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Oil Industry and Noise Pollution in the Humpback Whale (*Megaptera novaeangliae*) Soundscape Ecology of the Southwestern Atlantic Breeding Ground

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ABSTRACT

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The present work aims to assess acoustic overlapping between the humpback whale song and anthropogenic sounds around oil and gas platforms through spectral description and frequency comparison. Whales were monitored systematically in northeastern Brazil (11° S, 37° W to 14° S, 38° W). Acoustic and behavioral data were collected from 2007 to 2009, focusing on humpback occurrence around oil platforms. Diverse anthropogenic noises were registered in a similar frequency range as recorded cetacean sounds, which suggests overlapping of acoustic niches. Noise pollution from oil and gas production may potentially affect this species' communication, with implications for distribution and behavior in their breeding area. This paper is the first report of acoustic overlapping of oil platforms and cetaceans in the southwestern Atlantic Ocean. Given increasing gas and oil exploitation, efforts to improve the development and use of these acoustic methods are recommended in order to mitigate impacts on the marine life.

ADDITIONAL INDEX WORDS: *Cetaceans, anthropogenic noise, oil platforms, acoustic monitoring, Brazilian coast.*

INTRODUCTION

Noise may be defined as a sound that interferes with signal reception, potentially affecting animal ecology by disturbing common behavior (Richardson *et al.,* 1995). The marine acoustic environment is composed of diverse sources of noise, which are reflected in the varied acoustic perceptions and behavioral responses of different animal species, mainly vertebrates (Cato and McCauley, 2002; McCauley *et al.,* 2000a, 2000b; Miller *et al.,* 2000).

Noise in the Marine Environment

The acoustic environment that whales experience today is different from that which they faced about 50 years ago (*e.g.,* Andrew, Howe, and mercer, 2002), during the main whaling period. Tropical breeding areas have been especially changed due to increases in the human population. The animals spend about six months per year at tropical latitudes, finding a reproductive partner, breeding, giving birth, and taking care of young until the next migration to the poles (*e.g.,* Clapham, 1996).

Increases in the human population, concentrated in coastal zones, have resulted in increased boat-ship traffic and oil drilling. The resultant acoustic pollution levels may harm individual animals, causing temporary or even permanent injuries to their physiology and behavior (*e.g.,* Johnson *et al.,* 2007; Richardson *et al.,* 1995).

The Humpback Whale

The humpback whale, *Megaptera novaeangliae* (Borowski, 1871) (Cetacea, Balaenopteridae), is a cosmopolitan cetacean species distributed throughout oceans worldwide (Clapham and Mead, 1999). As migratory animals, they move yearly from high-latitude feeding areas, where they stay during the autumn and summer, to the breeding areas in the tropics, where they stay during the spring and summer (Clapham and Mead, 1999).

Humpback whales from the denominated "Breeding Stock A/BSA" (IWC, 1998) occur in Brazilian waters along a range of about 6000 km (Danilewicz *et al*., 2009; Lodi, 1994; Rossi-Santos *et al*., 2008; Tollenare, 1961; Wedekin, 2011), with the main breeding area in the Abrolhos Bank, Bahia State (Andriolo *et al*., 2006a,b; Martins *et al*., 2001; Wedekin *et al*., 2010).

Soundscape Ecology and Behavior: Importance of Sounds for Whales

Landscapes can be defined as functional ecological spaces where the observed patterns reflect the interactions between natural and anthropogenic processes (Wiens, Stenseth, and Van Horne, 1993; Wu, 2006). The acoustic environment is a landscape attribute composed by the heterogeneous distribution of objects and resources and their potential rearrangement through time, describing the spatial structure required to detect changes resulting from these interactions (Mazaris *et al*., 2009).

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Schafer (1977) was the first to define "soundscape" as the acoustic environment composed by a variety of sounds originating from different sources, such as natural and anthropogenic, emphasizing the way this environment is perceived and understood by any human or nonhuman individual, or by the society (Truax, 1999).

For instance, animals perceive their environment across many spatial scales at the same time, where background noises correspond to the long-range (coarse-scale) perception of environmental cues, while foreground sounds correspond to the short-range (fine-scale) perception of the environment (Mazaris *et al*., 2009).

Soundscape ecology represents a new branch of ecology, and it is the result of the integration of different disciplines such as landscape ecology, bioacoustics, acoustic ecology, biosemiotics, and others (Farina, 2014; Pijanowski *et al*., 2011). It is defined as the acoustic context resulting from natural- and human-originated sounds, and it is considered a relevant environmental proxy for animal and human life.

The humpback whale is also known as "singer whale" because of its unique characteristic of exhibiting a singing behavior, performed only by males, during their breeding season. Since the 1970s, many studies have described the acoustic structure of these songs (*e.g*., Arraut and Vielliard, 2004; Helweg *et al*., 1998; Maeda *et al*., 2000; Payne and McVay, 1971).

Humpback whale song probably functions to attract females (*e.g*.. Smith *et al*., 2008) and/or to repel other males (*e.g*., Tyack and Whitehead, 1983; Weinrich, 1995). The song consists of single notes that form repetitive phrases called themes, and different themes form a song (Payne and McVay, 1971).

Probable functions of humpback whale songs at the population ecology level, such as stock recognition by songs and cultural exchange between adjacent populations, have been reported (Darling and Souza-Lima, 2005; Dawbin and Eyre, 1991; Eriksen *et al*., 2005; McSweeney *et al*., 1989; Winn *et al*., 1981). However, many other aspects of the soundscape ecology of the species during singing behavior are still unknown, such as the song relation with the acoustic environment in which it is produced and also the diverse sound sources such as the anthropogenic noise also occurring during the breeding season.

In this study, I aim to contribute to the subject of the humpback whale soundscape ecology, describing and comparing, through time and frequency analyses, the acoustic niche of the whale songs and the anthropogenic noise in the southwestern Atlantic Ocean breeding ground, off the Brazilian coast.

The Oil Industry in Brazil

Petrobras, a state-owned company created by the Brazilian government in 1954, initially held a monopoly on the Brazilian oil industry (Kimura, 2005). The early 1950s was marked by the discovery of many oil reserves around the globe. Despite oil formation in roughly 3 million km^2 of sedimentary basins throughout the country, foreign oil companies pursued interests elsewhere and did not compete with Petrobras for Brazilian oil reserves (Matz, 2000).

International economic crises in the late 1980s and early 1990s caused increased investments in the energy sector, initiating many fusions with other companies to reduce costs and to enhance productive scale (Kimura, 2005; Matz, 2000).

The Brazilian law 9.478 repealed the Petrobras monopoly, authorizing other companies to drill in the Brazilian territory. This attracted a competitive market, which is increasing year by year (ANP, 2003; Machado, 2004).

The present work aims to make an acoustic analysis of anthropogenic noise originating from oil and gas exploitation in the Brazilian breeding ground for the humpback whale, as this endangered species is considered to be an important top predator in the marine ecosystem. Potential overlapping of the whale acoustic niche with these sounds is also analyzed and discussed.

METHODS

The methods are based on nonintrusive techniques to study cetacean ecology in the wild (Mann *et al.,* 2000), mainly through audio and image capture during field cruises in the study area, allowing spatial-temporal analyses of the marine environment in the northeastern Brazilian coast.

Study Area

The study site was a stretch of coast between the northeast states of Bahia and Sergipe, from Itacaré (14° S, 38° W) to Aracaju (11° S, 37° W). Praia do Forte (12° S, 38° W), about 60 km from the capital Salvador, is at the center of this area (see Figure 1). The region between Praia do Forte and Aracaju is characterized by long sand beaches, with large dune formation fringing the coastline.

The main oceanographic characteristic of the study area is a narrow continental shelf, approximately 15 km in width. The average depth on the shelf is 40 m, with tidal amplitude varying from 0.1 to 2.6 m (DHN, 1995).

The area also has large bays and estuaries, important to navigation, such as the Baía de Todos os Santos, surrounding Salvador, Bahia State, and the estuaries of the Vaza-Barris and Sergipe Rivers, near Aracaju City in Sergipe State.

In addition to anthropogenic pressure from large ports such as Salvador and Aracaju and the presence of traditional fishing communities, this area also hosts the largest petrochemical industrial center in the Southern Hemisphere, in Camaçari, Bahia State. The first set of coastal oil platforms established along the Brazilian coast is located near Aracaju, and additional platforms were recently installed in Bahia State, near the tourist destinations of Morro de São Paulo and Itacaré.

A decade ago, a consortium of organizations headed a public campaign to exclude the Abrolhos Bank, the most important area for humpbacks, from increasing oil exploitation blocks along the southeastern and northeastern coasts (Figure 1). The campaign was temporarily successful.

However, as humpback whale stock A grows in population (*e.g*., Zerbini *et al.,* 2006), the whales have spread to other areas of the Brazilian coast (Baracho-Neto *et al.,* 2012; Rossi-Santos *et al.,* 2008; Wedekin *et al.,* 2010), leading to increased conflict between whales and the oil industry in terms of the acoustic landscape.

Data Collection and Analysis

Boat-based surveys were utilized to search for whales along a predetermined route. When sighted, animals were approached

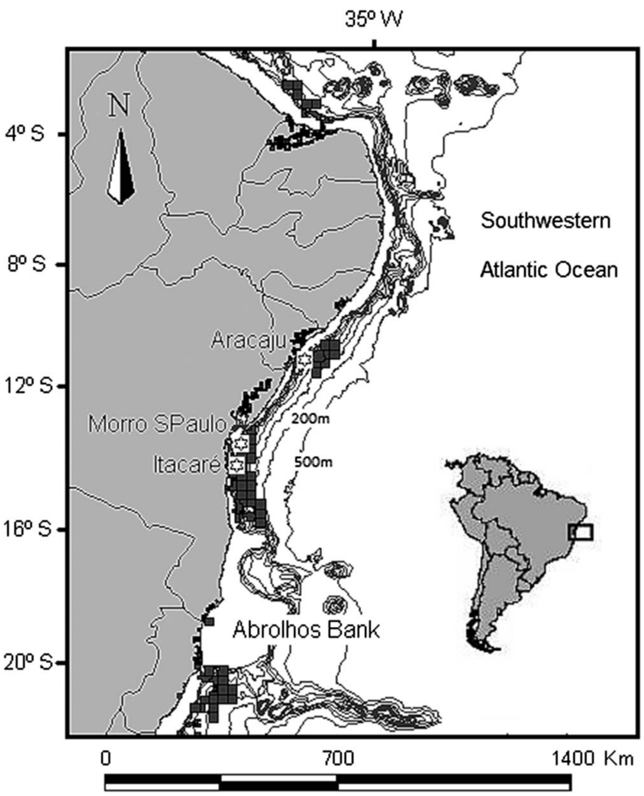

Figure 1. The study area, located between Itacaré, Bahia State (14° S, 38° W), and Aracaju, Sergipe State (11° S, 37° W), northeastern Brazil, presents a narrow continental shelf as the main oceanographic feature, attracting humpback whales (*Megaptera novaeangliae*) to breed close to the coast, where oil exploitation is increasing. Gray squares represent oil exploitation blocks, while star points represent the recorded platforms inside the study area. The Abrolhos Bank is indicated, as it is a concentration area of humpback whale distribution in Brazil.

to collect general data such as geographic location, behavior, individual photo-identification, skin biopsies, and acoustic recordings, following a standard protocol. Data on group structure were also recorded (see Rossi-Santos *et al.,* 2008).

The recording equipment used in this study varied as time progressed, due to technological advances in audio and video recording and the availability of these technologies in Brazil. In 2007, whale songs and sounds were recorded utilizing an analog-to-digital system (Sony VX-1000 video-camera) connected to a hydrophone (HTI SSQ-94). In 2008, our recorder was updated to a digital model (M-Audio MicroTrack Professional II digital recorder) with attachment to the same hydrophone, resulting in a frequency response up to 48 kHz.

The sound events were classified as foreground, those produced instantaneously and sharply near the sampling site (*e.g.*, fish, dolphins), or background sounds, those produced far away from the sampling site and originating from the whole surrounding landscape (*e.g.*, general noise, long-distance sound sea waves) (Mazaris *et al.*, 2009). All the acoustic subjects (whales and platforms) were recorded in the foreground acoustic range (visually estimated between 1 and 100 m).

In the laboratory, analog and analog-to-digital tapes were digitized, and raw sound data were exported to analysis software (Raven 1.3, Cornell University, USA). Audio was saved uncompressed WAV files in a database.

After digitization, only the foreground biological and anthropogenic sounds were analyzed through spectral visualization to determine physical parameters: begin frequency, end frequency, mean frequency, maximum frequency, minimum frequency, amplitude, and duration.

Data were selected using the best quality to visualize the complete signal, utilizing the screen cursor upon spectrograms, a sound graphic with axes of frequency, measured in Hertz (Hz), and time, measured in seconds (s). After a signal was selected, the software provided the precise measurements, and these numeric values were exported to a database software for *a posteriori* analyses.

Spectrographic Analyses

Time and frequency domains play an important role in the acoustic analysis (Rossing, 2007). Any acoustic signal can be represented either in the time domain, with its amplitude displayed as a function of time, or in the frequency domain, with its amplitude displayed as a function of frequency. The time domain representation of a signal is usually referred to as the waveform, while the frequency representation of a signal is usually referred to as the frequency spectrum (or just spectrum) of the signal (Au and Hastings, 2008).

Spectrum analyzers are often used to observe the spectral characteristics of continuous or long-duration (on the order of several seconds) signals. A spectrogram is a visual representation of the spectra of frequencies in a sound or other signal as they vary with time or some other variable (Rossing, 2007).

Among other advantages, these time-frequency portraits generated by the spectrograms seem to correlate well with our perceptions, providing important discrimination between different sounds characteristics (Alm and Walker, 2002).

Early analog spectrograms were applied to a wide range of areas, including the study of bird calls, with current research continuing using modern digital equipment and applied to all animal sounds (Brumm, 2013).

Contemporary use of the digital spectrogram is especially useful for studying frequency modulation (FM) in animal calls. Specifically, the distinguishing characteristics of FM chirps, broadband clicks, and social harmonizing are most easily visualized with the spectrogram. It is also employed in the development of the diverse fields of music, sonar, radar, speech processing, and seismology (Brumm, 2013).

RESULTS

Between 2007 and 2009, 527 hours of acoustic samples of humpback whales and environmental noise were recorded on 69 separate days. There were 166 distinct sightings of whale groups. Groups containing a singer male were confirmed with close-proximity (<100 m) underwater recordings.

Behavioral Observations

On six occasions, humpback whales were sighted less than 60 m from oil and gas platforms. Solo singer males constituted three of these sightings (122 minutes of observation and recordings). On one occasion, the solo singer was actively

Figure 2. The oil and gas industry produces anthropogenic noise in the marine environment in the course of daily operation. There are several different noise sources, mostly related to the platforms, such as the perforation process and the metallic structure sound reflection, but also related to supply boats moving around (photos: M. Rossi-Santos).

singing and presenting long and temporally similar breath intervals (14:00, 16:50, and 16:43 minutes). Females with calves and one escort male were recorded in two of these sightings (75 minutes total) and were observed constantly diving and avoiding the supply boat around the platform. On another occasion, a group of three adult animals, including one singer male, was observed.

Anthropogenic Noises

Several categories of anthropogenic sounds from oil and gas platform operations were recorded and analyzed (Figure 2).

Forty sound files from the collection period were selected for their superior signal-to-noise ratio (signal quality in relation to the background noise). Acoustic parameters were measured in these sound files: minimum and maximum frequency, and mean and standard deviation in frequency values (Table 1).

The source of distinct noises was identified as being direct (Figures 3, 4, and 5) or indirect (Figure 6) from the physical structure of the platform properly. Anthropogenic sounds varied in frequency from a minimum of 5 Hz to the top of the sampling rate of 48.000 Hz (Table 1).

Simultaneous Platform and Humpback Whale Recording

In 10 recording sessions, sounds of humpback whales and platform noise were detected simultaneously (Figures 7 and 8).

Table 1. *Acoustic parameters registered from the noise originated during oil platform operations* ($n = 40$)*, in the study area, recorded between 2007 and 2009. It is important to characterize anthropogenic noise in the ocean in order to make comparisons with the biological sounds produced by the acoustic communication of marine animals such as the cetaceans, aiming to mitigate human impacts in these animals' natural environment.*

Year 2007–2009	Minimum Frequency (Hz)	Maximum Frequency (Hz)	Central Frequency (Hz)	Amplitude (Hz)
Minimum	5	1009	23.4	1009
Maximum	5411	48,000	6029	48,000
Mean	415.3	19,031	1710	17,863
Standard deviation	427	7948	5743	9476

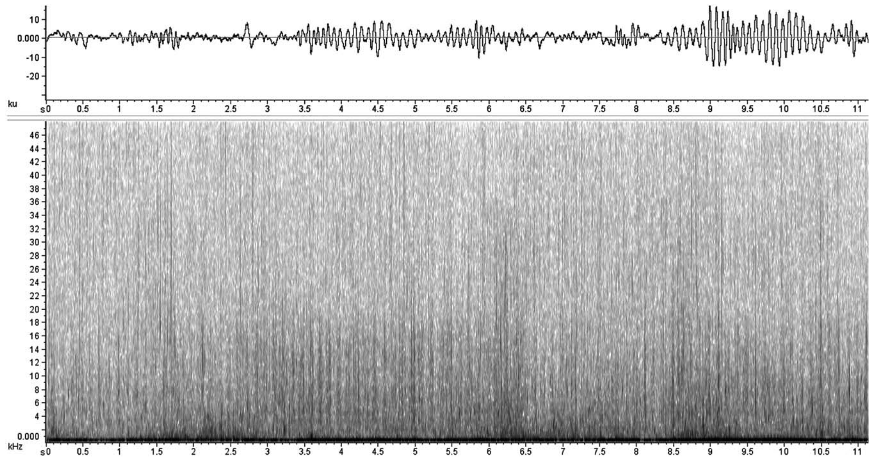

Figure 3. A spectrogram is an important graphic visualization of the time and frequency relation in the acoustic analysis. Here it is presented for low-frequency anthropogenic noise (<1 kHz), from the gas platform, probably originating from large engines, with pulsed vertical lines surpassing the recording limit of 48 kHz.

Sixteen whale sound elements, also called notes, were identified and described as part of the complex humpback whale song (Table 2).

Potential noise overlapping whale song can be visualized in Figure 9A, which compares anthropogenic noises and humpback whale frequency parameters (mean values from Tables 1 and 2 to minimum, central, and maximum frequencies). It is notable that the noise frequency parameters are always in larger mean values than the whale sounds (Figure 9), implying that their frequencies would be masked by a broader signal (the noise, in this case), in a progressive increase according to the noise source.

DISCUSSION

Noise pollution may have long-term effects on populations and communities, reshaping communities according to the level of noise tolerance between prey and predators. Several effects of noise on vocal animals include direct stress, masking predatory menace, and interference with the communication mechanisms in general (Brumm, 2013).

Anthropogenic Noise and Animal Behavior

The patchy distribution of the sonic environment creates "sonotopes" with variable noise conditions, which determine the final distribution of vocal species according to their level of tolerance and adaptive plasticity (Farina, 2014).

According to previous studies (*e.g.*, Richardson *et al.*, 1995; Wright *et al.*, 2007; Tyack and Janik, 2013), the effects of anthropogenic noise on animals are significant and generally call into consideration the management of human activities to mitigate these effects.

In terrestrial animals, such as songbirds, there is an increase in investigation of the characteristics of sound production in anthropogenic areas (*e.g.*, Nemeth, Zollinger, and Brumm,

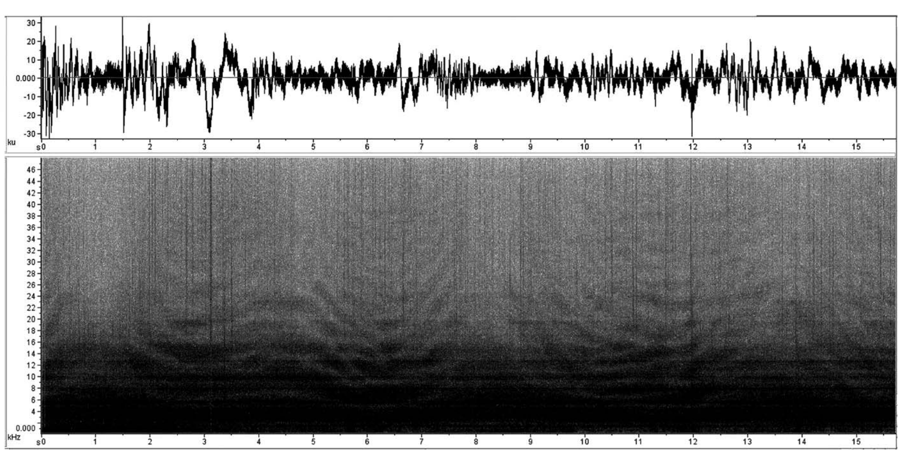

Figure 4. During the gas platform perforation process, a continuous noise was registered, with larger energy up to 15 kHz and horizontal harmonic bands, wave shaped, surpassing the limit of 47 kHz, indicating a broad frequency range for the anthropogenic sounds at sea.

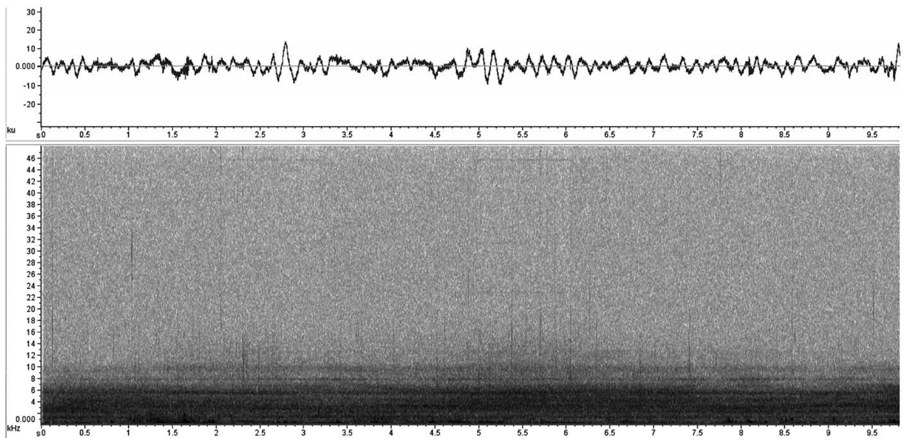

Figure 5. Spectrogram showing another type of anthropogenic noise from a gas platform, concentrated in horizontal bands with frequencies lower than 8 kHz, also related to the perforation process. Discrete pulsed lines in higher frequencies indicate farther pulsed sounds, such as those from an engine noise.

2012). For example, it has been shown that urban great tits (*Parus major*) sing with higher minimum frequencies in cities (Slabberkoorn and den Boer-Visser, 2006), and in traffic noise in particular (Slabberkoorn and Peet, 2003).

Anthropogenic noise in the marine environment is a "hot topic" in the scientific community (*e.g.*, Hatch and Wright, 2007). To date, however, the majority of published information on the effects of anthropogenic noise on humpback whales is related to behavioral responses to the whale-watching tourist industry worldwide, reported as avoidance or displacement from boats as a noise source (Au and Green, 2000; Erbe, 2003; Frankel and Clark, 2002; Miller *et al.*, 2000; Sousa-Lima and Clark, 2009).

In fact, noise produced by outboard and inboard engines creates complete sonic conditions in which many animals can suffer direct hearing injury or masking of communications (Richardson *et al.*, 1995). Au and Green (2000) have evaluated that the presence of boats close to a group of humpback whales (*Megaptera novaeangliae*) could create problems in these animals during the singing season (February–April) in Hawaiian waters.

Excessive noise can mask important aspects of communication among several aquatic species (*e.g.*, Hatch and Wrigth, 2007; Richardson *et al.*, 1995; Southall, Schusterman, and Kastak, 2001), including sexual and contact calls that enable individuals to meet and mate, feeding calls that facilitate food resource utilization, and mother and calf calls that enable maintenance of proximity. Thus, the potential of noise to impair survival, reproduction, and population growth demands attention (NRC, 2000, 2003).

Parks, Clark, and Tyack (2007) have discussed the effects of noise on acoustic communication in right whales (*Eubalena glacialis* and *Eubalena australis*) exposed to an increased level of ambient noise. In the right whale, an increase of ambient noise level is accompanied by a lower rate of call to avoid a masking effect from low-frequency noise.

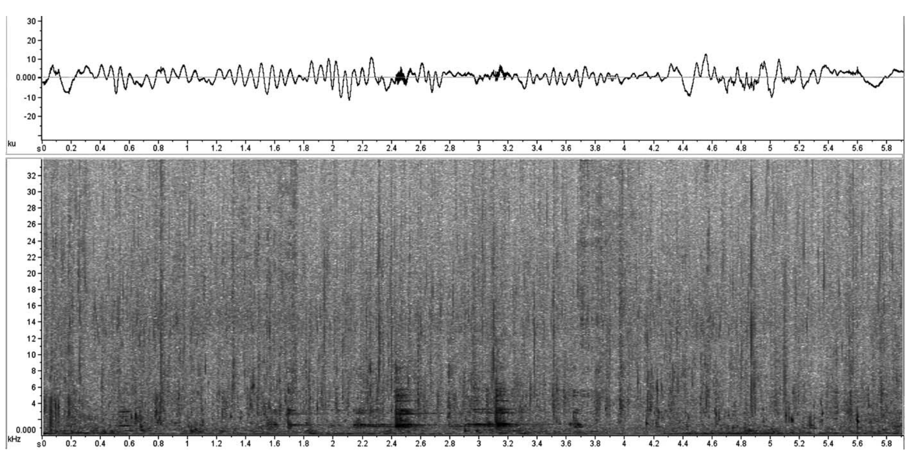

Figure 6. In this spectrogram, it is possible to identify a noise with frequencies between 1 and 12 kHz, heard as a pulsed and "metallic" sound. This was considered indirect from the platform because it is formed as a result of diverse chains and metallic cables moving with the sea currents.

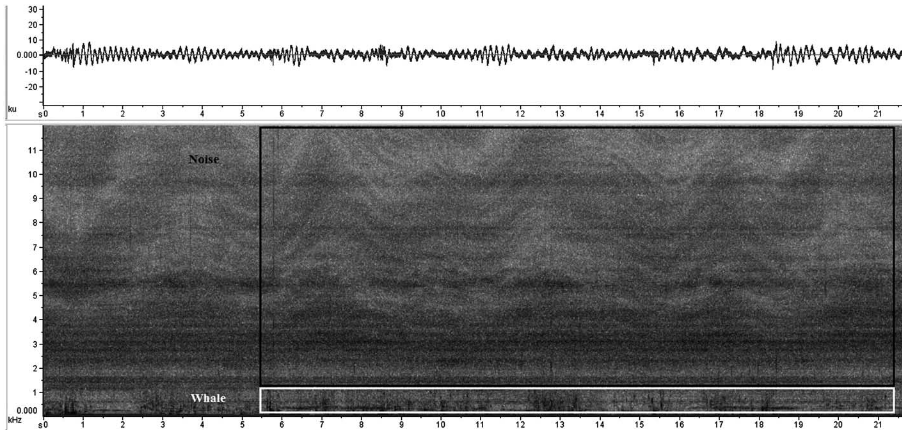

Figure 7. A frequency overlapping of anthropogenic noise from the gas platform is represented in this spectrogram, showing a continuous wave pattern, simultaneous with the low-frequency humpback whale notes (>1 kHz). Black rectangle is noise range, and white rectangle is a whale song part.

In the bottlenose dolphin, Buckstaff (2004) has found a different whistling frequency when boats were approaching, and whistles were more frequent at the beginning of vessel approach. This modification in the frequency of whistles may be caused by the necessity of animals to come close together but also to compensate for the masking effect on communication as the boat approaches.

Context may differentially affect cetacean behavioral and physiological responses to noise. For example, young animals may be particularly sensitive to acoustic stress as they are in critical periods of neurological development; even short-term exposure to noise may result in long-term consequences (Wright *et al*., 2007).

Furthermore, in the underwater world, sound has two major components: an acoustic nearfield (or foreground), where particle velocity dominates, and an acoustic farfield (or background), where the propagation of pressure dominates. Marine animals perceive these two sonic fields differently: The nearfield is perceived by sensory hair-like receptors, and membranous receptors are used to detect the farfield particle oscillation (Au and Hastings, 2008).

An extensive review about noise impacts in marine animal environmental perceptions, describing observed results on behavioral changes in diverse fauna, such as coral reefs, crustaceans, fishes, and mammals, is provided by Farina (2014).

The results of the present work provide important information about the foreground local acoustic environment, through time and frequency characterization, contributing to a better understanding of the soundscape ecology of the humpback whales in a broad interpretation of habitat perception (Farina, 2014; Truax, 1999).

The distinction into background or foreground sounds reflects different priorities of the acoustic environment. Locations dominated by backgrounds sounds receive sounds signals from the whole surrounding landscape. In contrast,

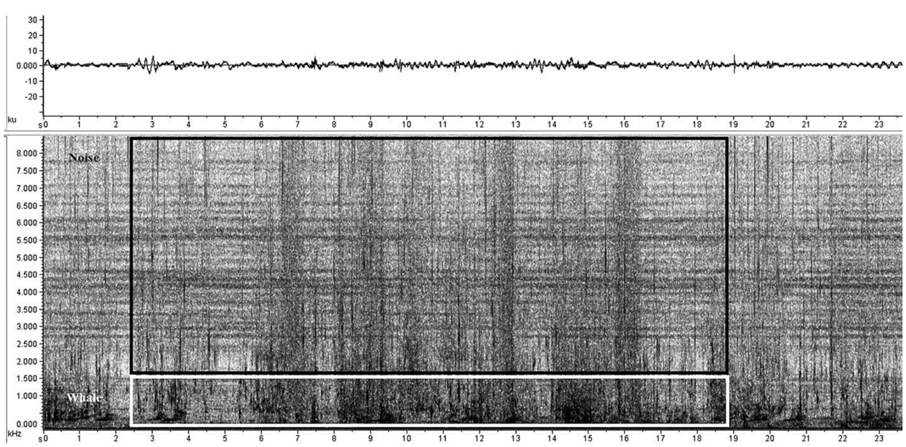

Figure 8. A frequency overlapping of anthropogenic noise from the gas platform is represented in this spectrogram, showing a cross and loud pattern, simultaneous with the low-frequency humpback whale notes (>1 kHz). Black rectangle is noise range, and white rectangle is a whale song part.

Table 2. *The humpback whale (*Megaptera novaeangliae*) is also known as the singer whale because its unique and complex reproductive display called song, which is composed by different notes arranged in phrases and themes, resulting in a long and repetitive call that is crucial for the reproductive success in the species. This table presents a set of humpback whale notes (*n = 65*) recorded around oil platforms off the Brazilian coast.*

	Minimum Frequency (Hz)	Maximum Frequency (Hz)	Central Frequency (Hz)	Frequency Amplitude (Hz)	Time Amplitude (s)
Min	40	262	140	64	0.37
Max	1092	10,186	2584	10,032	5.13
Mean	220	3277	483	3057	1.82

locations where foreground sounds are more intense are characterized by *in situ* production and propagation of sound (Mazaris *et al*., 2009).

Herein it is shown that the operation of oil and gas platforms in Brazil produces a broad spectrum of foreground acoustic noise that exceeds the range of the recording equipment (48 kHz). This suggests the need for future utilization of a broader frequency range recorder so as to fully ascertain the acoustic parameters of this noise.

Sounds registered from platforms are concentrated in low and medium frequencies (0 to 10 kHz). These frequencies constitute a large part of the acoustic niche of the humpback whale. It is evident that humpback whale song and oil- and gas-related anthropogenic noise are overlapping. Low-frequency components allow noise to propagate farther in the ocean.

The humpback whale behavior and group structure observed near the oil and gas platforms clearly indicate that the whales are utilizing these environments in their entire breeding area along the Brazilian coast. This exposes them to diverse sources of human impact (Marcondes and Engel, 2009; Neto *et al*., 2007; Rossi-Santos, Silva, and Monteiro-Filho, 2010).

The literature about the hearing capabilities of the humpback whale is still inconclusive. Au *et al*. (2006) report high-frequency harmonics surpassing 24 kHz, suggesting that the species may present an upper hearing limit as high as or even higher than this value.

There is little information about noise from oil and gas platforms in the literature. This study shows that whale and platform noise frequencies overlap in almost all analyzed spectra, which may cause masking of the whales' calls, as has largely been found in previous studies (*e.g*., Foote, Osborne, and Hoelzel, 2004; Richardson *et al*., 1995; Wright *et al*., 2007). These disturbances may have a negative impact on whale breeding success around noise sources, which may ultimately lead to decreased use of these areas for breeding, and consequent diminishment of the overall area of the seasonal breeding grounds.

Anthropogenic noise impacts have been shown to reflect in important animal changes, such as: hearing effects; psychological effects; behavioral effects; communication effects; social structural effects; habitat use effects; and cumulative effects (*e.g*., Hildebrand, 2004; Tyack and Janik, 2013; Weilgart, 2007).

Looking at the behavioral approach, belugas (*Delphinapterus leucas*) and narwhals (*Monodon monoceros*) were identified to react differently when exposed to a high-intensity icebreaker ship noise; belugas emitted more clicking and descending tonal sounds, while narwhals stayed in silence (Lesage *et al*., 1999).

There is evidence that gray whales (*Eschrichtius robustus*) and bottlenose dolphins (*Tursiops truncatus*) change their frequency range in order to avoid excessive noise in the environment (Würsig and Richardson, 2000).

Another study showed that sperm whales (*Physeter macrocephalus*) reduced clicking when exposed to seismic pulsed tones (Watkins *et al.,* 1993), sometimes at hundreds of kilometers away (Bowles *et al*., 1994). Rankin and Evans (1998), in the Gulf of Mexico, found that seismic operation caused a negative impact on the sperm whale communication and orientation, but nothing was noted for the other odontocete distribution.

Regarding the habitat use effects, there are some studies showing the displacement of cetacean populations, such as bottlenose dolphins (Evans, Lewis, and Fisher, 1993), harbour porpoises (Evans *et al*., 1994), belugas (Finley *et al*., 1990), and sperm whales (Madsen *et al*., 2002), associated with seismic operations and ship traffic. It is also known that humpback whales (Glockner-Ferrari and Ferrari, 1985), blue whales (Gordon and Moscrop, 1996), and bowhead whales (Richardson, Würsig, and Greene, 1987) abandoned some occurrence areas in response to anthropogenic activities such as shipping, aircrafts, and industrial drilling.

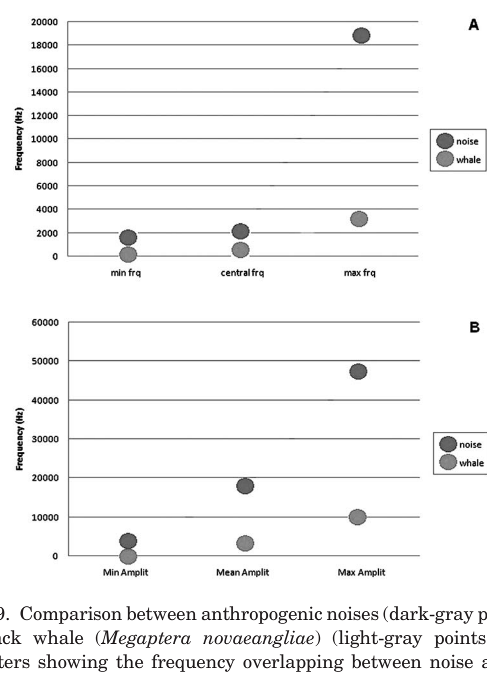

Figure 9. Comparison between anthropogenic noises (dark-gray points) and humpback whale (*Megaptera novaeangliae*) (light-gray points) acoustic parameters showing the frequency overlapping between noise and whale sounds: (A) Frequency in Hz (mean values from Tables 1 and 2 for minimum, central, and maximum frequencies). (B) Amplitude in Hz (minimum, mean, and maximum).

For the humpback whale, because the song is related to breeding success, changes in this behavior may affect demographic parameters (Weilgart, 2007). In fact, Maybaum (1993) registered evasion behavior in Hawaii, described as the increase in whale speed and path linearity, in response to a playback experiment using pulsed sonar tones of 3.3 kHz, suggesting that these sounds could be perceived as threats by the whales.

Similarly, Miller *et al*. (2000) registered changes in the song behavior of the humpback whales when exposed to low-frequency sonar (LFA). Songs were 29% longer during sonar playbacks, returning back to normal after the experimental exposure and suggesting that humpback whales sang longer to compensate for the acoustic interference and that this response presented a limited duration.

For the Brazilian coast, the obtained behavioral observations may indicate that despite the fact that there are males singing around the platforms, probably there are behavioral and physiological consequences, presently unknown, potentially harming their breeding season, causing avoidance of supply boats around the platforms, and triggering long diving behavior.

In a recent study, Risch *et al*. (2012) found that the humpback whale song was reduced simultaneously with an experiment (Ocean Acoustic Waveguide Remote Sensing [OAWRS]) located about 200 km away in the Stellwagen Bank Marine Sanctuary. For two consecutive years, their research monitored the OAWRS experiment for 11 days and then compared it with 11 more days before and after the experiment, showing the song absence during the acoustic experiment period and also showing how far an anthropogenic noise may affect whales in acoustic behavior.

Acoustic Environmental Conservation

The marine soundscape is modified by anthropogenic intrusion by shipping and small boats, drilling and mining seismic surveys, and by offshore wind farms, and this impact can mask important natural sonic cues (Farina, 2014).

For instance, we expect in future years that the receding of ice will cause further intrusion of human activity in the polar regions, accompanied by increased ambient noise in summer months by seismic air-guns associated with oil and gas exploration, in areas densely populated by blue, fin, and sperm whales (Klinck *et al*., 2012).

Hence, thinking in a marine management and conservation perspective, the present work contributes useful information to future research about descriptions of perceived environmental quality (*e.g.*, Miller, 2008) and to identification of areas with high acoustic quality (*e.g.*, Pheasant, Horoshenkov, and Watts, 2008).

In a recent paper, Farina and Belgrano (2006) demonstrated the need to evaluate and integrate additional elements, such as acoustics, in the study of landscapes, thus to proceed to an organism-centered view leading to the construction of cognitive landscapes. In this sense, the study of sounds as implicit time-dependent processes inherent in any landscape could provide an additional layer of information for landscape analysis, aiming towards the comprehension of cognitive landscapes (Farina, 2014; Farina and Belgrano, 2006).

Coastal ecosystems are threatened by pollution, overexploitation of natural resources, increases in commercial and recreational boat traffic, urban development, and global climate change (De Fontaubert, Downes, and Agardy, 1996). The synergistic interactions between these threats and anthropogenic noise exposure may lead to harder consequences for cetaceans in the coastal zone, as previously mentioned in diverse international Environmental Impact Assessments (for a review, see Wright, 2014).

The marine bioacoustics science is ascending in parallel to technological evolution, which helps the development of a countless number of new studies to face the complexity of factors involved in soundscape ecology. Despite this, in Brazil, these studies are still scarce, initiated in the late 1980s, and limited by the difficulty in equipment acquisition. There is an open field for studies to contribute to understanding the processes involved in a marine soundscape ecology scenario.

In this paper, when comparing the results of humpback whale song and anthropogenic sounds from the oil and gas industry in the study area, it is possible to identify an overlapping of acoustic niches, due to the broad frequency spectrum presented by the human noise, which is in similar frequencies as the registered humpback whale song notes.

Because the song is an important part of the complex breeding behavior for this species, it is pertinent to call attention to this anthropogenic intrusion in the marine acoustic environment, to avoid large ecological consequences and to promote oceanic and coastal conservation awareness.

CONCLUSIONS

The results of this study show that oil and gas platforms contribute to oceanic noise pollution by producing sound over a broad range of frequencies—including all frequencies in our measured acoustic range (0 to 48 kHz). Future studies, including experimental monitoring using improved technological acoustic tools, such as the utilization of a broader recording system and calibrated hydrophones, are suggested to fully ascertain the parameters of platform-produced sound.

The registered noises are concentrated in lower and mean frequencies (0 a 10 kHz), which is a large part of the humpback whale acoustic niche. Thus, a potential frequency overlapping was found between the humpback whale song and the anthropogenic noise originated from the oil industry in the Brazilian breeding ground.

Previous revision works (*e.g.*, Tyack and Janik, 2013) demonstrated that increased underwater noise causes marine mammals to alter the source level, frequency, duration, and redundancy of their signals. The evidence that marine mammals modify their calling behavior in response to anthropogenic noise also suggests that it does interfere with their ability to communicate.

Many important research questions could emerge from these observations, such as behavioral costs for masking compensation by marine mammals, physiological limits for noise exposure, local habitat degradation by excessive noise, and other nonacoustic factors that are important in predicting adverse effects of noise, such as underwater visual cues for animal distribution.

The integrative approach and interpretation of all these questions, such as performed within the context of soundscape ecology, may lead to a broad perspective with which to conciliate the modern human expansion with the conservation of natural environments, essential to a healthy and productive whole ecosystem.

This study is the first to provide systematic information about the soundscape ecology, including oil and gas platforms, in a humpback whale breeding ground in the South Atlantic Ocean.

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□ SUMMARY □

O presente trabalho tem como objetivo acessar a sobreposição acústica entre o canto da baleia jubarte e sons antropogênicos ao redor de plataformas de petróleo e gás, através da descrição espectral e comparação de frequências. As baleias foram sistematicamente monitoradas no nordeste do Brasil (11° S, 37° W - 14° S, 38° W). Dados acústicos e comportamentais foram coletados entre 2007 e 2009, focando na ocorrência de jubarte ao redor de plataformas de petróleo. Diversos ruídos antropogênicos foram registrados em uma amplitude de frequência semelhante aos sons gravados dos cetáceos, o que sugere uma sobreposição de nichos acústicos. A poluição sonora originada na produção de petróleo e gás pode, potencialmente, afetar a comunicação desta espécie, com consequências em sua distribuição e comportamento nesta área de reprodução. Este artigo é o primeiro a trazer informações sobre a sobreposição acústica entre plataformas de petróleo e cetáceos no Oceano Atlântico Sul ocidental. Frente à crescente exploração de petróleo e gás, se faz necessário desenvolver esforços para melhorar o desenvolvimento e uso dos métodos acústicos para serem empregados como monitoramento destas atividades.