reef sound showed a significantly shorter time to metamorphosis than individuals in the silent treatment, across all species. These results provide the first experimental evidence that underwater sound can advance the physiological development of larval decapod crustaceans.

Simpson et al. (2005) [20] demonstrated that larval fish orient toward underwater reef sounds by building 24 reef patches from dead coral on sand flats and at each patch they deployed underwater loudspeakers which broadcasted reef sound, predominantly consisting of snapping shrimp and fish calls. The results showed greater fish diversity and abundance on reef patches which broadcast reef sounds, compared to those which did not. Also, Tolimieri et al. (2000) [28] reported a median of 350 individual fish larvae entering light traps with sound (sound traps), compared to only 24 entering light traps without sound (silent traps). By using binary choice chambers with recorded reef sounds being played on one end, Tolimieri et al. (2004) [29] found that significantly more triplefin and damselfish larvae were orienting towards the sound during the night – coinciding with similar findings from Leis et al. (1996) [30] and Stobutzki and Bellwood (1998) [31].

Despite the vast amount of literature describing the possibility of sound as an orientation and settlement cue, very few studies have attempted to identify the specific sound frequencies to which fish and crustaceans are responding. Simpson et al. (2005) [20] found that higher frequency sounds (where 80% of the spectral energy was greater than 570 Hz – predominantly shrimp) attracted more fish taxa generally, compared to low frequencies (80% of spectral energy less than 570 Hz – predominantly produced by fish). What they also found was that pomacentrid (damselfish) larvae or juveniles were preferentially attracted to the higher frequency sounds, while apogonids (cardinalfish) were equally attracted to both high and low frequency acoustic signals. Thus, there is evidence that some fishes are discriminating between sound frequencies and are attracted to specific sounds (see also [8]). There is also evidence that some decapod crustaceans may be discriminating between sound frequencies with the mediation of settlement and metamorphosis to reef sound, rather than sound emanating from an estuary [32].

Anthropogenic sound: from discovery to understanding

Anthropogenic sound is any sound generated by human activity [33]. Anthropogenic sounds which are of specific concern are those which are within the audible frequencies of the receiver and are loud enough to overpower ambient sound levels [17]. In general terms, masking can be defined “when a noise interferes with or obscures a signal” [34]. Masking of natural ambient sounds is considered to occur when the anthropogenic sound is louder than biologically important sounds and thus impairs the receiver’s ability to detect and assess the source in space and time [17].

Underwater anthropogenic sound sources

Research investigating underwater anthropogenic sound has been increasing since the end of the First World War [35]. Anthropogenic sound is estimated to double in intensity every decade in coastal waters in some regions of the world with intense shipping activity [36,37]. The sources of anthropogenic sounds are wide-ranging and include ships, boats, seismic exploration devices (e.g. air guns), construction activities (e.g., pile driving) and sonar [38,39]. Shipping and boat sound is a major anthropogenic sound source and can increase ambient levels within harbours and open oceans considerably [40]. Motorized shipping has increased ambient sound levels at frequencies below 100 Hz in the deep sea by approximately 15 dB since the 1960’s [41,42,43]. Most shipping sound is low frequency (< 300 Hz [36]) and sound from a modern cargo ship travelling at 16 knots can emit frequencies at intensities over 150 dB re 1 μPa at 1 m at 10 Hz, over 160 dB re 1 μPa at 1 m at 100 Hz and 180 dB re 1 μPa at 1 m at 200 – 500 Hz [44].

Industrial construction activity is a major source of underwater anthropogenic sound. Such activity includes pile-driving, dredging, drilling, installing offshore wind farms and blasts from air guns and explosives [17,45,46] and can produce sound levels greater than 200 dB re 1 μPa @ 1 m [47,48]. Pile-driving is increasingly common in coastal waters and can produce frequencies between 20 Hz to more than 20 kHz, with most energy reported between 100 Hz and 200 Hz [17,49]. Marine dredging is used to deepen channels and harbours to mine seabed resources and it produces sound levels above 160 dB re 1 μPa @ 1m with much energy between 50 and 500 Hz [38,50,51]. Drill ships and semi-submersible drill rigs can produce sound levels of 191 dB re 1 μPa @ 1 m at broadband frequencies (10 Hz – 10 kHz) [38,52]. Explosions are often used during construction to remove subsurface structures and even in dredging when boulders are too large to be moved in one piece [17]. Explosions produce the highest sound level (274 dB re 1 μPa @ 1 m [38]) from a point source in the sea with the ability to travel great distances [6,17].

As the demand for energy rises each year, offshore wind farms and tidal turbines are becoming more common, with most of them being built in shallow waters (<20 m) [49]. Underwater sound emanating from wind farms has two main sources; air flow through the wind blades and machinery sound [53], producing underwater sounds below 1 kHz [54,55,56] at 154 dB re 1 μPa @ 1 m at a wind speed of 13 m s^{-1} [56]. Wind speeds, wind turbine size and the number of turbines affect underwater source levels and the distance at which fishes and marine mammals can hear them. Tidal turbines have been estimated to produce a source level of 175 dB re 1 μPa @ 1 m for frequencies between 200 and 8000 Hz [57]. Initial installation and

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turbine operation are the main sources of sound in tidal turbines.

Petroleum exploration is a source of high intensity sounds which can impact marine life. Such exploration can involve the repetitive use of high energy sound sources, such as airguns, which produce short, sharp low-frequency sounds [58] and source levels more than 230 dB re 1 μPa @ 1 m [59]. Military sonar and seismic surveys have also shown to impact marine mammals [60,61].

Potential sound impacts on marine organisms

Over the last 20 years, there has been an increasing concern for the impact these sounds have on marine mammals, fishes and invertebrates. Currently, however, there is not enough data to predict how anthropogenic sound will alter ecosystems [45]. Thomsen (2009) [17] describes several studies which have shown possible detrimental impacts from anthropogenic sound on marine organisms. Such impacts include disrupted communication among cetaceans and porpoises, as well as decreased abundance of cetaceans in areas of marine construction (such as wind farms, turbines, oil rigs, pile-driving and dredging) [17,44,48].

In fishes, hearing loss and increased mortality has also been linked to high sound levels [46], such as with the shiner surfperch [17]. Loud anthropogenic sounds induced stress responses and hearing loss in the goldfish *Carassius auratus* [62,63], while air-guns were found to severely (and evidence suggesting permanently) damage the hearing structures of fish [58]. High intensity sounds have been found to affect behavioural responses and act as a distraction to important acoustic signals, such as that given from a predator. For example, boat sound had a significant effect on the behaviour of the Caribbean hermit crab with simulated predators getting closer during sound playback experiments [64]. Similarly, three-spined sticklebacks (*Gasterosteus aculeatus*) showed poorer foraging performance (measured by decreased discrimination between food and non-food items and food handling errors) in treatments exposed to white sound (bandwidth 100 – 1000 Hz) compared to the silent control [65]. Sound transmitted from boats has been found to mask communication signals between vocal fishes, such as *Chromis chromis*, *Sciaena umbra* and *Gobius cruentatus* [66] and the Lusitanian toadfish, *Halobatrachus didactylus* [67], and disrupt the schooling behaviour of the blue fin tuna, *Thunnus thynnus* [68]. Ship sound has also been found to increase the secretion of the stress hormone cortisol in freshwater fishes [69] and seismic pulses were found to cause body malformations in scallop larvae [70]

The impacts of offshore wind farms are more localised than other anthropogenic sound sources, with wind farm construction being of greatest concern [49,71]. Actual recordings of offshore wind farms are rare, and little is known about their impacts on marine life. Sounds produced during the operation of a wind turbine were found to have little or no physiological impacts on fishes, harbour seals and porpoises [53,56]. Even within 10 m of an operating wind turbine, the received levels were much lower than those required to cause temporary and permanent hearing damage to fishes [56], and have been described as incapable of masking communication between harbour seals and porpoises [53]. However, some caution should be taken about interpreting potential impacts of wind farms on marine mammals and fishes as there are huge uncertainties surrounding the data on sound impacts [56] and thus, our understanding about offshore wind farms is poor.

Over the last 20 years there has been growing concern regarding the possible impacts of anthropogenic sound in the ocean. There is considerable evidence to suggest that anthropogenic underwater sound may impact many species and their behaviours (as in the Caribbean hermit crab and vocal fishes), yet currently, there is insufficient data available to support, or negate, the growing concerns that anthropogenic sound may change whole ecosystems. We need much more species- and habitat-specific data before conclusions can be drawn about how these sounds affect an ecosystem [45].

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In the Enviromental Court

SKYDIVE QUEENSTOWN LIMITED – Appellant

[2014] NZEnvC 108, 58p, [208] paras, 16 May 2014

Summary of Facts

A Direct Referral application by Skydive Queenstown Limited for a replacement resource consent to operate increased flight numbers from an airstrip at Remarkables Station, Queenstown. The central issue concerned the noise effects of the application on the neighbouring residents and recreationalists engaged in outdoor activities. The Court noted the airport was "unique" and the operation intensive, which caused more disturbance than a more conventional airport due to restricted flight paths.

The Court's view was that it was actually the number of plane movements that was the most crucial factor on effects, not the volume of noise or the total sound bucket. The application would roughly double the present activity;