Characterization of Open Water Explosions from Confiscated Explosives in the Philippines – Possible Implications to Local Marine Mammals

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ABSTRACT

Underwater noise poses serious threats to marine mammals, which rely on underwater sound primarily for communication, orientation, and foraging. In this study, underwater noise from dynamite fishing was analyzed to infer possible effects on local marine mammals, particularly cetaceans. Simulated explosions were performed on 9 July 2018 using confiscated explosives from illegal fishers in San Fernando, La Union. The acoustic properties of blasts from single pulse explosions were characterized using sound recordings captured by a hydrophone. Dominant frequencies from the sound recordings showed that the noise generated by the explosions can be perceived by marine mammals sensitive to the auditory bandwidth of 7 Hz to 180 kHz. Blast charge weights were estimated to determine sound pressure levels generated by the explosions at varying distances from the source. These results imply that marine mammals within 150 m of the explosion will experience debilitating injuries (e.g., acoustic trauma, disorientation) even from a single pulse. By characterizing the acoustic properties of these local explosives, its potential impacts to local marine mammals and other marine organisms can be elucidated. These acoustic calculations can be further enhanced by considering backscattered waves and determining the actual chemical composition of these explosives.

Keywords: marine mammals, cetaceans, underwater noise, underwater explosion, dynamite fishing, hydrophone

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INTRODUCTION

Many marine lifeforms can generate and perceive sound (Au et al. 1974; Popper et al. 2004; Henninger and Watson 2005; Bailey et al. 2010). Some of these are marine mammals that rely on underwater sound for communication, orientation, and foraging (Tyack and Clark 2000; Finneran 2015). Exposure to anthropogenic noise may pose serious threats to aquatic species such as marine mammals. Because of this, various research efforts have been conducted to determine the effects of underwater noise on marine mammals (e.g., Southall et al. 2007). Research programs have also been developed worldwide on investigate noise impacts to different marine mammal species (e.g., Erbe 2012). However, most of these studies examined impacts from large explosive loads. Characterization of the acoustic properties of small explosive loads like those from illegal dynamite fishing has not yet been conducted.

Noise may affect marine mammals in many ways. At higher sound levels, noise may interfere with marine mammal communication and hinder acoustic signal detection (Erbe 2012). Prolonged exposure can also affect the auditory system and may induce a shift in its hearing threshold (Southall et al. 2008; Pacini et al. 2017). Underwater noise may also pose physical threats such as concussive effects, damage to tissues and organs, and bubble formation (Erbe 2012). Noise can also induce stress and eventually cause health problems to marine mammals. Given the possible effects of noise to marine mammals, government departments in many countries now regulate underwater noise emission from industries.

In the Philippines, the Bureau of Fisheries and Aquatic Resources (BFAR) of the Department of Agriculture (DA) has the mandate to protect and manage cetaceans (i.e., dolphins and whales), while the Biodiversity Management Bureau (BMB) of the Department of Environment and Natural Resources (DENR) has jurisdiction over the dugongs. One of the threats to marine mammals is dynamite fishing and similar underwater noise that may induce acoustic trauma (Wahlberg 2002; McCauley et al. 2003; Aragones et al. 2010; Pacini et al. 2017). The amended Philippine Fisheries Code of 1998 explicitly criminalizes the conduct of dynamite fishing (RA 10654). However, despite the existence of regulatory law prohibiting dynamite fishing, this practice has persisted. Dynamite fishing, although possibly more common in shallow waters (~100 m), is also conducted in deep waters mainly to avoid being caught by authorities (Ignacio 2018) and to target larger schools of fish (2018 focus group discussion with Region 1 fishers conducted by Aragones L; unreferenced). In Region 1 of the Philippines, reported incidents of dynamite fishing during 2017–

2020 ranged from 44 m up to 12 km away from the shoreline (2021 May 13 letter from BFAR 1 to Aragones L; unreferenced). Illegal fishers usually use ammonium nitrate from crop fertilizers as their main explosive compound. Formulations of explosives vary among fishers, but they often use 350 ml glass bottles. While detonations from these explosives are generally small, the persistence of this illegal practice may induce debilitating injuries among nearby marine mammals and fish as well as destroy coral reefs. This study aimed to characterize the blasts from confiscated explosives in the Philippines and infer, based on the acoustic properties of a single pulse, the possible impacts on marine mammals, particularly cetaceans.

This study utilized confiscated explosives from different fishermen. As such, the magnitude of the explosives is not uniform throughout the trials. Moreover, the exact formulations of the explosives were unknown; there were variations in the compounds and total amounts used. Analyses were limited to the assumption that the explosion experiments occurred in open water with no influence of obstructions producing backscattered waves and that the explosives detonated at a fixed vertical distance upon falling into the water. Lastly, following regulations on such experiments, representatives from BFAR and the Philippine Coast Guard (PCG) ensured that no marine animals were present near the detonation site.

MATERIALS AND METHODS

Simulating and recording underwater explosions

The confiscated underwater explosives used were provided by the Northern Command of the PCG and the BFAR Region 1 office. Four explosives in separate 350 ml bottles were used in simulating dynamite fishing in open waters off San Fernando, La Union on 9 July 2018. The experiment was conducted in open waters (~200 m deep) in coordination with the PCG and BFAR 1 offices who provided personnel and equipment to ensure safety in the field. Four explosions were detonated approximately 12 m below surface water at varying lateral distances from the hydrophone (see Table 1). A Cetacean Research™ CR1A hydrophone with a SpectraDAQ-200 sound card was used for recording underwater sound generated from these explosions.

Table 1. Time of recording and actual distance of explosion from the hydrophone setup.

Trial	Time	Distance from Source (m)
1	10:18 AM	195.46
2	10:37 AM	267.25
3	10:50 AM	424.01
4	10:54 AM	773.47

Analyzing the acoustic pressure of the blasts

An explosion occurs when there is an outburst of energy in the form of light, heat, sound, and shock wave. A shock wave is compressed air or strong pressure that radially travels greater than the speed of sound (Ling et al. 2016). It happens when sound waves are constructively interfering with other similar sound waves arriving simultaneously, creating a violent change in stress, density and temperature. Shock waves are commonly produced by explosions, supersonic aircrafts, lightning, or other phenomena that cause sudden change in pressure. The release of strong pressure is not limited to air; it can also happen to other elastic mediums like water (Ridah 1988) and solids (Thurston 1974). In an underwater explosion, a shock wave also creates large underwater sound pressure that rapidly decays through time (Sayapin et al. 2006; Veksler et al. 2009; Liu et al. 2018).

The acoustic pressure of the blast was analyzed for each simulated explosion. To determine peak underwater pressure, sound recordings were calibrated using the SpectraPLUS software of the hydrophone, utilizing a transducer sensitivity value of -198 dB re 1V/ µPa and a transfer factor of 0.1259 mV/Pa. After calibration, plots of pressure (in Pa) over time were generated. Peak pressures were extracted from each plot per trial and summarized in Table 2.

Table 2. Estimated charge weight in grams of TNT.

Trials	Distance from Source (m)	Peak Pressure (Pa)	Charge Weight (g TNT)	Charge Weight (g NH_4NO_3)
1	195.46	52938.86	83.30	198.33
2	267.25	37238.66	83.68	199.24
3	424.01	30059.17	189.25	450.60
4	773.47	20039.45	391.85	932.98

Backscattered waves generated in the explosion may have produced peak pressures following the detonation. Backscattered waves can be in the form of scattered waves or reflected waves. Scattered waves result from waves that are incident on rough surfaces (Ainslie 2010) such as rocks, corals, soft bottom, etc. On the other hand, reflected waves result from those incident on smooth surfaces (Ainslie 2010). In this study, only the peak pressures depicting each explosion trial were considered. Peak pressures from backscattered waves were not analyzed as these are brought by external factors aside from the explosion itself.

Estimating the charge weight

The confiscated explosives come in different sizes and composition depending on the formulation of the illegal fisher involved. As such, estimating the charge weight of the explosion was performed by assuming that the explosives can be represented by the amount of trinitrotoluene (TNT) present in the blast charge. The charge weight was then estimated using the equation for shock wave pressure (Samareh salavati pour and Alizadeh 2012; Soloway and Dahl 2014) generated by the explosion,

$$P_0 = 52.4 \times 10^6 \left(\frac{R}{W^{1/3}} \right)^{-1.13} \qquad (1)$$

where P_0 is the peak incident pressure in Pascals, W is the charge weight in kg of TNT, and R is the distance between the hydrophone setup and the source of explosion in meters. The estimated charge weight, W, is expressed in kg of TNT because this compound has been used as a reference for the relative effectiveness of other explosive compounds (Soloway and Dahl 2014). Ammonium nitrate (NH_4NO_3), the most common explosive used by illegal fishers in the Philippines, has a relative effectiveness of 0.42 kg TNT (Soloway and Dahl 2014). This factor can be used to estimate the actual charge weight of the explosive in terms of NH_4NO_3.

Analyzing peak frequency and sound pressure levels from raw recordings

The raw recordings were processed to identify dominant frequencies and determine sound pressure levels (SPLs) at peak frequencies. First, the recordings were clipped to 30 seconds before and after detecting the explosion to minimize the noise in post-processing the data. Fast Fourier Transform (FFT) was done using the raw sound measurements to identify the peak frequency (dominant frequency).

Theoretical peak pressures and SPLs were calculated using the estimated charge weight of the explosion and the actual distance between the hydrophone and detonation source. Using equation 1, peak incident pressure per distance was estimated and then converted to SPL using the equation

$$\text{SPL re 1 μPa} = 20 \log_{10} \left(\frac{P_0}{P_r} \right) \qquad (2)$$

where P_0 is the peak incident pressure in Pa and P_r is the reference pressure in μPa. Analyses on marine mammal sensitivity are usually done using parameters derived from the generated shock wave, such as peak incident pressure, SPL, sound exposure level, and shock wave impulse. Moreover, the auditory bandwidth of select marine mammals are considered for specific sensitivity to sound generated by the explosion. In this study, analyses focused on interpreting acquired peak incident pressures and SPLs generated by the simulated explosions.

RESULTS AND DISCUSSION

Any experiment on explosives, particularly to simulate illegal dynamite fishing, is a challenge. The explosion experiment conducted involved recording the simulated explosion using a CR1A hydrophone with SpectraDAQ-200 sound card. Recordings were initially analyzed as raw voltage measurements against time as shown in Figure 1. Based on the figure, the absolute peak voltage measurements in all trials indicate the start of the explosion, representing the events of highest pressure change. Succeeding peaks of voltage measurements following the explosion were pressure changes from backscattered waves formed along the boundaries of the explosion. However, these succeeding peak voltages, which can be converted to peak pressures, were not analyzed.

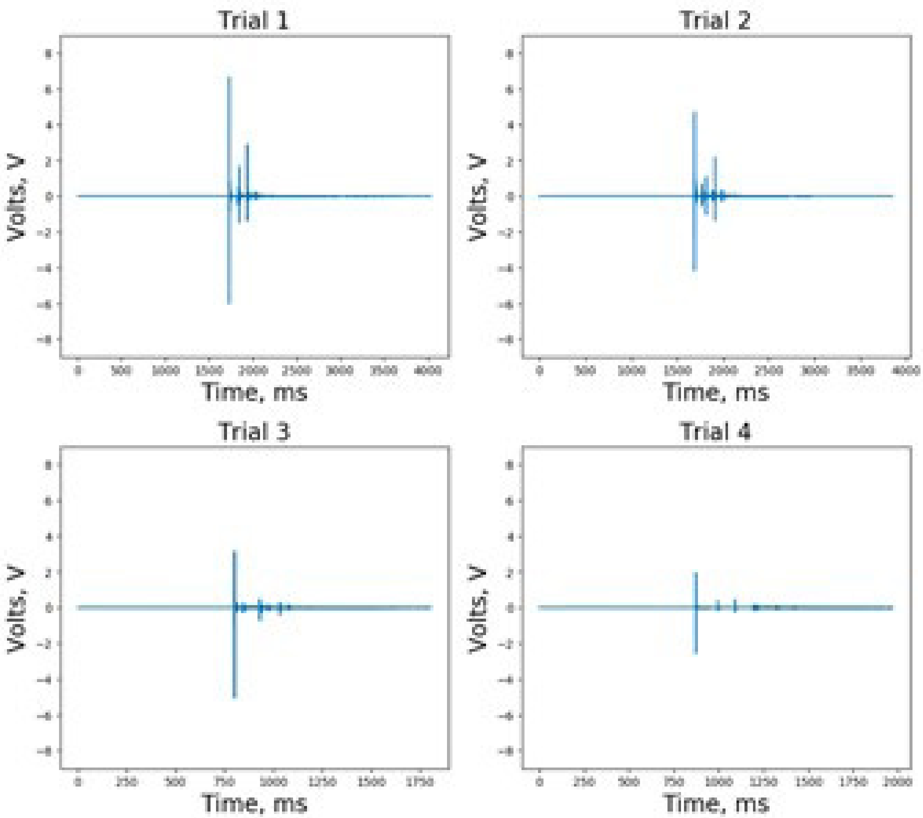

Figure 1. Raw signals (in Volts) recorded by the hydrophone during the simulated explosions.

FFT was implemented on the absolute voltage measurements from the recordings. Subsequently, the power spectra were obtained as shown in Figure 2. The power spectra show the frequency space of the raw signals after applying FFT. The amount of energy in every frequency emitted by the explosions was shown in these plots. The evident increase of power in every trial signified the considerable energy emitted by the confiscated explosives. In this experiment, the average frequency with the highest power was 12.1 kHz. The average frequency of the explosions is within the auditory bandwidth of any cetacean group, as summarized in Table 3, suggesting that the blast from these types of explosions may be perceived by marine mammals and may cause direct and even debilitating impacts (e.g., auditory injury or acoustic trauma) to individuals in the vicinity of the explosion.

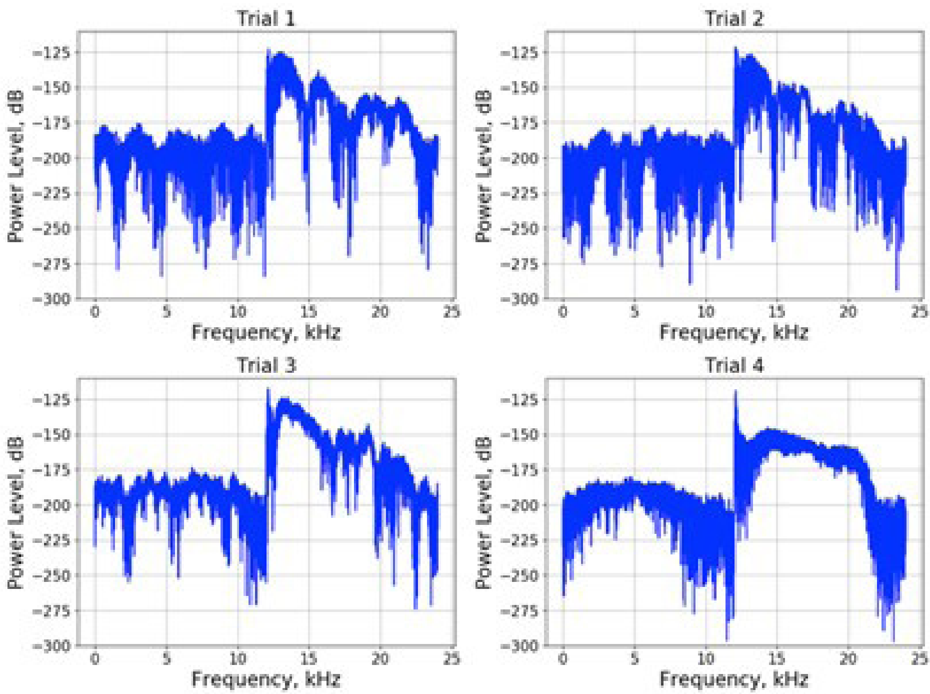

Figure 2. Power spectra of the explosions in dB.

Table 3. Cetacean criteria for injury from single pulse explosion (after Southall et al. 2008 and Mitchell et al. 2009).

Marine Mammal Group (Cetaceans)	Genera Represented	Estimated Auditory Bandwidth	Threshold for Injury from Single Pulses (Explosion)
Low-frequency	*Balaena, Caperea, Eschrichtius, Megaptera, Balaenoptera*	7 Hz to 22 kHz	230 dB SPL dB peak re: 1μPa or 23 psi peak pressure
Mid-frequency	*Steno, Sousa, Sotalia, Tursiops, Stenella, Delphinus, Lagenodelphis, Lagenorhynchus, Lissodelphis, Grampus, Peponocephala, Feresa, Pseudorca, Orcinus, Globicephala, Orcaella, Physeter, Delphinapterus, Monodon, Ziphius, Berardius, Tasmacetus, Hyperoodon, Mesoplodon*	150 Hz to 160 kHz	
High-frequency	*Phocoena, Neophocaena, Phocoenoides, Platanista, Inia, Kogia, Lipotes, Pontoporia, Cephalorhynchus*	200 Hz to 180 kHz	

Underwater explosions produce anthropogenic sound that may pose threats and induce injury and acoustic trauma to aquatic species (Wahlberg 2002; McCauley et al. 2003; Martin and Popper 2016). A set of criteria for marine mammal noise exposure was proposed by Southall et al. (2008), as summarized in Table 3. For a single pulse or explosion, a SPL of 230 dB re 1 μPa is set as the threshold for the onset of temporary threshold shift (TTS) and auditory injury to cetaceans (Southall et al. 2008). Criteria for other marine mammal groups were provided by Southall but only those for cetaceans were considered in this study.

SPL from the recordings was obtained to analyze the strength of the acoustic waves generated from the simulated explosions and relate it to possible injuries to marine mammals. Figure 3 shows the SPL obtained per trial in dB with respect to 1 μPa. The maximum peak values represent the pressure levels of the explosions per trial. The average SPL obtained at the dominant frequency of 12.1 kHz is 137.94 dB re 1 μPa. This SPL is more than the SPL range classified by Erbe (2012) using audiograms of various marine mammals. These marine mammals include representatives from Families Monodontidae, Delphinidae, Phocoenidae, Ziphiidae, Phocidae, Otariidae, Odobenidae, and Sirenia, which have minimum hearing thresholds of around 50 to 70 dB re 1 μPa at 10 kHz frequency (Erbe 2012). These marine mammals can therefore perceive the generated sound from these explosions. Note that Philippine marine mammals include delphinids, ziphiids, and a sirenian, the dugong (Aragones et al. 2010). The average SPL from the explosion is also close to 150 to 160 dB re 1 μPa, the SPL generated by multiple pulse explosions that caused changes in behavioral responses of humpback whales (Todd et al. 1996; Southall et al. 2008).

Behavioral changes demonstrated by humpback whales on these pressure levels were individual alertness, prolonged orientation, minor changes in locomotion speed and direction, moderate change in respiration rate, and minor cessation or modification of vocal behavior (Southall et al. 2008). Higher SPL is expected at closer distances to the explosion, which can be detrimental to marine animals in the area. The average SPL is also less than 230 dB re 1 μPa, the previously stated threshold for injury and onset of TTS on marine mammals caused by single pulse explosions (Southall et al. 2008). These results suggest that while the maximum SPL is less than the injury threshold, the dominant frequency and SPL values show that the sounds generated by this type of explosive are within the hearing bandwidth of cetaceans and may induce possible masking of sounds and changes to their behavior, to mention a few. Most of the groups of cetaceans mentioned in Table 3 (i.e., those using middle frequency bandwidth) are present throughout the Philippines (Aragones et al. 2010; Aragones et al. 2017; Aragones and Laggui 2019). Transmission loss of the acoustic pressure as it travels from the source up to the hydrophone setup may have reduced the energy of the generated shock wave upon reaching the hydrophone. Thus, it is important to further analyze the simulated explosions for possible effects to cetaceans based on the acoustic charge weight of the blast at closer distances from the explosion.

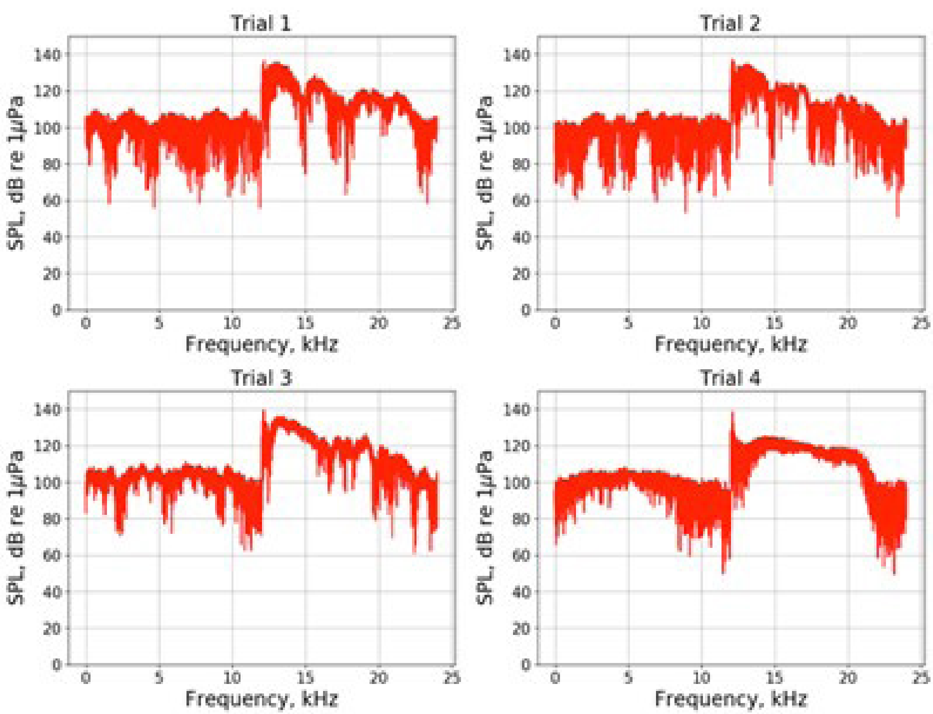

Figure 3. Sound pressure level (dB re 1 μPa) from the simulated explosions.

The simulated explosions were characterized based on its estimated charge weight. Because of the non-uniform composition of the explosives depending on the fisher, the exact explosive compounds used remained undetermined in this study. Instead, the explosives were assumed to be composed of ammonium nitrate (NH_4NO_3). Moreover, the charge weight of each explosion was estimated based on available literature (Samareh salavati pour and Alizadeh 2012; Soloway and Dahl 2014), which assume the blast charge weight in kilograms of TNT. The peak pressure values directly obtained from calibrated measurements in SpectraPLUS were used to estimate blast charge weight. Table 3 shows the estimated charge weight of each explosion both in terms of TNT and NH_4NO_3. Trials 1 and 2 have almost similar charge weights while trial 4 has the highest charge weight of 391.85 g of TNT.

Using the estimated charge weights, theoretical peak pressures were calculated. For the intended purpose of explosives used by illegal fishers, Keevin and Hempen (1997) established that mortality and internal damages in bluegill fish abruptly increased at 500 kPa peak pressure generated by a 2 kg charge of T-100 explosive detonated at 2 m depth. Theoretical peak incident pressures at varying lateral distances from the explosion were calculated from the estimated charge weight, as shown in Figure 4. Peak pressures from the simulated explosions reach 500 kPa at distances around 25 m to 45 m from the detonation site. This means that fishes within almost 50 m of the explosion will experience internal damages such as ruptured swim bladder or damages to the kidney, liver, spleen, and heart that may eventually lead to death. Therefore, the fish are easily collected by these illegal fishers upon explosion. Peak pressures of 23 psi or around 160 kPa cause physiological disruptions to all kinds of marine mammals (Mitchell et al. 2009). A range of about 73 m to 123 m away from the explosion trials generated peak pressures of approximately 160 kPa. Within this range, TTS may be observed in present marine mammals. Marine mammals experiencing TTS lose their hearing sensitivity, leading to failure in communication, orientation, and foraging (Tyack and Clark 2000). This may help explain the findings of Aragones and his colleagues in 2010, wherein they reported a relatively large proportion of live stranders (60%) in the Philippines.

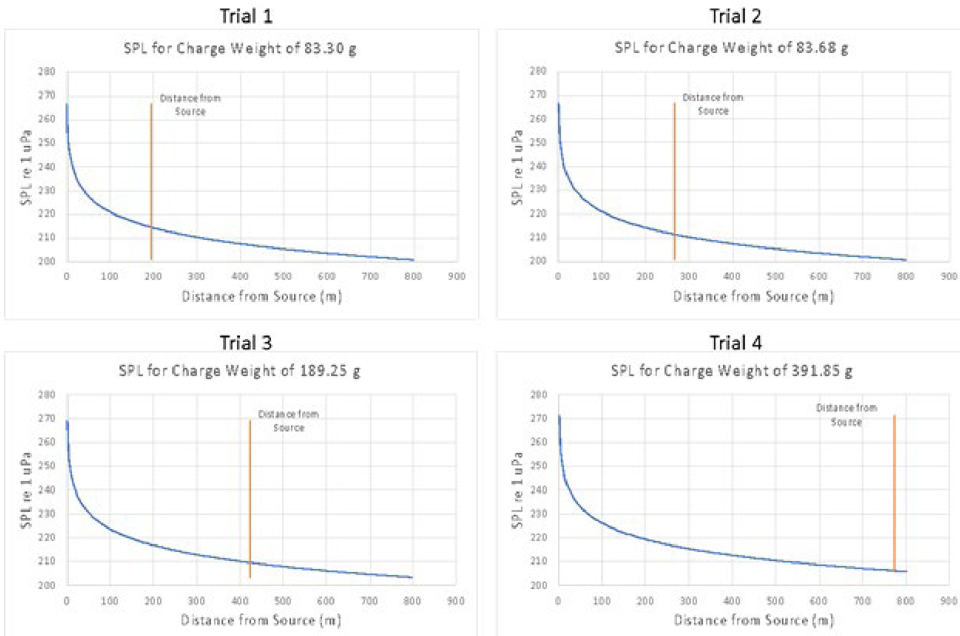

Figure 4. Theoretical peak incident pressure based on estimated charge weight.

SPLs generated by the blast were then estimated from pressure values and plotted with respect to distance from the source as shown in Figure 5. Demonstrated in the figure is the SPL generated when using g of TNT (in blue line) and g of NH_4NO_3 (in red line). SPLs from charge weights using relative effectiveness of NH_4NO_3 to TNT were projected in the blue line. Note that a slight difference in charge weight generated a different spectrum of SPLs. The plots show the decrease in SPL farther from the explosion. Moreover, orange lines depict the actual distance of the hydrophone setup to the blast. Also, from these plots, the maximum distance with an SPL value of less than 230 dB re 1 μPa was determined. This was estimated to project a minimum lateral distance a cetacean will be safe from injury caused by a single pulse explosion like dynamite blast.

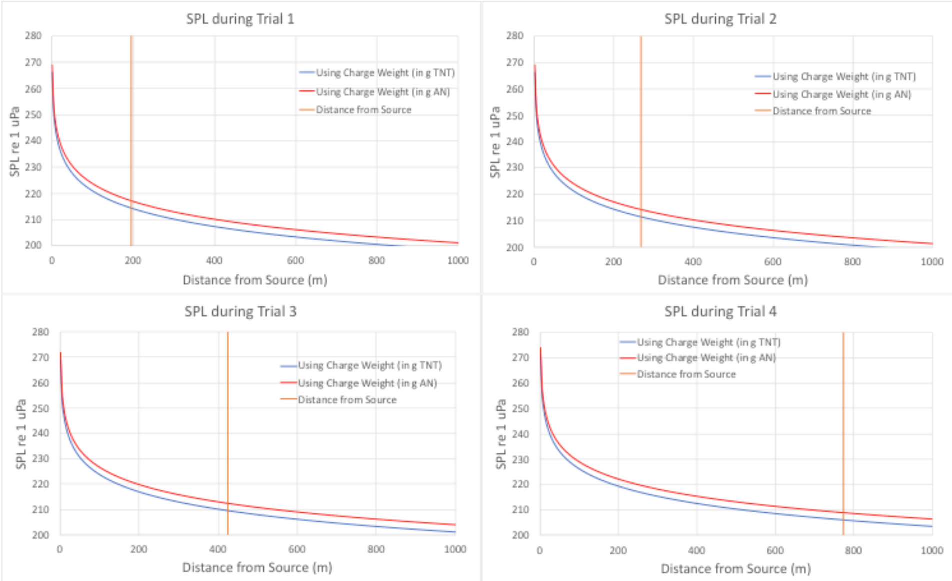

Figure 5. Theoretical sound pressure levels based on estimated charge weight. Orange lines indicate the distance between the source of explosion and the hydrophone setup.

Table 4 summarizes the minimum distance from the explosion site where marine mammals may be safe from injuries caused by single pulse explosions. The criteria for the injuries were based on the 230 dB re 1 *μPa* SPL threshold by Southall et al. (2008) and 23 psi peak pressure by Mitchell et al. (2009). As shown in the table, the trial 4 explosion has the farthermost distance (~123 m) that may be hypothetically declared a safe zone for cetaceans. Given the precautionary principle, this hypothetical distance will be extended to 150 m. Therefore, the safe zones for all trials were less than 150 m, suggesting that the dynamite blasts may affect fishes, dolphins and whales, and dugongs that are close to the explosion site. Lastly, the results are all true given the assumption that backscattered waves do not affect the measurements conducted and that the trials were done in open water far from obstructions. This study provides key results to elucidate the impacts of small explosive loads underwater. Most of the studies worldwide come from the United States Navy and Army and private institutions that all looked at large explosions, low frequency sounds, and the like.

Table 4. Identified safe zones for marine mammals during simulated explosions.

Trials	Distance from Source (m)	Peak Pressure (Pa)	Charge Weight (g TNT)	Distance from Source Not Safe for Marine Mammals Based on 230 dB re 1μPa (m)	Distance from Source Not Safe for Marine Mammals Based on 23 psi Peak Pressure (m)
1	195.46	52938.86	83.30	40.19	73.45
2	267.25	37238.66	83.68	40.25	73.56
3	424.01	30059.17	189.25	52.83	96.55
4	773.47	20039.45	391.85	67.34	123.07

Evidence of acoustic trauma from dynamite blasts have been reported in the Philippines (Pacini et al. 2017). The hearing loss due to dynamite fishing recorded in spinner (*Stenella longirostris*) and rough-toothed dolphins (*Steno bredanensis*) were based on hearing measurements using non-invasive auditory brain stem responses. Pacini and her colleagues (2017) concluded that this hearing loss was reflective of exposure to blasts and related impulsive sounds. This implies that these animals might have been just outside of the safe zone as they ended up stranded. We are just starting to understand impacts of dynamite blasts on marine mammals in the Philippines. The simulated single pulse explosion in open water is the minimum requirement to analyze possible effects of underwater noise on local marine mammals. Obstructions that affect sound, which are more predominant nearshore because of surface texture, are expected to produce intensified blast and prolonged multiple pulses from backscattered waves. The estimated 150 m safe zone may not necessarily be harmless. The dugongs, which are less agile than the cetaceans and often more nearshore, may be very vulnerable to the debilitating effects of these types of blasts, especially explosions done in shallow water. The dugong is one of the most common stranders in the Philippines (Aragones et al. 2017; Aragones and Laggui 2019) indicates the possible contribution of dynamite blasting. Further studies are required to elucidate the finer impacts of this illegal dynamite fishing practice on our vulnerable and charismatic marine vertebrates and coral reefs.

SUMMARY AND CONCLUSIONS

Marine mammals can create and detect underwater sounds that they use for communication, orientation, and foraging. Underwater noise such as dynamite blasts may pose serious threats to marine mammals in the form of behavioral responses and physical injuries (e.g., acoustic trauma). In the Philippines, illegal dynamite fishing persists even with enhanced law enforcement (e.g., establishment of the BFAR-Fisheries Resource Protection Group).

Sound recordings were generated from simulated blasts using typical confiscated explosives. The sound recordings were post-processed to depict pressure, power level, and SPL acquired from an underwater explosion. While it was determined that the dominant frequency of peak pressure is within the hearing bandwidth of marine mammals, the SPL obtained from the explosions may not necessarily imply imminent damaging injury caused by single pulse explosions. However, the low SPL obtained may be caused by transmission loss as the sound travels from the source to the hydrophone. Thus, further analyses were done regarding the charge weight of the blast at varying distances from the source.

Different charge weights were obtained from the four simulated explosions supporting the observed differences in explosive size and composition. Using the estimated charge weights (in kg of TNT), theoretical SPLs were plotted with respect to distance from the source of the explosion. Results showed that at closer distances (<150 m), the explosions may pose serious injury to marine mammals. It is important to note that these safe zones assume that the explosion does not produce backscattered waves. Therefore, animals outside this zone may still be impacted. Evidence of this comes from Pacini and her colleagues (2017) who reported hearing loss in two stranded cetaceans in the Philippines allegedly due to dynamite blasts. It is then recommended that future simulations and analyses consider surface reflection that may induce significant changes in acoustic pressure from backscattered waves. This can be done through explosion trials in shallow waters, which produce scattered and reflected waves based on surface texture. Lastly, the characterization of compounds present in the explosives may be helpful in accurately estimating the charge weight of the explosion.

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