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The Importance of Bioacoustics for Dolphin Welfare: Soundscape Characterization with Implications for Management

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THE IMPORTANCE OF BIOACOUSTICS FOR DOLPHIN WELFARE:
SOUNDSCAPE CHARACTERIZATION WITH IMPLICATIONS FOR MANAGEMENT

by

HEATHER RUTH SPENCE

A dissertation submitted to the Graduate Faculty in Psychology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York

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Abstract

THE IMPORTANCE OF BIOACOUSTICS FOR DOLPHIN WELFARE:
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Adviser: Professor Martin Chodorow

Sound is the primary sensory modality for dolphins, yet policies mitigating anthropogenic sound exposure are limited in wild populations and even fewer noise policies or guidelines have been developed for governing dolphin welfare under human care. Concerns have been raised that dolphins under human care live in facilities that are too noisy, or are too acoustically sterile. However, these claims have not been evaluated to characterize facility soundscapes, and further, how they compare to wild soundscapes. The soundscape of a wild dolphin habitat off the coast of Quintana, Roo, Mexico was characterized based on Passive Acoustic Monitoring (PAM) recordings over one year. Snapping shrimp were persistent and broadband, following a diel pattern. Fish sound production was pulsed and prominent in low frequencies (100 – 1000 Hz), and abiotic surface wave action contributed to noise in higher frequencies (15 – 28 kHz). Boat
motors were the main anthropogenic sound source. While sporadic, boat motors were responsible for large spikes in the noise, sometimes exceeding the ambient noise (in the absence of a boat) by 20 dB root-mean-squared sound pressure level, and potentially higher at closer distances. Boat motor sounds can potentially mask cues and communication sounds of dolphins. The soundscapes of four acoustically distinct outdoor dolphin facilities in Quintana Roo, Mexico were also characterized based on PAM, and findings compared with one another and with the measurements from the wild dolphin habitat. Recordings were made for at least 24 hours to encompass the range of daily activities. The four facilities differed in non-dolphin species present (biological sounds), bathymetry complexity, and method of water circulation. It was hypothesized that the greater the biological and physical differences of a pool from the ocean habitat, the greater the acoustic differences would be from the natural environment. Spectral analysis and audio playback revealed that the site most biologically and physically distinct from the ocean habitat also differed greatly from the other sites acoustically, with the most common and high amplitude sound being pump noise versus biological sounds at the other sites. Overall the dolphin facilities were neither clearly noisier nor more sterile than the wild site, but rather differed in particular characteristics. The findings are encouraging for dolphin welfare for several reasons. Sound levels measured were unlikely to cause threshold shifts in hearing. At three of four facilities, prominent biological sounds in the wild site – snapping shrimp and fish sounds – were present, meaning that the dolphins at these facilities are experiencing biotic features of the soundscape they would experience in the wild. Additionally, the main anthropogenic sounds experienced at the facilities (construction and cleaning sounds) did not reach the levels of the anthropogenic sounds experienced at the wild site (boat motor sounds), and the highest noise levels for anthropogenic sounds fall outside the dolphins’ most sensitive range of hearing.
However, there are anthropogenic contributors to the soundscape that are of particular interest and possible concern that should be investigated further, particularly pump noise and periodic or intermittent construction noise. These factors need to be considered on a facility-by-facility basis and appropriate mitigation procedures incorporated in animal handling to mitigate potential responses to planned or anticipated sound producing events, e.g. animal relocation or buffering sound producing activities. The central role of bioacoustics for dolphins means that PAM is a basic life support requirement along with water and food testing. Periodic noise is of highest concern, and PAM is needed to inform mitigation of noise from periodic sources. Priority actions are more widespread and long-term standardized monitoring, further research on habituation, preference, coupling and pool acoustics, implementation of acoustics training, standardization of measurements, and improved information access.
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Humans tend to be visually oriented, but sound is the primary sensory modality for dolphins. Dolphins are primarily adapted to using underwater acoustic stimuli (versus vision) and rely on sound production and hearing for survival. Sound is their primary means of communication. For these socially complex mammals, phonation is essential to all aspects of their life history, including development and reproduction (e.g. Connor, 2007). They rely on echolocation to forage, navigate and explore their environment (Hastings & Au 2012; Harley 2003). Dolphins have a broad range of hearing that accommodates their acoustic ecology; they can hear up to 180 kHz, well into the ultrasonic frequency range, supporting both lower frequency communication signals (e.g. <20 kHz) and high frequency echolocation (20-120 kHz) (Mooney, Yamato, & Branstetter, 2012).

Bioacoustics is central to dolphin interactions with each other and their environment, and attention to the impacts of sounds on dolphins is important for effective policy, both for wild and managed populations. Noise is typically defined as unwanted sound, yet this is subjective and situational. In this dissertation, the term noise is used to highlight sounds that would not historically have been present in dolphin habitats and especially those that indicate inefficiency as opposed to function, e.g. boat motor noise for which energy is lost in the form of sound. Few policies mitigating anthropogenic sound exposure exist for wild populations, and even fewer noise policies or guidelines have been developed for managing the welfare of dolphins under human care. Concerns have been raised that dolphin facilities are either too noisy, or are too acoustically sterile for dolphins under human care. However these claims have not been evaluated to determine the sounds that dominate facilities, and further, how these sounds
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compare to wild soundscapes. To address this need, this dissertation is comprised of three main investigations:

    Chapter 1) Research and policy related to the effects of sounds on dolphins are reviewed and recommendations provided for improving the welfare of managed care dolphins.

    Chapter 2) The soundscape of a wild dolphin habitat is characterized.

    Chapter 3) Soundscapes of managed facilities are characterized and compared with the wild site to address issues of acoustic sterility or overexposure.
Chapter 1

Dolphin Environmental Noise Policy: Online Database and Best Practices Analysis

Background

The question of whether animals suffer was notably posed in 18th century Britain by Jeremy Bentham as a consideration for legal protection for animals (Bentham, 1789). This led to pioneering legislation of animal welfare addressing the treatment of animals in the United Kingdom, which influenced development of legislation in other regions, including the United States (Adams, 2014). Animal welfare refers to the state of well-being of the animal, evaluated by measures of animal health, comfort, nourishment and safety. Measuring the wellbeing of an animal has been a major challenge to scientific research. For example, assessments of pain and distress in animals (e.g. Morton & Griffiths, 1985) are limited by communication, experiential, and sensory barriers. A variety of physiological and behavioral metrics for assessing pain and distress have been investigated and developed (e.g. Hawkins, 2014; Okafor, Remi-Adewunmi, Fadason, Ayo, & Muhammed, 2014; Weary, Niel, Flower, & Fraser, 2006), but putting them into practice and interpreting them in diverse situations and species is complicated (Mason & Mendl, 1993). Nevertheless, ongoing advances in the study of animal sensation, consciousness and cognition are providing further context for assessing and legislating welfare of animals in a variety of sectors including research, agriculture, entertainment, education, service, and as pets (Dawkins, 2015; Mendl & Paul, 2004).
Marine Mammals – A Specific Case History

Marine mammals once were primarily considered for their economic value, however they are now increasingly valued ecologically and individually. Whales were once important resources for meat, oil, and blubber, but this has shifted so that today they are important to tourism, aquariums, entertainment and related industries (Berta, 2006). Interest in maintaining healthy populations and individuals has grown with respect to both wild marine mammals and those under human care. Indeed, recent studies about self-awareness (e.g. Reiss & Marino, 2001) and consciousness (e.g. Harley, 2013) have opened intense debate about the proper treatment of marine mammals, whether they should be kept in captivity, and if so, under what conditions (e.g. Keith, 2010).

Marine mammal protection and regulation in the United States and internationally was historically developed to address whaling and has been expanded to deal with various forms of intentional and unintentional injury and harassment. Legislation has evolved from focusing on economic concerns to focusing on animal welfare, protection of cultural resources, and ensuring biological sustainability. In 1937, the International Agreement for the Regulation of Whaling was signed as an international environmental agreement to protect whale populations from overhunting. In 1946, it was succeeded by the International Convention for the Regulation of Whaling, which started with only 15 member governments and, with some fluctuation from withdrawals and rejoining, has grown to 89 members (ICRW, 1946). The ICRW set up the International Whaling Commission (IWC) as the governing body to act under the ICRW and implement its goals. The United States is a member nation, and its first incorporation of ICRW regulations into domestic law was the 1971 Pelly Amendment to the Fisherman’s Protective Act of 1967. This Amendment imposed import sanctions on nations violating ICRW or other
international fishery conservation programs ("Pelly Ammendment," 1971). Sanctions have been used in influencing other nations to comply with quotas, including Japan and the Soviet Union in 1974 (ELR, 1975). Around this same time, the United States added protections to marine mammals under human care. The Animal Welfare Act (AWA), passed in 1966 and which regulates treatment of animals in research or exhibitions, was amended in 1970 to include all warm blooded animals and therefore marine mammals. The AWA dictates the minimum standards of treatment for captive marine mammals (USDA, 2013).

Two major federal acts affecting marine mammals were passed in the early 1970s in the United States – the Marine Mammal Protection Act (MMPA) and the Endangered Species Act (ESA). Passage of the MMPA in 1972 greatly increased protections for wild marine mammals. The MMPA made it illegal for residents to kill, hunt, injure, or harass any wild marine mammal species. The MMPA also made it illegal to import animals or animal products without permits ("Marine Mammal Protection Act," 1972). In a 1994 amendment, the concepts of Level A and Level B Harassment were introduced as the two non-lethal impact categories used by the National Marine Fisheries Service (NMFS) in its regulatory role. Harassment is defined as the “act of pursuit, torment, or annoyance.” Level A is potentially injurious, whereas Level B is not injurious, but potentially disruptive of critical behavioral patterns ("Marine Mammal Protection Act - Ammendment," 1994). The expansion of protections broadened regulation to cover not only whaling and ship strikes, but also whale watching and forms of harassment incidental to other activities. The protections attempt to address the welfare of individual animals, which

1 Captive implies that one is held against one’s will. This is debated, especially for animals born within facilities and with no experience in the wild.
cumulatively across individuals can affect population health and sustainability, which is under oversight of NMFS.

The ESA of 1973 was enacted to protect animals in danger of extinction. The ESA covers many whale species, though its definition of marine mammal stocks in the ‘endangered’ or ‘threatened’ categories are less inclusive than the MMPA’s designation as ‘depleted’ (Lowry, Laist, & Taylor, 2007). In the ESA, an endangered species is considered to be “in danger of extinction throughout all or a significant portion of its range.” A threatened species is “likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range.” In the MMPA, designation of a species or population stock as depleted is applied to all endangered and threatened species. Additionally, designation is applied to any that is determined to be “below its optimum sustainable population,” as determined through consultation with advisory groups set up under MMPA, and with fewer animals than the number needed to result in maximum productivity of the population or species. Both the ESA and the MMPA are used to ensure that federal activities with potential for affecting the environment are reviewed and regulated with a permit process. Both acts apply to federal agencies because the National Environmental Policy Act (NEPA), requires US federal agencies to consider the potential environmental impacts of proposed major actions.

International legislation for protection of marine mammals has continued to expand. Protections through agreements among groups of nations have the advantage of broader reach, but also the complication of needing to ensure cooperation. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), which entered into force in 1975, regulates international shipments of cetaceans (1979). It is the only treaty regulating that international trade does not threaten survival of wild populations. The United States is one of the
convention’s 180 members. The United Nations Convention on the Law of the Sea (UNCLOS) was established in 1982 but did not come into force until 1994. UNCLOS guidelines encourage conservation of marine mammals in Exclusive Economic Zones. In international waters, the guidelines require the active participation of member states in cooperative efforts towards marine mammal conservation, but permit individual states to enact specific restrictions. However, there are no specific protections enforced by the guidelines and states are left to themselves to address and coordinate use and protection ("United Nations Convention on the Law of the Sea," 1982).

The IWC banned commercial whaling in 1986. Controversial debates continue over exceptions and enforcement. A major debate is over the allowance of killing whales as part of scientific research. Controversy surrounds the research conducted by the Japanese non-profit research organization, the Institute of Cetacean Research. Objections are made about the science not being credible, and that it is merely a cover for commercial whaling, since the whale meat taken is sold in shops and restaurants in Japan (Blok, 2011; Hirata, 2005). Controversies surrounding the import and export of whale meat by Japan and Norway remain. One issue at the heart of the debate over a country’s right to whale, is that the IWC is a voluntary organization without enforcement power. Nevertheless, agreements by member nations can lead to important protections and pressures on nations to provide means of mitigation and enforcement. More recently and regionally, the 1991 Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas (ASCOBANS) protects harbor porpoise and other local toothed whale species and is especially noted for efforts using acoustic warning systems to reduce bycatch (ASCOBANS, 1992). In 2008 the agreement was extended to a larger geographic area: Baltic, North East Atlantic, Irish and North Seas (ASCOBANS, 2006). Acts and conventions protecting and regulating marine mammals in the wild continue to undergo amendments and updates, some
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at a large scale and some with a large degree of specificity in region and activity type (e.g. Australian sardine fisheries: Hamer, M.Ward, & McGarvey, 2008).

Agencies with responsibilities for protecting marine mammals are mainly oriented toward wild populations. The main international agency responsible for protecting wild populations is the IWC, established in 1946 to manage whaling and promote whale conservation. In the United States, regulations for wild populations are overseen by the US Fish and Wildlife Service (USFWS) in the Department of the Interior, and the National Oceanic and Atmospheric Administration (NOAA) in the Department of Commerce. Two U.S. advisory bodies to congress are the Marine Mammal Commission (MMC) and the National Academy of Sciences (NAS). The MMC was established with the passage of the MMPA. It proposes criteria on education and conservation and reviews research and public display procedures (MMC). The NAS is private and non-profit, and provides scientific advice to the United States government through the National Research Council.

There are two main groups directly responsible for managing and overseeing the treatment of marine mammals under human care in the United States: the United States Department of Agriculture (USDA) / Animal and Plant Health Inspection Service (APHIS); and the NOAA National Marine Fisheries Service (NMFS). APHIS enforces and oversees the Animal Welfare Act by inspecting public display facilities for compliance with AWA guidelines on water quality, space, transportation and handling, food, and veterinary care. APHIS sets new standards as new need arises, such as addressing the rapid growth of the swim-with-dolphins industry (APHIS, n.d.). APHIS also produces and distributes technical reports compiling information on aspects of animal management and use that influence animal health (e.g. Spotte, 1991). The National Marine Fisheries Service (NMFS) (formerly NOAA Fisheries) regulates
permits for removal of marine mammals from the wild, their import into the country, and their transfer between facilities. Facilities must comply with applicable laws, including the ESA (endangered or threatened animals require additional research permits). The NMFS also manages the National Inventory of Marine Mammals, which serves as a central database of all animals held under human care in the United States and tracks any acquisitions, depositions, or transfers. Another role of the NMFS, in consultation with APHIS, is placing non-releasable rescued marine mammals into managed care facilities.

Legislation in the United States and internationally continues to evolve as scientific information on the potential for human activities to affect marine mammals grows. Marine mammals face many anthropogenic threats. Historically, commercial hunting may have reduced certain populations to dangerously low levels such that recovery may be difficult or impossible. Marine mammals continue to be taken as fisheries bycatch and entanglement issues resulting from abandoned fisheries are a concern for most species of marine mammals. Pollution, such as from pesticides and plastics, can negatively impact marine mammal health. High speed shipping is increasing, and ship strikes are a major threat to some large mysticete species. Noise, which will be discussed further in the following section, also impacts marine mammal health and survival and is a major concern of the U.S. Navy and the seismic industry. However, while each individual source can affect a marine mammal, it is the accumulation of multiple stressors on marine mammals that is of greatest concern. This poses a challenge to regulations addressing the larger complex range of combined factors potentially affecting marine mammals.
Importance of Sound to Marine Mammals

Marine mammals have evolved to rely on sound, many as their primary sensory modality. Sound transmission in water is much more efficient than is the transmission of light. Light is reflected off the ocean surface and is strongly and increasingly absorbed as it travels deeper into the water column, starting with the absorption of longer wavelength light (red, orange, yellow). By approximately 200 meters, little-to-no light remains. Sound, however, travels quickly in water – approximately 1500 m/s in seawater versus approximately 340 m/s in air - and is attenuated at a much lower rate per unit distance traveled. Sound propagation in water is also complex because propagation speed and distance depend on many factors, including temperature, depth and bathymetry (e.g., the Sound Fixing and Ranging (SOFAR) channel that acts as a waveguide enabling low frequency sound to travel for thousands of miles). The threat of noise pollution in the ocean is unique in that it can extend from tens to hundreds of kilometers from a noise source and does so soon after the noise is introduced.

Cetaceans are primarily adapted to using underwater acoustic stimuli (versus vision) and rely on sound production and hearing for survival. Sound is most likely their primary means of communication. For these socially complex mammals, phonation is essential to all aspects of their life history, including development and reproduction (e.g. Connor, 2007). Cetaceans use hearing to avoid sound-producing predators and listen for conspecifics (Au & Hastings, 2009), and odontocetes (toothed whales), which includes dolphins, rely on echolocation to forage, navigate and explore their environment (Harley, Putman, & Roitblat, 2003; Hastings & Au, 2012). Dolphins have a broad range of hearing determined using both behavioral and electrophysiological methods and some can hear up to 180 kHz, well into the ultrasonic frequency range (Mooney, Yamato, & Branstetter, 2012). The dolphins’ ability to localize and
discriminate frequency and intensity of sound is at least as good as humans (Ridgway & Au, 2009). In contrast to dolphins, assessing the hearing of mysticetes remains difficult because of the technical challenges associated with performing hearing tests on such large animals. No direct measures of hearing exist for baleen whales, however there are indirect indications, through anatomical modeling, frequency of vocalizations, and responses to acoustic playbacks, that some may hear infrasonic sounds (<100 Hz) (Ketten, Arruda, Cramer, Zosuls, & Mountain, 2013; Reidenberg & Laitman, 2004; Yamato, Ketten, Arruda, & Cramer, 2008).

Three ‘functional’ hearing groups have been proposed for cetaceans based on known or assumed hearing ranges: low-frequency (7Hz-22kHz), mid-frequency (150Hz-160kHz), and high-frequency (200Hz-180kHz) (NOAA, 2013). Low-frequency cetaceans are baleen whales, mid-frequency cetaceans include most dolphins and toothed whales, and high-frequency cetaceans include true porpoises, river dolphins, and a subset of oceanic dolphins whose phylogeny is debated (e.g. the genus *Cephalorhynchos*). Marine dolphins, which are considered mid-frequency specialists, generally have similar measured hearing ranges within the 150Hz-160kHz range (Brill, Moore, & Dankiewicz, 2001; Finneran & Houser, 2006; Houser & Finneran, 2006; Johnson, 1968; Popov, Supin, & Klishin, 1996). These designations, though addressing little of each species’ ecology, have been used by NMFS in establishing thresholds and criteria of impact for marine mammals exposed to anthropogenic sound.

Ocean noise is increasing globally because the amount and range of sound-generating activities by humans is on the rise (Hildebrand, 2009). Human-generated noise dominates the highly-propagating low frequency band (10 to 500 Hz), especially from commercial shipping and seismic exploration (Hildebrand, 2009). These add to a variety of natural abiotic sources of sound, which include earthquakes, lightning strikes, waves, storms and other weather events.
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Marine mammals also experience non-anthropogenic sound from a variety of biotic sound sources, especially snapping shrimp in coastal regions (Everest, Young, & Johnson, 1948; Versluis, Schmitz, von der Heydt, & Lohse, 2000). Snapping shrimp sounds are ubiquitous, persistent and broadband and are an important component of the acoustic ecology of coastal-dwelling marine mammals, including a number of dolphin species.

Dolphins. Dolphins are the most common and well-studied of cetaceans. Of approximately 35 or more species of dolphins, most are in the family Delphinidae (oceanic dolphins), although there are also four families of river or estuarine dolphins. Dolphins are found worldwide, mainly in temperate and tropical waters, in both coastal areas and the open ocean.

Wild dolphins face a variety of threats, both natural and anthropogenic. Dolphins are predators but still face predation from sharks and food competition from sharks (Heithaus, 2001) and other dolphins (Jefferson, Stacey, & Baird, 1991; Spitz, Rousseau, & Ridoux, 2006). Like all mammals, they also are susceptible to parasites (Aznar, Balbuena, Fernández, & Raga, 2001) and disease (Bossart, 2007). A major anthropogenic threat to dolphins is fisheries bycatch (Lewison, Crowder, Read, & Freeman, 2004), including well-known problems in the tuna fisheries which led to the dolphin-safe tuna movement (Hall, 1998). Chemical pollution is an issue, especially with heavy metals (Das, Debacker, Pilet, & Bouquegneau, 2003), because many chemical pollutants can accumulate in the fatty tissue of the blubber. Boat/shipping traffic can be an issue (Seuront & Cribb, 2011), as can habituation to boats and human feeding. The latter is particularly problematic due to their sociality; dangerous behaviors like taking food from humans can be spread through dolphin societies via cultural transmission (Donaldson, Finn, Bejder, Lusseau, & Calver, 2012).
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Bottlenose dolphins (*Tursiops truncatus*), the focus of this dissertation, are found in temperate and tropical waters worldwide and are the most commonly held cetacean under human care. Because of their ubiquity and robustness under human care, information from bottlenose dolphins is often used to create models for other species. Like other dolphin species, they are socially complex (Connor, 2007) and reliant on sound for communication and other functions. Coastal-dwelling bottlenose dolphins are exposed to anthropogenic sounds and natural sounds, as previously mentioned. Noise exposures for managed-care dolphins are less varied and of a different nature (i.e. due to the facilities that contain them), but are still of concern. Depending on the type of facility (e.g. open lagoons, natural water influx), bottlenose dolphins may still experience some natural sounds from shrimp and/or weather. They may experience boat noise if adjacent to the ocean and may experience noises from operations of the facility and life support equipment. However, unlike wild dolphins, dolphins under human care have limited opportunity to avoid or leave an area with noise.

**Potential Impacts of Sound on Marine Mammals**

Stranding incidents, with unclear cause but coincidence with underwater acoustic events, have led to concern and investigation into different ways that sound can impact dolphins and other marine mammals. It has been hypothesized that human noise can negatively impact dolphins via resonance, rectified diffusion, decompression sickness, auditory system insult, masking, and behavioral disruption. These are the main mechanisms that historically have been or are being considered by NMFS as mechanisms of impact and useful for establishing regulation.
Resonance. Any mass, including an air bubble in tissue or an air space in a marine mammal’s head, has a resonant frequency - the frequency that elicits the maximum amplitude of a vibratory response, as determined by the vibrating object’s physical characteristics. Intensified vibration of these air spaces via acoustic resonance was once hypothesized to cause tissue damage in diving marine mammals. In 2002, a working group for NMFS was convened to discuss the role resonance might have played in a mass stranding in the Bahamas that occurred coincident with the use of mid-frequency (1-10 kHz) active sonar in the area. The conclusions drawn based upon the modeling of resonance potential were that it was unlikely that resonance was a cause of the stranding. This was based on evidence from anatomical characteristics, the likelihood of the levels of received sound, and a lack of tissue damage anticipated due to resonance of biological structures/tissues in the stranded animals. That resonance of internal air cavities could have still contributed to the strandings, potentially through contributing to bleeding or by causing panic (Gentry, 2002) was not considered likely by workshop participants to have been a cause of stranding events (D. Houser, pers. comm.). Alternatively, the potential of rectified diffusion as a cause was raised and discussed by the 2002 working group and was followed up in a subsequent 2004 workshop convened by the Marine Mammal Commission (Cox et al., 2006).

Rectified Diffusion. Rectified diffusion is a mechanism by which sound exposure causes bubble growth in biological tissue. Microbubbles exist naturally in mammalian tissue, but their growth can cause vascular blockages, or emboli, and result in a variety of problems dependent upon the tissues affected. The process of rectified diffusion occurs when acoustic pressure fluctuations cause a bubble to oscillate volumetrically. When the bubble is large
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compared to equilibrium, gas diffuses in, and when it is small, gas diffuses out. However, more gas enters than leaves because the diffusion process is proportional to the surface area of the bubble - called the “area effect.” This is compounded by the “shell effect,” in which a layer of liquid surrounding the bubble is compressed when the bubble expands, and thus a higher concentration of gas just around the bubble increases diffusion of gas into the bubble. Across multiple acoustic (pressure) cycles, the bubble continues to grow (Houser, Howard, & Ridgway, 2001).

Concerns about sounds affecting bubble growth come from direct effects on bubbles, and enhancement of effects when there is super-saturation of dissolved gas caused by diving. Since marine mammals dive much deeper than humans, it was suggested that the dive profiles increased gas super-saturation near the surface, which in turn could increase the potential for rectified diffusion in deep diving marine mammals (Houser et al., 2001). Since bubble growth is caused by more gas entering the bubble than leaving as the bubble vibrates, this is enhanced by there being more gas available (i.e. super-saturation). Crum and Mao (1996) modeled bubble growth and determined that a marine mammal exposed to a Sound Pressure Level (SPL) of over 210 dB could experience bubble growth, and that if gas levels were elevated due to diving, that this threshold would be much lower. However, empirical determination of the levels of sound required to cause rectified diffusion indicates that the necessary exposure levels are unlikely for wild marine mammals.

Decompression sickness. Decompression sickness (DCS), or “the bends,” in human divers occurs due to tissue super-saturation with gas, primarily nitrogen gas. Following the discarding of rectified diffusion as a potential causative mechanism, DCS was explored as a
mechanism affecting marine mammals. Hooker et al. (Hooker et al., 2011) discuss evidence from tissue examination and gas modeling for the role of diving in promoting bubble growth, and that blood nitrogen levels may vary more than previously thought. Beaked whales stranded in association with naval sonar activity have been found to have both gas and fat emboli, which has been suggested as resulting from decompression during altered dive behavior (Fernández et al., 2005; Jepson et al., 2003). Based on these findings, Cox et al. (2006) identified DCS as an area of interest for further investigation. While research and discussion continue (Houser, Dankiewicz-Talmadge, Stockard, & Ponganis, 2009; White, Leighton, Saunders, & Jepson, 2007) the role of DCS in stranding, including causal relationships, e.g. do strandings cause bubble growth or does bubble growth cause strandings, remains unclear (Hooker et al., 2011).

**Auditory system insults.** Injury to the middle or inner ear is a potentially severe impact to the auditory system. It can be of varying seriousness, and its incidence has been found to be related to distance from an underwater acoustic blast producing a shock wave (Ketten, 2004). Rupture of the round or oval window or tympanic membrane, fracture of the ossicles or damage to the cochlea could result in a hearing deficit, with the severity of the deficit depending on where and how severe the trauma was (Ketten, 2004). Damage to inner hair cells results in loss of response to the relevant frequencies, and damage to outer hair cells results in elevated thresholds, probably due to loss of cochlear amplification that is achieved by these cells (Ketten, 2012).

A particular point of consideration in the regulation of noise impacts to wild animals is auditory fatigue, or threshold shifts (TS) in hearing (Schlundt, Finneran, Carder, & Ridgway, 2000; NOAA, 2013; Southall et al., 2007; Southall et al., 2008). A permanent threshold shift
(PTS) is an auditory injury, where the threshold does not return to pre-exposure levels, even weeks after exposure (Southall et al., 2007). For PTS, data are generally lacking, and it is not studied directly due to ethical concerns (Southall et al., 2007). For regulatory purposes, the onset of PTS has been extrapolated from temporary threshold shift (TTS) growth, and has been used to determine the onset of Level A harassment (i.e. injury) (Jette, Cembrola, Mitchell, & Fetherston, 2005).

A TTS is a form of auditory fatigue in which the noise-induced threshold shift has traditionally been thought to be reversible. While hair cell damage may be recovered and threshold sensitivity restored, recent work in mice indicates that there may be other lasting damaging effects (Kujawa & Liberman, 2009). Both rapid and delayed nerve damage can result from auditory fatigue, and may not be detected through traditional measures of TTS. Thus, some categorizations of TTS may still encompass long-lasting effects on hearing.

TTS has been described and measured in humans as motivated by noise regulations (Melnick, 1991; Southall et al., 2007; Southall et al., 2008). The first TTS studies in cetaceans similarly were prompted by regulations, and were conducted by the Navy to address concerns about noise impacts on marine mammals (Carder et al., 1998; Ridgway et al., 1997). TTS has been measured in response to a variety of acoustic stimuli including tones (e.g. Finneran, Carder, Schlundt, & Ridgway, 2005), impulsive sounds (e.g. Finneran, Schlundt, Dear, Carder, & Ridgway, 2002), and octave band noise (e.g. Kastelein, Gransier, Hoek, & Olthuis, 2012). TTS magnitude and growth are affected by the sound exposure level (SEL), but the magnitude of the shift is dependent upon the frequency, bandwidth and duty cycle and type of signal (single pulse, multiple pulse, non-pulsed).
Despite much research on TTS in bottlenose dolphins (Au, Nachtigall, & Pawloski, 1999; Finneran et al., 2005; Finneran & Schlundt, 2010; Finneran & Schlundt, 2013; Finneran, Schlundt, Branstetter, & Dear, 2007; Finneran, Schlundt, Dear, et al., 2002; Mooney, Nachtigall, Breese, Vlachos, & Au, 2009; Nachtigall, Pawloski, & Au, 2003; Nachtigall, Supin, Pawloski, & Au, 2001; Nachtigall, Supin, Pawloski, & Au, 2004) there are still many gaps in our understanding of factors contributing to the onset, magnitude, and recovery of TTS, including a comprehensive understanding of recovery curves (Southall et al., 2007). Also, TTS has only been examined under conditions where small shifts in the threshold are induced. However, this was recently addressed for amounts up to 23 dB (Finneran, Carder, Schlundt, & Dear, 2010).

**Masking.** Auditory masking is a form of acoustic interference in which perception of a signal by the receiver is affected by the presence of another sound. Signals that can be masked include conspecific acoustic communication, foraging and mating calls, as well as other biotic and abiotic cues such predator and reef sounds. Energetic masking is most likely when the masking sound and the sound of interest are similar in frequency and co-occur, and the sound of interest becomes inaudible. Informational masking occurs when the sound of interest is audible but cannot be sorted out from the masking sound (Clark et al., 2009). Masking of communication signals has become a subject of widespread concern, particularly with respect to reproductive impacts (Clark et al., 2009). Communication ‘space’ has putatively shrunk, in part due to shipping noise (Hatch, Clark, Van Parijs, Frankel, & Ponirakis, 2012), thus reducing the distances across which reproductive signals can be effectively broadcast. Masking is now often considered in potential impacts of human activities on marine mammals, including shipping and dredging (e.g. Jensen et al., 2009; Todd et al., 2015).
Acoustic masking was first investigated in dolphins by C. Johnson in the 1960s. In controlled experiments, he calculated critical bandwidths for the masking of tonal signals with broadband noise (Johnson, McManus, & Skaar, 1989; Johnson, 1968). While narrowband signals are tonal, broadband sounds cover a wide range of frequencies. Researchers later explored broadband masking effects in the laboratory, usually using Gaussian noise (e.g. Au, 1990; Finneran, Schlundt, Carder, & Ridgway, 2002). More recently, Branstetter, Finneran and colleagues described the limitations of using Gaussian models, showing that they are dissimilar to natural-type sounds, which tend to be comodulated noise. Comodulated noise is amplitude-modulated, and the temporal changes happen together across frequencies. Masking predictions based on Gaussian noise tend to overestimate the amount of masking. In the presence of different types of comodulated noise, a “masking release” occurs that enables the detection of a signal at a lower signal-to-noise ratio than predicted from Gaussian models (Branstetter & Finneran, 2008; Trickey, Branstetter, & Finneran, 2010). Thus, the potential for masking by anthropogenic sources is real, but the degree to which masking actually occurs remains to be determined.

**Behavioral Disruption.** Marine mammal behavior is complicated to study because it is variable, context-dependent, and is performed by animals that are often beyond visual observation (e.g. diving). Behavioral changes induced by sound exposure are important as they may be indicative of physiological impact, such as stress, and can impact biologically important activities (e.g. energy gain, reproduction). Behavioral responses can be subtle, such as changes in respiration, brief changes in orientation, signs of irritation such as chuffing and tail slapping, changes in dive behavior and changes in phonation patterns. Other behavioral responses
potentially have direct links to animal fitness, such as mother calf separations, site abandonment, and abandonment of foraging or breeding behaviors.

For wild marine mammals, behavioral response research has advanced rapidly in recent years. A variety of techniques including hydrophone networks, aerial surveys, tagging and modeling have revealed decreases in duration, extent and frequency of foraging dives in various species exposed to simulated sonar signals, including killer whales, long-finned pilot whales, and beaked whales (e.g. Sivle et al., 2012; Tyack et al., 2011; Wensveen et al., 2015). In some cases, reductions in echolocation production were also documented (e.g. Tyack et al., 2011) as were changes in the direction of travel, often away from the sound source.

Various sound sources have been investigated. For effects of shipping noise, historically it has been considered to be low frequency and mostly of concern for baleen whales, however documentation of higher frequency components in ship noise prompted research into behavioral effects on an exposed tagged beaked whale observed to have an unusual foraging dive (Aguilar Soto et al., 2006). There are however limitations to this and similar lines of research, including low numbers of observations and the potential for the presence of the observation vessels to be a confounding factor in determining the acoustic impacts. Behavioral responses to seismic surveys include avoidance responses, displacement, and vocalization changes (Gordon et al., 2003; Weilgart, 2013). For dredging noise sources, masking and short-term behavioral responses are considered most likely, however reactions vary as they are activity and species specific (Todd et al., 2015).

Another focus of research is behavioral responses to acoustic harassment devices. This has included work on avoidance behaviors to pingers and acoustic deterrents on gillnets (Berrow et al., 2009; Carretta & Barlow, 2011; Dawson, Northridge, Waples, & Read, 2013; Leeney et
Avoidance responses to these devices are typical and exploited in fisheries management, however again responses can be variable. Dolphins also can habituate rapidly to acoustic harassment, especially in the presence of food sources.

Behavioral responses of dolphins to sound while under human care have been observed during TTS research. The probability of a response was observed to increase with increasing received sound level, and behavioral changes included avoidance of the site of exposure (either previously or in progress), aggression and refusal to participate (e.g. Houser, Martin, & Finneran, 2013; Ridgway et al., 1997; Schlundt et al., 2000). Recently, a targeted study with captive bottlenose dolphins documented changes in behavior in response to a one second 3 kHz sound. Behavioral changes included changes in respiration, chuffing and tail slapping, and a refusal to complete trained task behaviors following exposure to the simulated sonar signal (Houser et al., 2013). At received SPLs below or at 160 dB, habituation to repeated exposures was rapid. At received SPLs of 185 dB, all dolphins refused to participate in the performance of study behaviors (Houser et al., 2013).

Thresholds of behavioral change and magnitudes of responses are quite varied. Many factors contribute to this including species and individual variability in sound sensitivity, and differences in prior experiences and thus habituation and sensitization. Studies differ in their determinations of thresholds of avoidance response to areas with sonar activities (e.g. Antunes et al., 2014; Moretti et al., 2014). In this case, sensitivity and experience are likely both factors, since the papers address different species, and the animals in Moretti et al. (2014) are on a Navy range and commonly experience sonar activity.

Dolphins and Noise Policy Analysis
Wild. Regulatory protections for dolphin noise exposure are mainly for wild populations. This is achieved primarily through NMFS review of permits for projects potentially causing acoustic harassment (either Level A “injury” or Level B “non-injurious”). In 1995, NMFS set exposure limits for seismic air gun blasts – 190 dB re: 1 µPa root-mean-squared (RMS) SPL for injury in odontocete cetaceans\(^2\) – as a precautionary estimate with limited data, and not taking into account peak pressure or impulse of the signal. In 1997, a panel of experts was convened to assess acoustic criteria and suggested that this level could be harmful and that the threshold be lowered to 180 dB re: 1 µPa, but that it could vary by species. Approaches to complying with these criteria have varied, depending on the species, and type and duration of noise. A major problem was lack of information on which to base thresholds (Southall et al., 2007). Through the mid-2000s, NMFS explored options for updating the old acoustic threshold criteria with new information and outside input, going through a scoping process and working to create an Environmental Impact Statement (EIS) for establishing new noise threshold criteria. Factors under consideration included variability of ambient sound levels across locations, and potential physiological and behavioral responses (AEI, n.d.). A panel of experts synthesized available data and set guidelines for injury and behavioral disturbance thresholds, based primarily on TTS data (Southall et al., 2007). NMFS and the National Ocean Service, collectively the National Oceanic and Atmospheric Administration (NOAA), continued to review policy guidelines, and in 2013 published a draft of updated guidance on assessing

\(^2\) “Re: 1 µPa” means referenced to one micropascal. This is standard for sound measurements in water, versus 20 µPa in air (American National Standards Institute S1.1 Standard Acoustics Terminology 1994).
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acoustic threshold levels for TTS and PTS that relies both on cumulative sound exposure level and peak sound pressure level. The criteria incorporate advances in scientific knowledge yet add complexity. The proposed guidelines address impulsive versus non-impulsive sounds and account for the differing hearing sensitivity of species through frequency weighting of the sound (i.e. through auditory weighting functions).

NMFS generally relies upon the group applying for a permit to determine if their action has the potential to impact on marine mammals. NMFS has not published rules and regulations for determining the impact of human-caused sound on marine mammals, though they have the authority to determine whether or not they agree with the assessment of impact in the proposal and whether or not to issue a permit for incidental harassment based upon the estimated number of animals to be harassed. As a result, policy is partially driven by groups applying for permits, the action proponents, who have to justify their choice of criteria and thresholds for impact (i.e. what constitutes an impact and at what level of sound exposure does it occur). For federal agencies, much of the justification is laid out in an environmental analysis that precedes any major action. These analyses may be in the form of an environmental impact statement (EIS) or environmental assessments (EA). According to NEPA, an EIS is required for actions expected to significantly affect the quality of the human environment such that the prospective impacts are understood and disclosed in advance. Human environment in this sense means “the natural and physical environment and the relationship of people with that environment” ("NEPA Regulations," Sec. 1508.14). EAs are more concise and is used to determine if preparation of an EIS is necessary and aid compliance with NEPA is an EIS is not necessary ("NEPA Regulations," Sec. 1508.9). When federal agencies are the applicant for an incidental harassment
authorization, the negotiations and decisions regarding the criteria and thresholds of impact often have a widespread effect on policy transformation and implementation.

An example of how criteria are developed via an EIS is how the US Navy addresses dolphin noise exposure in EISs for at-sea training and testing activities. Under NEPA, it is not required that all risks be avoided, though activities involving risks to marine mammals have to comply with the MMPA. A ‘small take authorization’ under the MMPA may be granted if a small number of animals are to be affected and the effect is not expected to have a significant impact on the population or species. The 2008 Northwest Training Range EIS evaluated risks of noise exposure on marine mammals from mid-frequency sonar, aircraft overflights, and underwater detonations (Navy, 2008). Ship traffic was evaluated but only in the context of the potential for ship strikes. Potential exposures were modeled and evaluated for injurious (Level A) or non-injurious (Level B) harassment based on sound source characteristics, propagation modeling, and the likely presence and abundance of different marine mammal species. Non-auditory system responses in the form of tissue damage resulting in injury, and auditory system responses in the form of PTS, constituted Level A harassment. Level B harassment was represented by TTS, masking, and significant changes to natural behaviors. Two behavioral changes – flight response and predator response – could also constitute Level A harassment. For dolphins, TTS levels are based on work by Finneran and Schlundt (Finneran, et al. 2005; Finneran & Schlundt, 2010; Finneran et al., 2007; Schlundt, et al. 2000). PTS levels are predicted based on TTS levels, with an assumption that PTS occurs at 20 dB of TTS. Behavioral responses were modeled and used in the SURTASS LFA Sonar EIS. The modeling incorporated relative parameters of the sound, in received levels relative to basement received level. It also incorporated TTS effects, and previously observed behavioral responses. Extending from each
modeled sound source, exposure zones were delineated representing the area in which Level A or Level B harassment would occur based on accumulated energy exposure and the maximum received sound pressure level. These were then used to estimate the number of animals that would be affected based upon animal densities and the proposed thresholds of impact. Prior to developing a final estimate of impact to marine mammals, NMFS concurred with the proposed criteria and thresholds for impact.

Models used to predict impact vary and several different models have been used for major Navy activities and have been accepted by NMFS. Wartzok et al. (2012) evaluated three acoustic exposure analysis models used in US Navy EISs: the Naval Undersea Warfare Center (NUWC) Area-Density model, the NUWC exposure model (NEMO), and the Science Applications International Corporation (SAIC) model. Each model approached the issue of animal distribution and movement differently, but all utilized similar criteria and thresholds for impact. A major finding of the evaluation was that uncertainty in animal distributions likely minimized the ability to make accurate predictions with any of the models (Wartzok et al., 2012).

Shortly after the analysis, the Navy developed a new model, the Navy Acoustic Effects Model (NAEMO), which is currently the standard modeling approach applied to Navy environmental impact analyses (e.g. Navy, 2014). This model has been accepted by the NMFS for current modeling purposes, yet the criteria and thresholds for impacts resulting from different sound sources (e.g. sonar vs. explosives) continues to be negotiated upon subsequent renewals of permits for major actions.

The NMFS also determines which sources need to be considered in actions with the potential to affect marine mammals. Taking the example of the US Navy Atlantic Fleet Training and Testing EIS (2013), NMFS agreed to the proposition that certain sound sources did not need
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to be considered. Specifically, some sonars were excluded because of their operational
characteristics; in particular, sources that were narrow band, had a downward-directed beam,
were very high frequency, or had low power levels and short pulse lengths/durations were
permitted to be excluded from the analysis. NMFS agreed that these properties lowered the
likelihood of an animal being exposed to a level that would cause significant impact through
reductions in received level, having frequencies outside the range of animal hearing, or having a
beam that decreased the possibility of ensonifying an animal.

As part of its regulatory authority, NMFS also considers the role of possible alternative
actions (less change) and/or the implementation of mitigation measures to reduce impact. As part
of the EIS process, the federal agencies have to make the case for needing the proposed action,
but must also provide alternative actions that could be taken. Typically, the alternative actions
achieve a lesser degree of the goals set forth by the action proponent. Mitigation methods can be
used to lessen the impacts of the action where impacts are expected. For example, the U.S. Navy
employs a variety of protective measures based on altering activities based on expected animal
presence, deploying trained “watchstanders” to report presence of marine mammals so activities
can be altered or halted, and implementing various sound source power reduction procedures for
when animals are in close proximity.

A common difficulty in setting acoustic impact thresholds is a lack of supporting data;
however, while limited data is an issue, misinterpretation, inappropriate extrapolations or over-
selling findings or models can also be problematic. One issue raised by Wartzok et al. (2012) in
the review of models for predicting acoustic impacts to wild marine mammals was that a model
that is good and precise could be misinterpreted because the scientific data are not sufficient yet
to support it, and users could overstate the findings. From a regulatory perspective, there will
never be a time when complete information is available for integration into policy. Regulatory agencies often address this issue by employing the precautionary principle.

Regulating noise exposure through permit processes and assessments of environmental impact has the advantage of potentially being flexible to address specific situations, but it can also make it difficult to implement policy changes in a timely manner. Additionally, because of a lack of information and the slow pace at which science is completed, criteria are necessarily applied across diverse situations, which makes maintaining consistency in regulation difficult. Gathering new data takes time, and codifying it into regulation also takes time. Guidelines can be quicker to implement than laws, but regulatory guidelines are only “suggestions” for best practice and are only as good as the extent to which they are voluntarily followed and updated. Resources for enforcement are limited, which impacts reliable monitoring and oversight of mitigation. Furthermore, NMFS regulation covers major activities like seismic exploration. It does not cover the majority of sound producing activities which operate at a smaller scale, such as fish finders and boat motors, particularly recreationally in coastal waters. As a result, currently regulatory practices for wild dolphins do not address the subtlety and range of effects of noise in wild dolphin habitats.

**Managed Care.** Few noise policies or guidelines have been developed for dolphins under human care. While NMFS actively regulates acoustic activities to some degree for wild animals, APHIS does not for managed care animals. It has been proposed that the sound of pumps, music and other anthropogenic sources in managed care populations causes stress and harms the hearing of managed care marine mammals (e.g. EAAM, 1995; 2011). Similarly, concerns have been raised about pool acoustics at the other extreme, that the environment is
acoustically sterile, affecting sound production (e.g. Clark, 2013). However, little research has been performed to substantiate either of these claims.

Considerable veterinary research has extended the life of dolphins under human care. A recent report on dolphins in the U.S. Navy Marine Mammal Program using data collected from 2004 to 2013 provided the median lifespan as 30.1 years, which is higher than that reported for wild dolphins (Venn-Watson, Jensen, Smith, Xitco, & Ridgway, 2015). However, aside from veterinary care, research on managed dolphins has primarily focused on applications to wild animals. Managed populations are more easily accessed for studies that cannot be performed in the wild, although limited diversity of species requires extrapolation of results across species boundaries (Houser, Finneran, & Ridgway, 2010). Ironically, although considerable bioacoustic research has been performed with managed care dolphins, the results of such studies often do not feed back into the welfare of dolphins under human care. While many aspects of the managed dolphin environment are controlled, including space requirements, water quality, social needs, enrichment, and food, the soundscape is not highly managed, nor in most cases is it known.

Few management procedures and practices address acoustic impacts, and those that do are both voluntary and limited. Couquiaud (2005), proposed loose acoustics guidelines for indoor and outdoor pool design. Noise sources of major concern were those typically associated with facility construction or maintenance – e.g. drilling, explosions or pile driving activities. Other noises of potential concern included life support systems and distortion from the pool walls. At the heart of the concern for these types of sound exposures is that, unlike wild dolphins, managed dolphins cannot leave the area.

Couquiaud advised that acoustics should be considered in the planning of a facility and discussed explicitly with contractors. Dolphins should not be exposed to loud background or
sudden noises and periodic monitoring should be employed to check for changes in the acoustic environment. Facilities should not be located near shipping, dredging, or drilling activities, e.g. marinas and shipyards. Pool construction should consider irregular, varied non-geometric shapes, from natural materials (versus concrete), and the walls should be slanted (e.g. at a 10 degree angle) towards the outside. This minimizes artificial echoes. To reduce high frequency background noise, filtration plants should use low noise pumps and be placed away from pools, with buffering underneath and insulation of pipes. Moving parts, including floating platforms, gates and latches should be padded with rubber joints. The in-air environment should be protected from noise as well, for the benefit of the dolphins and the human staff.

Two well-known groups that extend membership to certain facilities compliant with inspection procedures are the Alliance of Marine Mammal Parks and Aquariums (AMMPA) and the broader Association of Zoos and Aquariums (AZA). The AMMPA code of best practices includes that facilities “[e]nsure that dolphins are not exposed to noises of sufficient intensity or type within their range of hearing to cause auditory discomfort or distress to the animals” and “[a]coustically isolate sound-generating mechanical equipment and have a plan in place to monitor equipment noise” (AMMPA, 2013). However that is the entirety of the discussion. The AZA bases facility accreditation decisions on the size and “nature” of animal accommodations and on the physical and psychological welfare of the animals, the latter of which can be difficult to determine. While instructions to assess sounds are not explicitly described in the handbook, acoustics could be considered part of the “nature” of the accommodations.

Since acoustics are not heavily regulated through law or membership criteria, responsibility falls mostly to the individual institution. Some aquariums are involved in acoustic research (e.g. Scheifele et al., 2012), and some aquariums have installed full time sound
monitoring systems (e.g. Gaydos & Bahan, 2014). A challenge in these types of efforts is that they require trained acoustics experts for set-up, maintenance and interpretation, which are not typical of individual institution resources. The status of regulations for managed care dolphins differs greatly from that of wild dolphins.

**Best Practices**

Noise policy for managed populations is practically non-existent. Available research is often not incorporated into policy. Monitoring for dolphin health and welfare, both physical and psychological, is challenging but advancements are being made. An example of physical monitoring is hearing tests. Behavioral hearing tests have been the standard for marine mammals, though rely on a long and involved training process (Schlundt, Dear, Green, Houser, & Finneran, 2007). New methods developed using Auditory Evoked Potentials, measuring brain waves in response to sound, provide a faster approach and enable more options for hearing testing and more animals to be tested (Finneran et al., 2008; Finneran, Mulsow, & Houser, 2013; Finneran, Mulsow, Schlundt, & Houser, 2011). An example of psychological monitoring is evaluation of stress. Advances in blood analysis of stress hormones (e.g. cortisol, aldosterone) under varied conditions (e.g. Copland & Needham, 1992; Houser, Yeates, & Crocker, 2011; Waples & Gales, 2002) is improving our understanding of the role of factors such as timing and adaptive response in these indicators.

Types and levels of sound are not currently regulated for managed populations. While major data gaps exist, especially assessment of managed dolphin soundscapes and evaluation relative to wild environments, we do know that some sounds have physiological and/or behavioral effects on dolphins as discussed. To avoid behavioral and hearing disruptions,
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dolphins would need to be protected from sounds likely to cause even the briefest TTS
(Nachtigall et al., 2004; Schlundt et al., 2000; Southall et al., 2007), and especially from very
loud sounds in the more sensitive part of the dolphins’ hearing range, e.g., levels over 190 dB re:
1 µPa, between 1kHz and 32kHz. Duration thresholds should also be considered, as longer
duration sounds likely have higher impact (e.g. Mooney et al., 2009). This should be investigated
further through more research on habituation and sensitization effects, and over longer
timescales (days and weeks versus minutes and hours). As with wild regulations, different levels
of sound could be designated as having different levels of impact. Acceptable noise thresholds
could vary in frequency for different species to account for differences in sensitivity. An
advantage is that much of the science informing wild regulations comes from research in
managed care environments, however much important data are still needed.

Preventing problems is preferred to reacting to problems (e.g. EPA, 2015). In this regard,
establishment of acoustic monitoring - which forms the basis for evaluations of both short and
long term effects, and enables identification of sound levels and types, setting baselines, tracking
changes, and making comparisons - should be implemented in dolphin facilities. For continuous
monitoring, different facilities present different problems (e.g. management, coordination,
logistics, expertise) and each facility will need to implement monitoring that is both effective and
feasible given its constraints. However, periodic monitoring could be achieved by incorporating
it as part of self-inspection processes, or as part of approval by membership organizations (e.g.
AZA, AMMPA). Known noise-producing projects should be planned well ahead of time and
should identify additional monitoring of dolphins and potential mitigation measures.
Additionally, new facilities and facility upgrades are opportunities by which recommendations
for improving noise conditions can be implemented during the construction phase (e.g.
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Couquiaud, 2005). While the approach to monitoring that would be best for collecting data is monitoring a very wide frequency range (e.g. 100Hz-160kHz), 24-7, this is probably generally unrealistic in terms of equipment, time and expertise resources that would be required to collect and interpret the data. Rather, a standardized sampling approach similar to those used in wild sites – e.g. 30 seconds every 15 minutes - would provide a more manageable amount of data that could be supplemented with more continuous monitoring if there were particular activities of interest. The larger the frequency range monitored the better, but even a relatively small frequency range (e.g. 100 Hz - 20 kHz) would be useful, and many sounds of concern such as construction sounds that may extend into higher frequencies have lower frequency components that could be used to identify sound sources. Data management plans would ideally be set up to facilitate sharing of recordings among facilities and researchers to enable more comparisons to be made.

It is difficult to determine what sounds may be stressful for a particular group of dolphins. It may be that certain sound properties are important, and/or that familiarity with the sound is important. The acoustic monitoring would be even more valuable if combined with other types of behavioral and physiological monitoring of the dolphins. Physiological monitoring could include hearing tests, fecal or blood collections for stress hormones, and periodic health assessments; behavioral monitoring could include observations for baseline or aggressive/annoyance behaviors (e.g. chuffing, tail slaps).

A way to gain more perspective on variation in stress response would be to investigate preference. One method would be to observe and compare time spent in regions with differing sound properties, and to collect other physiological and behavioral data. Another more interactive way to address this would be to provide some degree of choice and control to the
dolphins over their soundscape. In a limited fashion this could be accomplished via a “dolphin radio,” with paddle presses triggering a different type of sound to be played. In this way a dolphin could indicate preference for one sound type over another by the relative number of presses or amount of time it was played.

Implementation of policy will require overcoming challenges of working with commercial facilities. On a voluntary basis, i.e. if policy is in the form of guidelines, challenges include implementing monitoring plans that can accommodate schedules and routines, determining acceptable and effective facility instrumentation, preventing animal access to recording devices, and providing appropriate training to facility personnel on the use, analysis, and interpretation of acoustic data. Professional organizations providing memberships to facilities could address this by suggesting and facilitating protocols for setting up useful research and monitoring programs. Also, training could be provided for all levels of staff to help get their involvement and support, monitor changes in the environment and in behavior, and to enable more research to be conducted because staff could be more actively involved.

Policy at all levels (individual facilities through global agreements) would be ideal, beginning with membership organizations and from there working both bottom-up and top-down. Membership organizations can provide individual facilities with needed information, support and incentives, while providing a unified voice to inform larger scale regulations. These organizations are also well positioned to receive input from diverse stakeholders including scientists, trainers, and veterinarians in the process of proposing, revising and implementing new policies.

Policy can be guided by comparing soundscapes of facilities with the natural environment. Concerns have been raised that facilities are too noisy, or are too acoustically
sterile, however these claims have not been evaluated. There are important gaps in scientific information on managed soundscapes. A very basic one is, what are the common sounds, and further, how do they compare to wild soundscapes? Also, more information is needed about the effect of noise on dolphins in managed-care environments, including, what sounds do dolphins prefer, are dolphins stressed by noises they are exposed to, and, are dolphins sensitized or habituated to the noise? Another important area to address is the impact of long term noise exposure. This knowledge is critical baseline information for developing effective policy. Needs described in this paper could be addressed top down, bottom up, or in some combination. These are areas where funding needs to be provided and scientists need to be involved. The following list suggests priority actions for scientists, facilities, funding organizations, membership organizations and policymakers to improve existing guidelines, policies and protocols for managed dolphin populations.

A) Soundscape monitoring, in managed and wild habitats to enable comparisons

Soundscape monitoring involves collecting and analyzing data. Recordings necessary for characterization of soundscapes and comparisons among managed and wild habitats could be collected through deployment of autonomous marine passive acoustic monitoring systems that can be programmed with a sampling schedule, e.g. 30 seconds every 15 minutes (e.g. Lammers, Brainard, Au, Mooney, & Wong, 2008). These systems have many advantages over portable devices, especially because they do not require constant human presence. Recording and analysis could be done by appropriate experts. (For further discussion see Chapters 2 and 3.)
B) Research on effects of noise, in particular preferences, stress, sensitization/habituation, and long-term impacts

Research on the effects of noise as it relates to stress could be accomplished by characterizing long term trends in stress hormones obtained from voluntary samples (e.g. feces, blood) and comparing to wild populations. Over the long term, comparisons could also be made within the same individual, and with known noise-exposure events.

C) Research on pool acoustics, including product development and testing for altering the soundscape/reverberation

Acoustic characteristics of different important sounds – e.g. dolphin phonations, construction noise, echoes – could be assessed under different pool conditions – e.g. pool shape, material. Alterations of pool acoustics could be accompanied by behavioral observations, physiological measures, and/or preference measures.

D) Education/training in acoustics for staff

Education and training should be for all staff, but especially staff who have the opportunity to observe the animals. The successful model of citizen science monitoring for invasive species (e.g. Delaney, Sperling, Adams, & Leung, 2008)
could be used to inform design of educational materials to help staff recognize behaviors or sounds of potential concern. Training could include providing and explaining use of checklists — a simple but effective tool gaining popularity in healthcare facilities (e.g. Van Klei et al., 2012) — for steps to take to prepare for and mitigate construction or other sporadic noise producing activities.

E) Standardization of measurements

Comparisons of dolphin habitats are complicated by different research studies using not only different stimuli and conditions, but also different methods of measurement or reporting on the measurements in different ways. A preliminary step is to ensure that the type and methods of measurement are reported, e.g. distance from the animal or sound source, and also units and reference levels. Further steps involve developing and employing standardized measurement and analysis techniques across facilities and recordings, e.g. addressing both sound level and spectral analysis by calculating Power Spectral Density and Sound Pressure Level. This is in addition to other more targeted research studies for which other metrics might be appropriate.

F) Facilitation of access to information

All actions to improve policy would be facilitated by easier access to information. This includes scientific information that is understandable and synthesizable, and information on what other facilities or regions are doing. With better data and more
informed use of that data, it is possible to make better decisions. Access is facilitated by making publicly available an online database dBPod, discussed in the next section, which models a potential method to improve data accessibility and distribution, and facilitates addressing disparities between research on cognition, sensory systems and behavior, and established policy and best practices.

Online Database

Management of noise with relevance to the impact it has on marine mammals has caught both public and regulatory agency interest, but it remains under-represented in policy. A challenge for addressing this need is the limitation in current online search options that focus on this topic. Currently available tools, such as Google scholar, may facilitate finding indexed literature but do not assist in the identification of gray literature (e.g. governmental reports) nor the synthesizing of information in this topic area. Lack of standardization (e.g. the reporting of units for sound exposure) complicates searching for, and finding patterns in, research and policy works related to sound and marine mammals.

Addressing the need to improve access and integration of information on policies and practices related to dolphin noise exposure and monitoring, this paper presents the development of a new online interactive website and searchable database – “The dolphin Bioacoustics Policy online database (dBPod): Find documents about the effects of sound on dolphins and related practices.” The dBPod is designed to facilitate improved management of marine mammal populations that primarily rely on acoustic signaling and hearing as their primary sensory modality. To support this goal, dBPod provides a compilation of existing public information on both managed and wild populations, related to sound policies, practices, exposures and
responses. This enables greater public access to research findings and policy discussions relevant
to dolphin care and welfare, thus enabling greater public engagement in policy development,
facilitating policy discussion through consolidation of accessible information.

**Structure.** Consideration of the information and search options required focused on the
goals of providing static pages of information, but also interactive searchable content. The
database would not necessarily provide direct access to documents themselves, due to
consideration of copyright laws, but would provide a way to find out that the documents exist,
what they contain, and if they would be of interest to the user. Setting up the site required design,
construction and revision of the database itself and of the interactive features. The process was
iterative, as decisions about interactive features affected database design and vice versa.

**Content management.** For the Content Management Platform, Drupal 7 provides a
balance of flexibility and usability. The site platform is expected to continue to be supported for
approximately 8 years. Drupal 8 was considered but rejected because it was still in beta-testing at
set-up time. Drupal is open-source. It provides a core on which to build custom functionality
with various optional modules. Strong points of Drupal over WordPress for this project include;
the ability to create more advanced search options, and to organize data in taxonomy structures
(as opposed to a more linear blog format). Document entries can be labeled with multiple layers
of category information, all of which can be searched.

Database construction was based on content type creation. A new content type, “pod,”
was created by designating the number (30), names (e.g. title, sound sources, species) and types
(e.g. text, integer) of fields into which data could be entered. Methods of information entry were
also designated (e.g. text field, check boxes). The fields were created based on considerations of how the data would be accessed and searched for. This required extensive consideration of how to categorize different aspects of the included documents, especially sound characteristics that, as discussed, are not clearly categorized but needed to be searchable and sortable. Through the ‘Views’ module, an underlying Taxonomy structure was created. This structure includes the categories/vocabulary supporting the categories of information and the search features. One type of field is called term reference, which means a term from the taxonomy, and using this type enabled taxonomy terms to be included in pod content. (For the Taxonomy definitions and explanations of categories / fields see Appendix A.) Due to the wide variety and nuance of sound classification, emphasis in dBPod was made on sound sources, which correlate with properties of the sounds and highlight the target source for policy making. After creation of the pod structure, document information was entered into the available fields. This involved finding, reading and pulling information from a variety of documents.

**Interaction.** Three methods chosen for options to interact with the data are; filter, browse, and search. The browse method enables the user to sort the document entries by one parameter, e.g. year. The filter method provides lists of categories from which the user can decide what types of information to include or exclude, e.g. only shipping noise. The search method enables the user to do a keyword search.

Sometimes, differences in terminology or usage of jargon can obscure meaning and make searching for information more difficult. With dBPod, I have provided explanation of jargon and enabled different users with different backgrounds to access and understand the same information where possible. Additionally, related terms are linked. For example, acute versus
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chronic exposure is an important concept, but “acute” and “chronic” are defined differently by different users. So these terms are defined in the context of dbpod tags that set up specific definitions based on quantifiable time periods that can be applied more concretely to referenced documents, but still relate to the concept of acute versus chronic.

Access. The dBPod database can be accessed for free online at “dbpod.graciass.net” and is hosted on the server of the CUNY New Media Lab.

The database is meant for a broad range of anticipated users, including stakeholders, politicians, policy analysts, educators, scientists, and activists. Usage will be tracked as possible. Anticipated usage is for accessing very specific areas of information, as well as synthesizing larger areas of information and identifying needs, leading to proposing policy changes to address the needs.
Chapter 2

Bioacoustic Characterization of a Coastal Marine Soundscape in Quintana Roo, Mexico

Introduction

Wild dolphins are exposed to a variety of biological and other natural and anthropogenic sounds. The most common and high amplitude sound in tropical and subtropical coastal waters globally is due to snapping shrimp, which provide an ecologically important sound used as a navigational cue by larval fish, coral and crustaceans (Montgomery, Jeffs, Simpson, Meekan, & Tindle, 2006). It is a broadband sound that dolphins encounter in the wild, and potentially influences their acoustic ecology via masking (Branstetter & Finneran, 2008). Other biological sounds include fish and other marine mammals, whereas abiotic sources of natural sounds include earthquakes, storms, and lightning strikes. Some of these latter events, though transient in nature, can produce sounds of extremely high amplitude and broad bandwidth (e.g. lightning strikes). Anthropogenic sources dominate low-frequencies (100 - 500 Hz), primarily from shipping and seismic exploration; construction and sonar also contribute to low- to mid-frequency (100Hz – 25 kHz) ocean noise (Hildebrand, 2009).

Dolphin responses to sound can be grouped into physiological and behavioral responses, a categorization scheme that has been employed in prior assessments of the impact of anthropogenic sound on marine mammals (Navy, 2013). Types of physiological effects documented include tissue damage, temporary and permanent hearing threshold shifts, and changes in heart rate, stress hormone levels, and immune function (Jepson et al., 2003; Miksis et al., 2001; Romano et al., 2004; but see Houser, Yeates, Crocker, Martin, & Finneran, 2012). Many of the more severe effects are due to the sound being of high amplitude whereas other
responses may be more contextual in nature (e.g. stress responses). Behavioral responses are wide ranging and might include subtle changes in respiration, brief changes in orientation, fluke slapping, changes in phonation patterns or levels, mother calf separations, changes in dive behavior, and abandonment of foraging or breeding. Indeed, site avoidance responses have been exploited in fisheries management; pingers and acoustic deterrents on gillnets are designed to cause avoidance responses by dolphins (Burke, 2004; Cox, Read, Swanner, Urian, & Waples, 2004; Tyack, 2008; Waples et al., 2013; Wartzok, Popper, Gordon, & Merrill, 2003), although responses can be variable and some dolphin populations habituate rapidly to the deterrent, putting them at risk of the nets.

The physical characteristics of sounds are likely important to the probability and magnitude of a response from a sound-exposed dolphin, e.g. frequency, duration, rise time, bandwidth, amplitude, etc. Marine dolphins generally hear within the 150 Hz-160 kHz range (higher than human hearing, within 20 Hz - 20 kHz), with decreased sensitivity at the lower and upper frequencies. Not all received sound is distracting or harmful and some sounds may be considered either useful or neutral. Other sounds hold particular importance to dolphins, including phonations from other dolphins and return echoes from echolocation. Different types of phonations are used in different behavioral contexts; for example, different phonations may be used to accommodate different spatial distances of communication (Lammers, Schotten, & Au, 2006). The presence of sound, whether it causes a response or not, can also potentially mask phonations or other acoustic cues. Auditory masking is a form of acoustic interference in which

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1 Note that very few humans or dolphins can hear the whole range. Many sounds go undetected at the extreme frequencies.
perception of a signal by the receiver is affected by the presence of another sound. Signals that can be masked include conspecific acoustic communication, foraging and mating calls, as well as other biotic and abiotic cues such as predator and reef sounds. Masking can result in altered activity patterns and space over which communication can occur, and the amplitude and frequency of repetition of acoustic calls, and can thus potentially affect group cohesion, social dynamics, and energetic costs associated with communication (Janik, Parijs, & Thompson, 2000; Jensen, Beedholm, Wahlberg, Bejder, & Madsen, 2012).

Acoustic environments of dolphins vary regionally, due to differing biotic (e.g. species) and abiotic (e.g. weather) factors. Comparisons of similar habitat types across regions reveal differences in the soundscape patterns such as the daily cycles of sounds, e.g. diel patterns of coral reef sound in the Atlantic and Pacific oceans (Lammers, Brainard, Au, Mooney, & Wong, 2008; Staaterman, Rice, Mann, & Paris, 2013). Acoustic patterns can also vary with depth (e.g. deep water versus coastal reef), latitude, and proximity to human activities. In the United States, the NOAA CetSound project is mapping marine mammal presence via acoustic monitoring of phonations and in relation to anthropogenic noise (NOAA, 2013). Passive acoustic monitoring (PAM) can provide long term data to compare acoustic patterns between habitats, which is important, since many dolphins or populations of dolphins may exploit different habitats due to migration, adding spatial variation to the temporal variation in soundscapes experienced by the animals.

Several species of dolphins, including bottlenose dolphins (Tursiops truncatus), have been documented in the MesoAmerican Reef (MAR) region; however, there is little to no scientific monitoring of these populations. The MAR is the largest barrier reef system in the Western hemisphere and is second only to the Great Barrier Reef globally. Located in the
Caribbean Sea, it extends over 1000 km from the tip of the Yucatan peninsula in Mexico along the eastern coast of Central America to the Bay Islands in Honduras. The MAR ecosystem dynamics include significant upwelling in the north, which draws migratory species for feeding, and rich biodiversity throughout, including a wide variety of corals, algae, fish, crustaceans, cephalopods, sharks, and dolphins. It is world renowned for its coastal tourism, especially Cancun, Mexico which receives millions of visitors per year (over 4 million in 2013) (CCVB, 2014). Threats to ecosystem health come from a variety of anthropogenic factors including water pollution such as sewage and agricultural run-off, over-harvesting of commercial species, invasive species, and physical touching of corals. Threats also come from natural factors, such as storms, which have caused coral bleaching events (McField et al., 2005).

The sounds experienced by dolphins in the MAR region are as yet undокументed. Despite the salience of the MAR, scientific research in the region is sparse. A Google-Scholar general-search on “Great Barrier Reef” yielded approximately 191,000 results, whereas searches of “Mesoamerican Reef,” “Meso-American Reef,” and “Belize Barrier Reef” (a portion of the reef classified as a Protected Area by the International Union for the Conservation of Nature) combined yielded only approximately 14,896 results – a difference of more than an order of magnitude. Results were mainly research articles and technical reports. Investigations conducted in the MAR region to support conservation efforts typically rely on sporadic visual surveys. Visual surveys can provide information on species presence and abundance, but can only be completed under good weather and visibility conditions, with trained observers, and when resources permit. On the other hand, PAM has the potential to provide needed data to acoustically characterize dolphin habitat. It is relatively low cost, and can operate autonomously,
collecting data regularly during the day and night and during bad weather conditions. This approach can enable characterization of the soundscape of a location over time.

Characterizing the soundscape of wild dolphins on a section of the MAR would facilitate understanding the acoustic nature of this dolphin habitat. The present study involved conducting PAM for one year at a MAR site off the coast of Quintana Roo, Mexico, a site where dolphins are known to frequent (R. de la Parra, pers. comm.). Sound types are described, and where possible, sources are identified, including whether or not they are anthropogenic. It is predicted that the soundscape will be dominated by natural sounds, mainly broadband sound from snapping shrimp, with a daily cycle of occurrence. Recording at regular intervals over one year provides a measure of seasonal and daily variation. Furthermore, the monitoring provides a context for comparing the variability and range of sounds encountered in various managed populations, and enable differences to be identified and explored for potential benefits to the welfare of managed care dolphins.

Methods

Location. The recording site was just north of Isla Mujeres, Quintana Roo, Mexico [21° 17' 37" N 86° 45' 10.2" W] with a depth of 13 meters (Figure 1). The northern tip of Isla Mujeres was approximately 3 km to the south. The coast of Quintana Roo, north of Cancun was approximately 6km to the west. Isla Contoy was approximately 20 km to the north. The continental shelf was approximately 100 km to the east. The area of ocean to the west of Isla Mujeres was protected by the island and designated as a national marine protected area (“Parque Nacional Costa Occidental de Isla Mujeres, Punta Cancún y Punta Nicuz”).
Boat traffic was common at the site and surrounding region, including within the Protected Area where it was permitted but regulated. Boat traffic included many small fishing boats and three ferries operating three to nine round-trips daily from the mainland. The site itself was not a recreational destination but boats passed through the area and fishing was permitted at the site. The site was part of the same coral barrier reef as the protected area. The seafloor was sea grass and sand with patchy coral cover, having been disrupted when a fiber optic telephone cable was installed. The species present consisted of many passing pelagic species including barracuda, king fish, tuna, jacks, manta rays and dolphins.

**Recording.** Acoustic recordings were collected using a stationary hydrophone system, the Ecological Acoustic Recorder (EAR), attached to a mooring resting on the sea floor (Lammers et al., 2008). The EAR hydrophone was a Cetacean Research Sensor Technology SQ26-01, an omnidirectional hydrophone with flat sensitivity up to 28 kHz and a fixed gain of 44 dB. The EAR was programmed to record 30 seconds of audio every 15 minutes at a sampling rate of 64 kHz. Note that the range of the flat frequency response of the hydrophone and the sampling rate employed limits the frequency band to the lower end of the dolphin hearing range (which can extend up to 150 kHz). However, the frequency range monitored does encompass the frequency range of communication signals such as whistles and enables detection of echolocation clicks (although not the accurate characterization of frequency content). No filtering was performed during recording.

For deployment and retrieval the site was accessed by boat, and a team of divers installed and collected the EAR system on the sea floor at a depth of 13 m. The system was deployed and recordings were made from November 22, 2011 to May 28, 2012. The EAR was then taken out
of the water for data retrieval and system maintenance and was redeployed from June 1, 2012 to November 30, 2012.

**Analysis.** Binary recorded files were retrieved from the internal hard drive of the EAR after the end of each recording period and transferred to a computer. A log text file documented the time and date of each recording. Recordings were screened by ear to check for anomalous or artifact sounds. Files were to be excluded if more than 50% of the file was clipped (i.e. sound amplitudes exceeded the dynamic range of the recording system); however, no such recordings were found. Clipped portions of files were identified and excluded from root-mean-squared sound pressure level (RMS SPL), power spectral density (PSD)\(^2\) and 1/3 octave band sound pressure level analyses.

Analyses involved both quantitative and qualitative methods. The binary files were converted to wav files using MatLab (MathWorks, Natick, MA), and processed with an FFT size of 8192 bins and windowed with a Hanning window. Spectral analysis was conducted by calculating the PSD and 1/3 octave band sound pressure level for twelve 24-hour periods – one per month over the year of recordings. PSD and one third octave band analysis were also conducted for a recording obtained during Hurricane Ernesto on August 8, 2012, and for one month, September 15 to October 15. Clipped portions of files, corresponding to voltages where \(x>1.249\) V and \(x\) is the absolute value of the recorded voltage, were excluded from analysis. The means and 5% and 95% confidence intervals were calculated from non-clipped portions of the

\(^2\) Sometimes called Noise Spectral Density (NSD)
file. Results were analyzed for a frequency band between 100 Hz-28 kHz; the 100 Hz high-pass was instituted because of concern about potential low-frequency filtering associated with the hardware setup (M. Lammers, pers. comm.) and the 28 kHz low-pass was instituted to consider only the flat region of the recording hydrophone and to avoid aliasing.

The RMS SPL was calculated from each 30 second binary file to examine day/night cycles and other patterns in the overall sound pressure level. Clipped portions of files were identified and calculations were obtained after removing one second of sound before and after the clipped portion. The RMS SPL was then plotted as a function of time throughout the day and across days.

Spectrograms were also obtained. Files were converted to wav format and plotted in Raven (Bioacoustics Research Program, The Cornell Lab of Ornithology, Ithaca, NY) with a window size of 1024.

Random samples of 100 files (50 from each deployment period) were examined in detail to identify (when possible) sources of biotic, abiotic and anthropogenic sounds. Additional files of interest, e.g. with notable sound events determined through the screening process, were also examined. Sound sources (such as snapping shrimp and boat motors) were identified based on audio playbacks and spectrogram analysis.

**Results**

Between November 22, 2011 and May 28, 2012, a total of 18,036 30-second audio files were recorded; 18,035 files were included in the analysis (one was excluded because of the sound of SCUBA equipment during deployment – the area is not normally a dive site). Between June 1, 2012 and November 30, 2012, a total of 17,194 30-second files were recorded; 17,189
files were included in analysis (five were excluded because of sounds from deployment). In total 35,224 recording files were available for analysis, representing 136.5 GB of data.

The mean PSD calculated for each sample day of each month of the year is presented in Figure 2. Originally, December 14, 2011 was used as a sample day, but revealed a much higher PSD than the other sample days throughout the year. This was found to be due to a storm. The following day, Thursday, December 15 2011 was therefore used instead. The noise PSD was greatest between 5 and 10 kHz and between 500 Hz to 1000 Hz. Overall, the frequency-dependent variation in noise PSD ranged from 55-75 µPa²/Hz. The variability was mainly below 1 kHz, as values were relatively stable above 1 kHz.

One third octave band spectral analysis was calculated for the same 12 days and is presented in Figure 3. Peaks were found at similar frequency ranges as for the PSD, however the overall sound was more constant across the 1/3 octave bands. Overall sound levels ranged between 70 and 120 dB RMS SPL across the frequency range analyzed. While mainly stable across the year, the months of December, March, June and November had elevated mid-frequency sounds (~500 – 5,000 Hz). Natural weather events altered the frequency distribution of the sound, e.g. the PSD and 1/3/octave band analysis for Hurricane Ernesto, which occurred on August 8, 2012 with elevated high frequency abiotic sounds (Figure 4).

The average RMS SPL was 115 dB (SD=1.6; min=110; max=137) for both deployments and was stable across both deployments; 115 dB RMS SPL for the first deployment (SD=1.6; min=110; max=137) and 115 dB RMS SPL for the second deployment (SD=1.5; min=91.5; max=116.4) (Figures 5-7). A diel pattern was observed with higher RMS SPL occurring at dawn and dusk (Figures 5-7). Spikes in the RMS SPL and maximum SPLs generally occurred during daylight hours. Based on .wav file playback and spectrographic analysis, for all files exceeding
130 dB RMS SPL the source of the higher SPLs was determined to be boat motor sounds (Figures 8-9). There was some variation across the year in daily peaks, with greater frequency in January, February and July. Variation around 115 dB remained relatively stable throughout the year, however periods of reduced sound level were observed in March and June, and to a lesser extent in April and October.

Snapping shrimp, fish, boat motors, and surface waves were identified as the major sound sources within the soundscape. Broadband snapping shrimp sounds were persistent throughout the recordings. Fish sounds were clearly present in 88% of the recordings (based on a random sample of 100) (Figure 10). This is a conservative estimate as it is possible that low-level fish sounds may not have been distinguishable due to masking from boat motors, wave action, or snapping shrimp. The frequency range for fish sounds was approximately 100-1000 Hz, and the sounds were often pulsed (Figures 11-12). The species composition of vocal fish at the site was unknown, however during deployment and retrieval site visits many bluestriped grunts (*Haemulon sciurus*) were observed. These fish make similar sounds to those recorded (DOSITS, 2015). Boat motors were clearly present in 12% of the recordings (Figures 10, 13). Boat motor noise is broadband across the recording spectrum in some cases and more tonal in others (Figure 14), which is possibly reflective of the different makes and models of boat motors and whether they are outboard or inboard. If boat motor noise was identifiable in any portion of a recording, it tended to be identifiable throughout the recording, although the amplitude and tonal characteristics could show variability. Surface waves were faint but audible in the majority of files, which reflects the shallow depth at which the recorder was placed.
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Discussion

The soundscape at the Isla Mujeres recording site was typified by natural sounds, however there was important periodic contribution by anthropogenic sources. Broadband sound of snapping shrimp was persistent throughout and was the greatest noise source in almost all recordings. The daily pattern in the ambient noise consisted of increases in noise at dawn and dusk, mainly due to snapping shrimp activity. This aspect of the pattern in soundscape variability is consistent with other sites globally, such as in Hawaii (Lammers et al., 2008), and in New Zealand (Radford, Jeffs, Tindle, & Montgomery, 2008). Other aspects of the daily cycle, such as comparison of levels between day and night, are more variable. Different patterns can occur over time and also within regions, for example two sites in Hawaii with opposite patterns (Lammers et al., 2008). Monthly or seasonal patterns were not distinguishable as the noise characteristics were very consistent across these measurement periods; indeed, the daily and hourly variation and patterns in noise were stronger than the monthly variation.

Sound production by fish was pulsed and common in the low-frequency (100 – 1000 Hz) band, and might be produced by *H. sciurus*. Sound production mechanisms in grunts are not clearly known, though recent research on French grunts (*Haemulon flavolineatum*) provides evidence for specialized jaw movements, where teeth grinding produces stridulatory sounds with the main frequency around 700 Hz (Bertucci, Ruppé, Van Wassenbergh, Compère, & Parmentier, 2014). This is similar to the acoustic pattern observed in recordings from Isla Mujeres, though fish sound production can vary greatly among related species (Fine & Parmentier, 2015) and *H. sciurus* may differ from *H. flavolineatum*. Sounds were frequent but generally not overlapping and chorusing was not observed.
Boat motor noise was sporadic - however, when present it was responsible for large spikes in the noise. When boat noise was present it could exceed the ambient noise (in the absence of a boat) by 20 dB. Since distance to the vessels could not be determined, there could be potentially much higher amplitude at closer distances. Boat motor noise tended to be present throughout recordings where it was identified, but consecutive recordings did not tend to have boat motor noise. Thus, the presence of boats appeared to be transient within the region. Boats were likely crossing the site but not stopping, or boats powered off motors if remaining in the area. Boat motor noise contributed to higher RMS SPL levels during the day than in the night and appeared to contribute to noise between 500 Hz – 25 kHz, which is consistent with sounds made by small vessels (Hildebrand, 2009).

Surface waves were the most notable abiotic contributor to the soundscape, and while less prevalent than shrimp or boat motor sounds, their low frequency components could mask fish sounds. During the recording period, the most recognized storm event was Hurricane Ernesto on August 7-8, 2012. Rain and surf sounds are clearly evident in recordings obtained during this period. Elevated RMS SPL during this period would be expected; however, this was not readily apparent. Spectrographic analysis from a recording sampled during the storm reveals high frequency (15 – 28 kHz) pulses. One-third octave band analysis contained acoustic energy which was relatively level across frequencies but with high variation across time, and the PSD analysis revealed greater contribution at higher frequencies (Figure 4).

Some unexpected periods of ambient noise reduction were observed (Figures 5-6), but the reason for the drop in sound levels was not clear and occurred across frequencies. Possible explanations are an overall difference in level of snapping shrimp activity, possibly related to weather, or perhaps small-scale abiotic weather changes. Review of archived online weather data
for the region revealed drops in wind speed at approximately the same times as the drops in ambient noise; however, this is not sufficient to conclude that weather was the cause. Similarly, the reason for patterns of higher mid-frequency noise in certain months is unclear. June is high season for whale sharks and thus higher sound levels could be explained by greater small vessel traffic, however this does not explain the pattern during winter months.

Patterns of PSD and 1/3 octave analyses were similar for sample days across the year. This indicates that seasonal patterns were not strong over the year of recording. It could be that recording for multiple years would provide a context for identifying seasonal patterns. There could also be aspects of the sampling scheme that obscured patterns or changes, which could potentially have been investigated using more frequent sampling and additional parameter calculations.

Dolphins are commonly sighted in the area (R. de la Parra, *pers. comm.*) but dolphin phonations were not detected in the recordings. This could be due to an absence of dolphins in the region, or that dolphins in the region were insufficiently close to the EAR for communication or echolocation signals to be recorded. Given the commonality of dolphin sightings in the region, the latter explanation seems the most likely. Dolphins tend to be acoustically active creatures producing whistles and other acoustic signals for communication and social cohesion and it seems unlikely that they would be present but quiet. Observational behavioral data concurrent with wider band recordings need to be collected in order to correlate dolphin presence with acoustic activity.

Anthropogenic characteristics of this soundscape have implications for dolphin welfare. While boat motor noise is not as frequent as fish sounds nor as pervasive as snapping shrimp sounds, when it is present it potentially overwhelms the natural soundscape. Similar to the way
many cases of boat motor noise masked fish and other sounds in the analysis for this study, boat motor noise could potentially mask cues and communication sounds for dolphins. This could interfere with foraging, navigation and/or communication.

Other behavioral and physiological effects, such as the production of stress hormones, are possible (see Chapter 1). Dolphins have been found to have responded to boat traffic in a variety of ways, from increasing synchronous breathing (Hastie, Wilson, Tufft, & Thompson, 2003), to changing acoustic behavior (Buckstaff, 2004), to avoiding the area (Lusseau, 2005), all of which may also be associated with a stress response. Stress responses in dolphins are not well understood, and existing research on stress responses to acoustic stimuli are generally related to short-term exposures (Esch, Sayigh, Blum, & Wells, 2009; Romano et al., 2004).

Dolphin habitat soundscape patterns at the Isla Mujeres site are dominated by natural sounds, but also prominent boat motor noise throughout the year that may impact dolphin physiology or behavior. This area is outside of the protected area site, and boats are not regulated as they are within the protected area. Sounds heard at the recording site would also probably be heard in much of the protected area and vice versa. The finding that boat motor noise is a major contributor to the soundscape of this dolphin habitat highlights the need for further research to determine whether additional boat traffic regulation would support effective protection of the site.
Figure 1. Map of Isla Mujeres site. EAR deployment location is at the yellow circle.
Figure 2. Waterfall plot of Power Spectral Density calculated over 24 hours on every second Wednesday for one year at Isla Mujeres site, December 2011 - November 2012. (December 14 was replaced by December 15.)
Figure 3. Waterfall plot of 1/3 octave band spectral analysis calculated over 24 hours on every second Wednesday for one year at Isla Mujeres site, December 2011 - November 2012.  

(December 14 was replaced by December 15.)
Figure 4. (Next two pages) Plots of acoustic analysis during Hurricane Ernesto. (A) PSD, (B) one third octave, and (C) spectrogram, for midnight on August 8, 2012. (Supplemental audio 2.1)
Figure 5. RMS SPL for Isla Mujeres site 1st deployment November 22 2011 to May 28 2012 (top) and magnified view (bottom) of noise reduction occurring approximately between samples 11,500 and 12,000 and between samples 14,000 and 15,000, corresponding to March 21 to March 26 2012 and April 16 to April 26 2012 respectively

(Dark bands indicate night – 6:30pm to 6:30am; clipped portions of files were removed)
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Figure 6. (Next two pages) (A) RMS SPL for Isla Mujeres site 2nd deployment June 1, 2012 to November 30, 2012 (top) and magnified view (bottom) of a dip occurring approximately between samples 1500 and 3000, corresponding to June 17 through July 2 2012. (B) (top) PSD and, (bottom) RMS SPL, for one month at Isla Mujeres Site, September 15 to October 15 2012. (Dark bands indicate night – 6:30pm to 6:30am; clipped portions of files were removed)
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A
Figure 7. (Next six pages) RMS SPL averaged over 30 second files every 15 minutes by month. RMS SPL averaged by month, by deployment period, and overall from November 22 2011 to November 30 2012. n=number of files; std=standard deviation; min=minimum; max=maximum. Smaller n in May is due to retrieval period where the equipment was out of the water for maintenance and data collection. (Calculations were made after clipped portions of files were removed)
October

November
Figure 8. (Next two pages) Power Spectral Density (A) and 1/3 octave band (B) calculated for each 30 second recording from 6am to noon on September 4, 2012. Spectrograms for the (C) 9:45am (Supplemental audio 2.2) and (D) 10:00am (Supplemental audio 2.3) recordings illustrate the variation due to boat motor noise.
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**Figure 9.** (Next two pages) Spectrograms of 5 example files with average RMS SPL > 130 dB. High values were determined to be due to motor noise. (Supplemental audio files 2.4-2.8)
Figure 10. Bar graph comparing percentage of recordings containing distinguishable sound produced by fish versus sound produced by boat motors (n=100).
Figure 11. Spectrograms of low-frequency sound production by fish. (Supplemental audio files 2.9-2.10)
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Figure 13. (Next two pages) (A, B, C) Spectrograms of recordings with boat motor noise (Supplemental audio 2.14-2.16) compared with (D) a spectrogram without boat motor noise (Supplemental audio 2.17)
Figure 14. (Next three pages) (A) Spectrogram of highly tonal boat motor noise at ~4 kHz (Supplemental audio 2.18). (B,C,D,E) Other spectrograms of distant boat motor noise (Supplemental audio 2.19-2.22)
Bioacoustic Characterization of Facilities with Managed Dolphin Populations in Quintana Roo, Mexico

Introduction

Bottlenose dolphins are the most common marine mammal maintained in managed care facilities. Various types of facilities maintain bottlenose dolphins, including swim-with-dolphins companies, zoos, aquaria, and the U.S. military. Facilities are found worldwide, on all continents excluding Antarctica. Animal welfare considerations generally required of facilities include space requirements, water quality, food and feeding procedures, physical habitat characteristics, human interactions, and dolphin sociality and interactions (Couquiaud, 2005). Some aspects of dolphin welfare are regulated through legislation and intergovernmental agreements (see Chapter 1). In the United States, the Animal and Plant Health Inspection Service (APHIS) (part of the United States Department of Agriculture (USDA)) inspects public display facilities for compliance with Animal Welfare Act guidelines on water quality, space, transportation and handling, food, and veterinary care (e.g. (Spotte, 1991). APHIS not only enforces but sets new standards to match changes, such as the rapid growth of the swim-with-dolphins industry (APHIS, n.d.). Further voluntary standards are established through membership-granting organizations such as the Alliance of Marine Mammal Parks and Aquariums, which has members in the U.S. and in other countries (AMMPA, 2013).

Dolphins are socially complex and their phonations are essential to all aspects of their life history, including development and reproduction (Connor, 2007; Fripp et al., 2005; Tyack & Clark, 2000). They also rely on echolocation to navigate their environment and hunt food.
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(Harley, Putman, & Roitblat, 2003; Hastings & Au, 2012). Concerns have been raised by animal welfare groups about the potential for pool acoustics to impact the welfare of dolphins maintained under human care. Hypotheses about the acoustic impact of facilities on dolphin welfare come at two extremes – noisy and acoustically sterile. Ironically, the two need not be mutually exclusive. There is speculation that welfare issues arise from anthropogenic noise at dolphin facilities, mainly music and mechanical operations such as pumps (e.g. (EAAM, 1995; 2011), whereas other speculations focus on the lack of biotic sounds and complex objects/textures as inhibiting the natural use of acoustics, most specifically echolocation (e.g. Clark, 2013). To address potentially noisy environments, water pumps and other machinery in dolphin facilities are often designed to reduce energy loss in the form of noise. To address potentially acoustically sterile environments, various acoustic enrichment schemes have been suggested and investigated. These include introduction of objects to induce echolocation behavior (e.g. Delfour & Beyer, 2012) and playbacks of dolphin phonations (e.g. Kristiansen, 2008). However, the effect of the acoustic environment within dolphin facilities, if any, on dolphin welfare has not been established and whether enrichment strategies are needed or effective in addressing the speculative claims has not been ascertained.

Some recordings of dolphins and other animals, especially fish, are taken in tanks; however, the recordings are generally not designed to characterize the acoustics of the tank habitat (e.g. Conti, Roux, Fauvel, Maurer, & Demer, 2006; Rountree et al., 2006). Furthermore, research in this area is limited, in part, because of the logistical challenges of working at managed care facilities. Permissions to deploy equipment in dolphin facilities may be met with resistance and methods have to be flexible to meet the particular scheduling and other needs of the facility and staff. Recordings that are made may be considered proprietary making
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comparisons with other facilities difficult. Furthermore, the efforts generally require personnel experienced in underwater acoustics to be on-site as there are few dolphin facilities with personnel trained in underwater acoustics.

A few studies of pool acoustics have been performed in indoor facilities, most notably at the Georgia Aquarium where there was an assessment of spillover of music into a beluga exhibit (Scheifele, Clark, et al., 2012) and an assessment of noise and vibration in dolphin tanks (Scheifele, Johnson, et al., 2012). The former study examined whether music from nearby events could be detected in recordings in the beluga tank, and whether that might pose problems for the belugas. A resulting recommendation from that study was that sound pressure in the ballroom should be kept under 95 dBA (A-weighted sound pressure level (dB re: 20 µPa) based on human hearing thresholds with reduced sensitivity at low and high frequencies) such that the in-tank RMS SPL is kept under 120 dB re: 1 µPa at frequencies of 1kHz and above (Scheifele, Clark, et al., 2012). The other study measured noise from life support systems of a newly constructed bottlenose dolphin exhibit before animals were introduced. They found that there was minimal overlap of life support system noise with dolphin hearing (Scheifele, Johnson, et al., 2012).

Outside of these studies, there exists little reportable information on noise conditions experienced by dolphins, or marine mammals in general, maintained at managed care facilities.

Evaluation of claims about the deleterious acoustic nature of dolphin facilities requires characterization of the average noise levels at the facilities, and assessment of variability due to anthropogenic activities and sounds produced by the animals (as well as other biotic and abiotic contributions). Measurements should be compared to similarly collected data within natural environments inhabited by the same or similar species. This study investigates the acoustic environment for a group of outdoor dolphin facilities in Quintana Roo, Mexico. The soundscape
is characterized at each of four acoustically distinct facilities, compared to one another, and with measurements from a wild dolphin habitat (Chapter 2). It is hypothesized that pools will have lower sound levels than a wild location due to having lower levels of non-mammalian biological noise, and that the most common and high amplitude sound sources will be the dolphins themselves. If non-biological sound is a major contribution to the noise budget, then it is hypothesized that it will likely be dominated by the water quality and management facilities (e.g. pumps). Due to the impedance differences between air and water, the contributions of music broadcasts and other sounds (e.g. from tourists) in air are expected to be minimal. It is further hypothesized that the greater the biological and physical differences of a pool from the ocean habitat, the greater the acoustic differences will be from the natural environment. Lower levels of non-mammalian biological noise, high contribution of non-biological sounds, and/or other acoustic differences from the natural environment would indicate potential areas to target for further investigation because the differences in the animals’ acoustic environment would differ from the acoustic habitat to which they are adapted. Such differences and their potential impact on dolphin welfare remain uninvestigated.

Methods

Facilities. The dolphin facilities investigated in this study are maintained by Delphinus/Via Delphi Institute for Research on Marine Mammals. The Delphinus dolphinariums are outdoor pool facilities located on the eastern coast along the Mexican Caribbean, and from south to north are named Xel Ha, Xcaret, Riviera Maya, and Interactive Aquarium (Figure 1). Each site consists of outdoor pools, some of which are interconnected and separated with water permeable barriers, mainly gates that have holes that allow water flow, but which may also be
opened to allow dolphins to pass from one pool to the next. Fixed and floating platforms and walkways allow trainers, veterinarians and visitors to access different pools. Pools vary in size and shape. Xel Ha has an approximate area of 2,220 m² with an average depth of approximately 3.5 m. Xcaret has an approximate area of 1,300 m², with an average depth of approximately 3.5 m. Riviera Maya has two parts connected by a small tunnel; for the section in which the EAR was deployed the approximate area is 760 m² with an average depth of approximately 3 m. Interactive Aquarium has an approximate area of 808 m² with an average depth of approximately 3.5 m.

While the sites are all managed by the same organization, they are structurally different. The sites can be qualitatively ranked in order of similarity to natural environments, from lesser to greater, based on the physical and biological qualities of the pool habitats: Interactive Aquarium, Riviera Maya, Xcaret, Xel Ha (Table 1). The Interactive Aquarium is the most unique of the sites. The pools at the Interactive Aquarium are made of concrete and are smooth, whereas the other sites are made of natural rocks. The water is pumped and filtered at Interactive Aquarium whereas natural water influx provides the primary water circulation method for the pools at the other sites. Interactive Aquarium is located near a lagoon but is not directly connected to it. The pool water is clear, and there are no other species such as snapping shrimp or fish living in the pools with the dolphins.

Riviera Maya has two sections of pools, one that is close to the ocean separated by a rock wall and a second that is longer and narrower and which is connected to the first by a narrow tunnel. The pools are mainly separated by plastic fencing beneath wood platforms, making for generally open connections between the pools. The pool bottoms are mainly level and covered with rocks, mud and seaweed masses. There are other species present, including fish and
snapping shrimp. Natural water influx is supplemented with pumps used in the afternoons to recirculate the water.

Xcaret pools are located in a bay open to the ocean. Pools are similarly partitioned as in Riviera Maya and the pool bottoms of the facilities are also similar. Other marine species are present in the pools, including fish and snapping shrimp, and there is natural water influx and outflow.

Xel Ha pools are adjacent to the ocean but surrounded by rock. The bathymetry at Xel Ha is complex, with many rocks and boulders. Pool partitions are mainly plastic fencing, and there are other marine species present, including fish and snapping shrimp. Pool water is cycled via natural water influx and outflow.

**Dolphins.** Delphinus facilities house bottlenose dolphins (*Tursiops truncatus*) in small groups. Group composition is managed and sometimes varied in response to social interactions, breeding behavior (e.g. male rut), and births. Since births occur throughout the year, the population represents a wide range of ages, including juveniles. During the periods of the recording sessions reported here, there were approximately 20 dolphins at Xel Ha, 23 at Xcaret, 26 at Riviera Maya, and 8 at Interactive Aquarium. Dolphins were mainly adults with some juveniles, in mixed groups (age and sex) of 2-8 individuals, often with related dolphins. At Xcaret and Interactive Aquarium there were also mothers and dependent calves.

**Recording.** Acoustic recordings were collected using a stationary hydrophone system, the Ecological Acoustic Recorder (EAR) (Lammers, Brainard, Au, Mooney, & Wong, 2008) (Table 2). The recording hydrophone within the EAR system is a Cetacean Research Sensor
Technology SQ26-01, an omnidirectional hydrophone with flat sensitivity up to 28 kHz and a fixed gain of 44 dB. The frequency band over which recordings were made does not cover the entire range of hearing of the dolphin, but it does encompass the frequency range for communication signals such as whistles, and enables detection of echolocation clicks (though not accurate characterization of their frequency content). The EAR was programmed to record 30 seconds of audio every 15 minutes at a sample rate of 80 kHz.

In September to October 2014, the EAR was deployed at Xel Ha, Xcaret, Riviera Maya and Interactive Aquarium (Table 2). The EAR recorded at least 24 hours at each location, with 68.75 hours at Xel Ha (September 24-27), 44.5 hours at Xcaret (September 27-29), 24.25 hours at Riviera Maya (September 29-30) and 47.25 hours at the Interactive Aquarium (September 30-October 2). Deployment involved securing the EAR to a large stone mooring with ropes, and lowering it to rest on the bottom of a pool (using SCUBA). Specific locations were determined in consultation with Delphinus staff, addressing considerations that included avoiding common pool entries and exits, avoiding disruption of operations, and separating equipment from the animals so that they would not interact with it (Figure 2). At Xel Ha, the EAR was located on a low flat shelf near a corner of a large pool (approx. depth 3 m). At Riviera Maya, the EAR was located in the second section close to the center of a large pool (approx. depth 3 m). At Xcaret, the EAR was located near the plastic fencing barrier between two central pools (approx. depth 3.5 m). At Interactive Aquarium, the EAR was located in the center of a smaller holding pool connected to a large pool (approx. depth 2.5 m).

Each facility was sampled over a minimum of 24 hours to encompass the range of daily activities experienced by the dolphins (Table 2). The dolphins were part of programs to interact with the public, primarily in swim-with-dolphin programs that occurred during the day. Dolphins
interacted daily with trainers for feeding and training and were also tended to by veterinary staff, as needed. Pool cleaning occurred daily. In Xel Ha, Xcaret and Riviera Maya dolphin trainers used brushes to clean the platforms and remove algae, and used rakes to remove leaves or other objects that may have fallen into the pools. In the Interactive Aquarium, in addition to a 24-7 mechanized filtration system, there are dedicated pool cleaning staff that uses brushes and a siphon. Siphoning is performed once per day. Construction events are not routine practices; however, some construction events were captured during the recording time period. These were small maintenance or structural projects rather than large events such as creating new pools. Information was collected about activities at the facilities during the sample recording times to provide context for the recordings. This was achieved through discussions with staff and consultation of logs of schedules and maintenance. For a subset of recordings, activities were verified through visual observation.

**Analysis.** Binary recording files were retrieved from the internal hard drive of the EAR after the end of each recording period and transferred to a computer. A log text file documented the time of each recording and enabled the time and date to be known for each file. Recordings were screened by ear to check for anomalous or artifact sounds. Files were to be excluded if more than 50% of the file was clipped (i.e. sound amplitudes exceeded the dynamic range of the recording system); however, no such recordings were found.

Analysis involved both quantitative and qualitative methods. Spectral analysis was conducted by calculating the power (noise) spectral density (PSD) and 1/3 octave band sound pressure level. Binary files were converted to wav files using MatLab (MathWorks, Natick, MA), processed with an FFT size of 8192 bins and windowed with a Hanning window. The PSD
was calculated for each site. Clipped portions of files, corresponding to voltages where $x > 1.249$ V and $x$ is the absolute value of the recorded voltage, were excluded from analysis. The mean PSD and 1/3 octave sound pressure levels, as well as associated 95% confidence intervals, were calculated from non-clipped portions of the file. Clipping was generally due to dolphins echolocating directly on the hydrophone.

The root-mean-squared sound pressure level (RMS SPL) was calculated over each 30 second file to examine day/night cycles and other patterns in the overall sound pressure level. Clipped portions of files were identified and calculations were made after removing one second before and after the clipped value.

Spectrograms were also obtained. Files were converted to wav format and plotted in Raven (Bioacoustics Research Program, The Cornell Lab of Ornithology, Ithaca, NY) with a window size of 1024.

Random samples of 100 files (25 from each deployment period) were examined in detail for biotic, abiotic and anthropogenic sounds. Additional files of interest, e.g. showing high or unusual sound events, were also examined. Sound sources (such as snapping shrimp and pool cleaning) were identified based on audio playback and spectrogram analysis.

Comparisons were made among facilities with respect to the broadband RMS SPL, 1/3 octave band sound distribution, and sound PSD. Individually identified sources were compared to determine their individual contributions to the soundscape. Data from Delphinus facilities were also compared with data from a wild site, Isla Mujeres (described in Chapter 2) in order to characterize the similarities/dissimilarities between the managed-care and the wild environments.
Results

Between September 24, 2014 and October 2, 2014, a total of 739 30-second audio files were recorded at the four Delphinus facilities sampling over a collective 184.75 hours. At Xel Ha, 275 files were recorded over 68.75 hours from September 24 to 27. At Xcaret, 178 files were recorded over 44.5 hours from September 27 to 29. At Riviera Maya, 97 files were recorded over 24.25 hours from September 29 to 30. At Interactive Aquarium, 189 files were recorded over 47.25 hours from September 30 to October 2.

Xel Ha, Xcaret and Riviera Maya were more similar to each other than with Interactive Aquarium for both PSD and the 1/3 octave band analyses (Figures 3-6). The sound PSD measured at these three sites was flatter across the measured frequency bands than sounds from the Interactive Aquarium (Figures 3, 5). The Interactive Aquarium had the highest PSD values overall, with contributions mainly coming from between 100 – 1000 Hz (Figure 5). The Interactive Aquarium also showed less variation in PSD and 1/3 octave band analyses (Figures 3-6). Analyses using 1/3 octave bands showed similar results, with Interactive Aquarium having higher 1/3 octave band SPLs than the other three sites, particularly in the 100 – 1000 Hz range (Figures 4, 6). Variation however was more similar across sites for 1/3 octave bands than for PSD (Figures 3-6).

The average broadband RMS SPL within all of the facilities was greatest at Xcaret (mean=117.3±4.7 dB) and Xel Ha (mean=115.5±3.4 dB), which were over 6 dB higher than the average broadband RMS SPL at Riviera Maya (mean=108.5±2.7 dB) and Interactive Aquarium (mean=109.1±1.6 dB). The overall average was 113.4 ±4.9 dB. Xcaret followed by Xel Ha had higher than overall average RMS SPL, and Interactive Aquarium followed by Riviera Maya had
lower than average. Variability in the broadband RMS SPL was greatest at Xcaret followed by Xel Ha, Riviera Maya and Interactive Aquarium (Table 3; Figure 7).

Xel Ha and Xcaret demonstrated a daily pattern of two noise peaks per day, one roughly around dawn and the other roughly around dusk. Based on audio playback, this was largely due to increased dolphin sound production. The peaks were elevations of approximately 5 - 10 dB over the average level. Riviera Maya and Interactive Aquarium appear to have higher RMS SPL and more variability during the day than during the night, which seems to be due to variations in dolphin phonation activity as well as anthropogenic sounds. At Xel Ha, there is a distinguishable pattern of dolphin phonations being more prevalent during the day than during the night, which is also apparent in the 1/3 octave bands corresponding to the main range of dolphin vocalizations (approximately 1 – 20 kHz) (Figures 4, 6).

Based on audio playbacks and spectrogram analysis of the random samples (n=100, 25/site), common sound sources were dolphins, shrimp, fish, and various anthropogenic sources. Overall, 73% of recordings clearly contained phonation sounds from dolphins, 75% had snapping shrimp, 13% had fish and 37% had anthropogenic sounds (Figure 8). Snapping shrimp were broadband, short duration pulses and fish vocalizations were generally low frequency (approximately 100-1000 Hz) pulsed sounds. Dolphin phonations were varied, including squawks, buzzes, and whistles (Figure 9). At Xel Ha, 8% of the reviewed recordings had dolphin sounds, 100% had snapping shrimp, 8% had fish and 28% had anthropogenic sounds. Anthropogenic sound sources were varied, and were mainly rattling of the platform as it was being walked on, cleaning with a brush, and voices. At Xcaret, 100% of the recordings had dolphin phonations, 100% had shrimp, 36% had fish, and 16% had anthropogenic sounds. Anthropogenic sounds consisted mainly of platform rattling and pool cleaning with a brush. At
Riviera Maya, 96% had dolphin sounds, 100% had shrimp, 8% had fish, and 4% had anthropogenic sounds. Anthropogenic sounds were generated mainly by cleaning activities, although there may be other sounds from circulating water or movement of people in the water that were not clearly distinguishable. At the Interactive Aquarium, 100% of files contained sounds from pumps. In 8% of the files, dolphin phonations were still distinguishable. Dolphin phonations were surely more prevalent but were difficult to identify due to the constant pump sounds. No fish or shrimp were present. For other anthropogenic sounds, hammering was present in 8% of files. At Xel Ha, Xcaret and Riviera Maya, splashing was clearly present in some recordings, but it was not clearly attributable to either dolphins or people.

Structural coupling of construction noise, mainly hammering, was observed at Xel Ha and Interactive Aquarium (Figure 10). While sounds in air do not transfer well into water, there are situations where this sound leakage can occur. Noise from surface construction leaked into Xel Ha and the Interactive Aquarium pools. Additionally, sounds from movement of the platforms propagated into the water, e.g. from walking. While rare, it was possible also for in-air human voices to be detected underwater, though the content or context was not distinguishable.

Distinctive brush cleaning sounds were identified at Xel Ha, Xcaret and Riviera Maya (Figure 11). The brushes were used by hand and were not mechanical. The sounds were similar across sites – broadband and short in duration (approximately 0.5-1.5 seconds), with short but slightly longer intervals (generally approximately 1-2.5 seconds). The sounds were distinguishable even when overlapping with dolphin phonations.

Some recordings had minimal dolphin and human activity and the background noise could be examined. Interactive Aquarium had no snapping shrimp yet the RMS SPL was found to vary over time, primarily due to pump noise (Figure 12). The pump noise was persistent, even
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though there was variation across recordings, presumably due to different components of the life support system working at different times. There was generally little variation in the pump noise within a recording.

Discussion

Facilities differed from each other in soundscape characteristics. Contrary to expectations, sites with more natural characteristics i.e. Xel Ha and Xcaret actually had higher RMS SPL than Interactive Aquarium and Riviera Maya. They also had more variability. However, spectral analysis reveals that Interactive Aquarium differs greatly from the other sites, particularly in its high levels of low-frequency sounds. Further analysis through listening and spectrograms strengthens the clarity of the difference of this site from the others, with the most common and high amplitude sound being pump noise at Interactive Aquarium, versus biological sounds at the other sites.

The most common and high amplitude sound sources were expected to be the dolphins themselves, and while dolphins were found to be a major sound source, snapping shrimp were also pervasive at Xel Ha, Xcaret and Riviera Maya. At Interactive Aquarium, non-biological sound was the main contribution to the recordings. As expected, in this environment the source was water circulation pump systems. Fish and shrimp were absent. Unlike the pervasive mechanized pump cleaning system at Interactive Aquarium, pool cleaning by hand with a brush can be heard at Xel Ha, Xcaret and Riviera Maya for a small portion of the day (<20%). This sound is nevertheless very distinctive and clear in the recordings in which it is present. The presence of this sound at Xcaret both with and without many dolphin phonations indicates that the phonations were probably not a response to the cleaning sounds. That said, during site visits
it was observed that dolphins were generally more active and vocal when people were present in the immediate vicinity.

Taken together, results do indicate that the greater the biological and physical differences between the pool and the ocean habitat, the greater the acoustic differences from the natural environment, especially in the case of Interactive Aquarium relative to the other dolphinariums. The differences among the other three sites were more subtle, and may indicate less importance of bathymetry and sporadic recirculation as distinguishing features. In the case of RMS SPL, Interactive Aquarium is distinguished not so much by a difference in average level, but by lesser variability, due in large part to the fact that the most persistent high amplitude sound is pump noise. A possible criticism of this is that the EAR deployment in this location was more protected from direct dolphin interaction, which would contribute to the assessment of lesser contribution by dolphins to this soundscape. A counter hypothesis is that the dolphins vocalize less due to the structure of the facility. This would require further investigation. In either case, the continual presence of the pump noise, and lack of snapping shrimp, are the major differences from the soundscapes of the other sites (Figures 8, 12).

Part of the pump system was visible nearby (approx. 5 meters) to the recording area however time constraints did not permit in depth assessment of the system. The system includes multiple pumps, with equipment dedicated to filtration, chlorine generation, skimming and other functions. Especially due to proximity to the pool structure, additional buffering and insulation could greatly mitigate pump noise in the pool.

While as expected in-air sounds did not have a major contribution to the underwater soundscape, some coupling was observed for human-generated sounds. Sound does not transfer efficiently from air to water, but solid structures coupled to the water will facilitate sound
transfer. Structural coupling can transfer sounds with little loss of acoustic energy compared to the transfer of acoustic energy from air to water. Coupled construction sounds (mainly hammering – Xel Ha and Interactive Aquarium) and people walking on the floating platforms (Xel Ha and Xcaret) were clearly identifiable. This is an important consideration for mitigation of noise, especially since it can be unexpected because of the usual negligibility of in-air sound transfer.

The Delphinus facilities share similarities and differences with a wild soundscape (Figures 6-8, 13; also see Chapter 2). Shrimp and fish sounds were common at both. Waves were present at both, however presumably due to different causes (weather versus human or dolphin movement). Anthropogenic sounds were present at both, but sources differed (e.g. boat motor sounds at the wild site, cleaning sounds at the dolphinariums). For RMS SPL for the same time of year, Xel Ha, Xcaret and Riviera Maya sites generally had more variability than Isla Mujeres site. Riviera Maya and Interactive Aquarium were lower in RMS SPL than Isla Mujeres (Figure 7, Chapter 2 Figure 6). Interactive Aquarium had a higher overall noise PSD than the wild site, and Xel Ha, Xcaret and Riviera Maya generally had a lower distribution of noise PSD than the wild site. The wild site was mostly flat across the frequencies measured, with a slight rise toward higher frequencies. This contrasts particularly with Interactive Aquarium, characterized by greatest contributions to the noise PSD at frequencies below 1 kHz. The findings highlight the importance of spectral analysis versus RMS SPL measurements alone in monitoring of dolphin habitats.

The Delphinus facilities were neither clearly noisier nor more sterile overall than the wild site, but rather differed in particular characteristics. Compared with the wild location at Isla Mujeres, lower overall sound levels were hypothesized for Delphinus facilities, and two of four
facilities had lower RMS SPL (Riviera Maya and Interactive Aquarium) and three of four had lower PSD than the wild site (Xel Ha, Xcaret and Riviera Maya). This is in part due to having lower levels of non-mammalian biological noise, as expected. However, other sounds, in particular pump noise in the case of Interactive Aquarium, are strong contributors to the soundscape patterns (Figure 12). The wild site also had periodic anthropogenic additions to the soundscape – boat motor noise. Boat-motor noise is sporadic and more common during the day, whereas pump noise is persistent. Boat-motor noise is also more variable in frequency content than the pump noise, depending on factors which include motor type (e.g. inboard or outboard) and speed. More naturalistic sites, Xel Ha and Xcaret, had a day-night cycle comparable to the wild site with peaks of RMS SPL occurring approximately around dawn and dusk. As with the wild site, the pattern is in part due to snapping shrimp acoustic activity, however unlike the wild site dolphin activity patterns have a major contribution to this pattern at the managed care facilities.

Dolphins do not hear equally well across different frequency bands, so it is important to consider the findings in the context of dolphin hearing sensitivity. Bottlenose dolphins and other marine dolphins, which are considered mid-frequency specialists among cetaceans, generally have measured hearing ranges within the 150Hz-160kHz range (Brill, Moore, & Dankiewicz, 2001; Finneran & Houser, 2006; Houser & Finneran, 2006; Johnson, 1968; Popov, Supin, & Klishin, 1996). Audiograms provide context for dolphin sensitivity at different frequencies (Figure 13). Based on auditory evoked potential hearing measurements, bottlenose dolphins appear most sensitive above 10 kHz, especially in the 30 – 100 kHz range (Finneran et al., 2008). Patterns of 1/3 octave band noise were similar for the Isla Mujeres site and the more natural sites, e.g. Xel Ha, but the Interactive Aquarium had higher levels overall and especially in the lower
frequencies (Figure 13). Though there was elevated noise at Interactive Aquarium compared with the other facilities and the wild site, the highest 1/3 octave band noise levels at Interactive Aquarium were actually at lower frequencies than the dolphins’ more sensitive range (Figure 4, 13). For the wild site, the highest 1/3 octave band noise levels were around 10 kHz, slightly lower than the dolphins’ most sensitive frequency range. SPL (1/3 octave) levels seem to fall off moving up towards 100 kHz, though the highest portion of the range could not be measured in this study. Boat motor noise is strongest in lower frequency components but includes noise in the dolphins’ more sensitive range. Interestingly, the high frequency noise generated by hurricane Ernesto at the wild site is in the dolphins’ more sensitive range (Chapter 2 Figure 4).

Implications of these findings are encouraging for dolphin welfare. First, sound levels were unlikely to cause threshold shifts in hearing because RMS SPL levels were below those anticipated to cause TTS at frequencies below 10 kHz (Southall et al., 2007). Clipping was very minimal (only portions of five files were affected) and less than for the wild site, and unlikely to change this pattern. Second, in three of four facilities, prominent biological sounds in the wild site – snapping shrimp and fish sounds – were present, meaning that the dolphins at these facilities are experiencing biotic features of the soundscape they would be adapted to in wild soundscapes. Third, the anthropogenic sounds experienced at the facilities (construction and cleaning sounds) (Figures 10-11) did not reach the levels of the anthropogenic sounds experienced at the wild site (boat motor sounds) (Chapter 2 Figures 7-8, 12-13). Fourth, the highest noise levels for anthropogenic sounds fall outside the dolphins’ most sensitive hearing range.

This study provides the foundation for further investigation into the implications of managing soundscapes for managed dolphin habitats. Sources of particular interest and possible
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care are pump and construction noise. Pump noise is potentially a constant presence, but may vary in amplitude depending on the number of pumps operational at any given time. This provides an interesting situation to investigate the extent to which dolphins habituate to the pump noise due to its constant presence, and/or whether they respond to changes in amplitude. Contrastingly, construction noise can be highly variable, involving continuous sounds (e.g. drilling) and/or pulsed sounds (e.g. hammering, pile driving). Each tool has a different acoustic signature. Sound varies also with distance and materials being operated on. Construction timing could be planned and behavioral responses observed to attempt to assess the possible effects of the construction noise on dolphin physiology and behavior. Additionally, coupling could be minimized through using lower noise tools, changing where and how tools are used, and buffering (Couquiaud, 2005). The changes in acoustic characteristics of the anthropogenic sound could be measured and matched with behavioral responses assessed through passive acoustic monitoring and visual observation.
### Table 1. Physical and biological characteristics of the dolphinariums

<table>
<thead>
<tr>
<th>Facility</th>
<th>Construction</th>
<th>Bathymetry</th>
<th>Water Circulation</th>
<th>Shrimp &amp; Fish</th>
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<td>Concrete</td>
<td>Smooth</td>
<td>Pumps</td>
<td>No</td>
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<td>Rock</td>
<td>Simple</td>
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</table>

### Table 2. Recording schedule from September 24 to October 2, 2014

<table>
<thead>
<tr>
<th>Facility</th>
<th>Deploy Date</th>
<th>Deploy Time</th>
<th>Retrieve Date</th>
<th>Retrieve Time</th>
<th># Samples</th>
<th>Total Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xel Ha</td>
<td>Sept 24</td>
<td>14:30</td>
<td>Sept 27</td>
<td>11:30</td>
<td>275</td>
<td>68.75</td>
</tr>
<tr>
<td>Xcaret</td>
<td>Sept 27</td>
<td>14:45</td>
<td>Sept 29</td>
<td>11:30</td>
<td>178</td>
<td>44.50</td>
</tr>
<tr>
<td>Riv. Maya</td>
<td>Sept 29</td>
<td>14:00</td>
<td>Sept 30</td>
<td>14:30</td>
<td>97</td>
<td>24.25</td>
</tr>
<tr>
<td>Int. Aqua.</td>
<td>Sept 30</td>
<td>17:45</td>
<td>Oct 02</td>
<td>17:15</td>
<td>189</td>
<td>47.25</td>
</tr>
</tbody>
</table>

### Table 3. RMS SPL averaged by facility. n=number of files; sd=standard deviation; min=minimum; max=maximum.

<table>
<thead>
<tr>
<th>Facility</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xel Ha</td>
<td>275</td>
<td>115.5</td>
<td>3.435</td>
<td>110.0</td>
<td>130.8</td>
</tr>
<tr>
<td>Xcaret</td>
<td>178</td>
<td>117.3</td>
<td>4.746</td>
<td>109.4</td>
<td>128.4</td>
</tr>
<tr>
<td>Riviera Maya</td>
<td>97</td>
<td>108.5</td>
<td>2.673</td>
<td>105.2</td>
<td>116.3</td>
</tr>
<tr>
<td>Interactive Aqua.</td>
<td>189</td>
<td>109.1</td>
<td>1.646</td>
<td>107.2</td>
<td>118.0</td>
</tr>
</tbody>
</table>
Figure 1. Map of Delphinus facilities, from North to South: Interactive Aquarium, Riviera Maya, Xcaret and Xel Ha.
Figure 2: Photos and diagrams of Delphinus facilities, including location of EAR deployment indicated by a yellow star.
Figure 3. Waterfall plots of Power Spectral Density over 24 hours (in one hour bins) from midnight to midnight at four Delphinus dolphinarium sites: Xel Ha (September 25, 2014), Xcaret (September 28, 2014), Riviera Maya (September 29-30, 2014), and Interactive Aquarium (October 1, 2014). Note: Range of PSD axis varies in order to display detail. At Riviera Maya, hours 0-13 (i.e. midnight to 1pm) occurred the day after hours 14-23 (i.e. 2pm-11pm).
Figure 4. (Next two pages) Waterfall plots of 1/3 Octave band over 24 hours (in one hour bins) from midnight to midnight at four Delphinus dolphinarium sites: Xel Ha (September 25, 2014), Xcaret (September 28, 2014), Riviera Maya (September 29-30, 2014), and Interactive Aquarium (October 1, 2014). Note: Range of 1/3 octave axis varies in order to display detail. At Riviera Maya, hours 0-13 (i.e. midnight to 1pm) occurred the day after hours 14-23 (i.e. 2pm-11pm).
Figure 5. (Next two pages) Mean Power Spectral Density averaged across all samples for Delphinus sites:  Xel Ha $n=275$ recordings (68.75 hrs), Xcaret $n=178$ recordings (44.50 hrs), Riviera Maya $n=97$ recordings (24.25 hrs), and Interactive Aquarium $n=189$ recordings (47.25 hrs). Recording period: Sept 24 - Oct 2 2014. “Hrs” are total time over which recording sampling occurred. Shaded areas are 5% to 95% confidence intervals. Note: Range of PSD axis varies in order to display detail.
BIOACOUSTICS FOR DOLPHIN WELFARE

Riviera Maya

Interactive Aquarium
Figure 6. (Next three pages) Mean 1/3 octave band SPL (dB re 1 uPa) averaged across all samples for four Delphinus sites and the wild site: Xel Ha $n=275$ recordings (68.75 hrs), Xcaret $n=178$ recordings (44.50 hrs), Riviera Maya $n=97$ recordings (24.25 hrs), and Interactive Aquarium $n=189$ recordings (47.25 hrs). Delphinus recording period: Sept 24 - Oct 2 2014. Isla Mujeres $n=800$ recordings (200 hrs). Isla Mujeres recording period: Sept 24 – Oct 2 2012. “Hrs” are total time over which recording sampling occurred. Shaded areas are 5% to 95% confidence intervals. Note: Top range of 1/3 octave axis is extended to accommodate higher values for Interactive Aquarium site.
Interactive Aquarium
Figure 7. Comparison of the time-varying RMS SPL for Delphinus sites Xel Ha, Xcaret, Riviera Maya and Interactive Aquarium from September 24 to October 2 2014 (top) and Isla Mujeres site (bottom) for the same time period (Sept 24 – Oct 2) in 2012. (Dark bands indicate night – 6:30pm to 6:30am)
Figure 8. Bar graph of percentages of files with sounds present from dolphins, shrimp, fish and anthropogenic sources at each dolphinarium (n=25), overall (n=100) and compared to the wild site (n=100, see chapter 2) based on random sample. Dolphin sounds include whistles, squawks and clicks. Shrimp sounds are from snapping shrimp. Fish sounds are low frequency, pulsed sounds. Anthropogenic sounds include pump, cleaning and construction sounds for the dolphinariums, and boat motors for the wild site.
Figure 9. Spectrogram of example recording from Riviera Maya (September 30 2014, 11am) with varied dolphin phonations throughout. (Supplemental audio 3.1)
Figure 10. (A) Spectrogram depicting coupling of construction noise at Xel Ha site. Hammering is steady from 9s to 14s, followed by setting down metal tools (19-20s). Dolphin whistles are also present, as well as pulsed phonation between 9.5 and 11s. (Supplemental audio 3.2) (B) Spectrogram depicting coupling of hammering at Interactive Aquarium; the pulses are visible every .25 to 1 seconds in the lower frequencies <3 kHz (Supplemental audio 3.3.)
Figure 11. (Next two pages) Spectrograms of sounds of pool cleaning activity (vertical bars indicate scraping sounds) in (A) Xel Ha (Supplemental audio 3.4), (B) Xcaret (Supplemental audio 3.5), (C) Xcaret with overlapping dolphin phonations (Supplemental audio 3.6), and (D) Riviera Maya (Supplemental audio 3.7).
Figure 12. (Next three pages) Spectrograms of ambient soundscape during periods of low dolphin and human activity at (A) Xel Ha (Supplemental audio 3.8), (B) Xcaret (Supplemental audio 3.9), (C) Riviera Maya (Supplemental audio 3.10) and (D&E) Interactive Aquarium (Supplemental audio 3.11-3.12).
Figure 13. Third octave band analysis for wild site, Xel Ha and Interactive Aquarium compared with dolphin audiogram. Black line is dolphin audiogram (data from Houser, Gomez-Rubio, & Finneran, 2008). Blue line is Isla Mujeres, green line is Xel Ha and red line is Interactive Aquarium.
Conclusion

Dolphins are sonically oriented, so bioacoustics is of central importance in establishing effective policy. Chapter 1 described the need for acoustics policy for managed dolphin populations. Chapter 2 determined that boat motor noise was the major anthropogenic noise contributor to a wild dolphin habitat. Chapter 3 determined that dolphin facilities that were more biologically and physically similar to wild habitats also had more similar soundscapes. Findings from my dissertation research begin to address the six priority actions I described in Chapter 1, for scientists, facilities, funding organizations, membership organizations and policymakers to improve existing guidelines, policies and protocols for the welfare of managed dolphin populations.

A) Soundscape monitoring, in managed and wild habitats to enable comparisons

Chapters 2 and 3 described how I conducted soundscape monitoring in both a wild habitat and managed habitats. I used an autonomous marine PAM system to record day and night, and analyzed the data to assess and compare the soundscape characteristics. Overall the dolphin facilities were neither clearly noisier nor more sterile overall than the wild site, but rather differed in particular characteristics. Anthropogenic sounds of concern for further investigation were boat motor noise for the wild site, and construction and pump noise for the dolphin facilities. Spectral analysis and audio playback helped to identify important features of the soundscapes and should be incorporated in methods going forward.
Every dolphin facility should partner with bioacoustics experts to institute a PAM program. At a minimum, baseline testing for at least 24 hours should be done at every site, using sampling methods similar to those described in Chapter 3. Results should be published or otherwise made publically available. PAM should be repeated as often as possible to check for unexpected changes. Planned construction or other noise producing activities should be evaluated and buffering or other mitigation measures tested. PAM should be implemented and analyzed before, during and after to evaluate the effectiveness of the mitigation.

B) Research on effects of noise, in particular preferences, stress, sensitization/habituation, and long-term impacts

Chapter 1 describes possible mechanisms for studying preferences, including time spent in different locations of the pools, and a radio-like playback device the dolphins could operate themselves. In Chapter 3, I identified variation in pump noise as the potential basis for a study of habituation. Behavioral responses could be measured in response to changes in pump noise. Recordings at these facilities could continue and the collected data used as baseline data for noise-exposure events. With PAM alone, changes in phonations could be assessed; however, a more comprehensive data set could be achieved through combining this information with voluntary biological samples (e.g. blood, feces) for hormone analysis, i.e. behavior and physiology could be coupled.

C) Research on pool acoustics, including product development and testing for altering the soundscape/reverberation
BIOACOUSTICS FOR DOLPHIN WELFARE

Pool acoustics research includes describing the physical and biological characteristics of the pools and recording pool acoustics under variable conditions (e.g. pump operations, construction, trainer interactions). This was approached in Chapter 3 with the development and implementation of physical and biological screening and quantitative and qualitative acoustic ranking of facilities based upon recordings made throughout the range of normal activities at each site. Biophysical similarities to wild sites are likely good indicators of overall soundscape similarity, and could be used to inform plans for new facilities or changes to existing facilities. Pool locations and construction should be informed by priorities and considerations reviewed and described in this dissertation.

Investigations of dolphin preferences and hearing capabilities could potentially form the basis for developing new products and strategies for altering pool acoustics to improve the welfare of managed-care dolphins. Change can be disruptive, and altering acoustics might mean, for example, gradually providing buffering and other measures to mitigate entrance of anthropogenic sounds to the pool, e.g. construction noise.

D) Education/training in acoustics for staff

During the process of conducting research at the dolphin facilities, I provided acoustics training to staff, including administrators, veterinarians and trainers. This facilitated the research and increased the staff’s knowledge of how acoustics might impact the dolphins, as well as how their actions might contribute to the dolphins’ acoustic environment, either intentionally or unintentionally. The dBPod database could be used as a means to facilitate the building of
E) Standardization of measurements

Chapters 2 and 3 describe the development and use of standardized measurement and analysis techniques across facilities and recordings. Both sound level and spectral analysis were addressed by calculating power (noise) spectral density, 1/3 octave band and root-mean-squared sound pressure levels. Measurements were standardized in this study across the five measurement sites better enabling meaningful comparisons between them. Comparisons were also able to be made across situations and time – one year for the wild site, and at least 24 hours for the managed care facilities. Reporting of measurements in this study include appropriate set-up, reference levels and units information so that their meaning is clear. The dBPod database includes descriptions of different types of measurements, what they mean and how they relate to each other. Further investigations using similar methods and measurements could be conducted to enable comparisons with additional wild dolphin habitats, situations and time. Like procedures for measuring noise in terrestrial environments currently under evaluation, the standardization of recordings for dolphin facilities should be formally developed and approved through the Acoustical Society of America (ASA) and American National Standards Institute (ANSI).

F) Facilitation of access to information
BIOACOUSTICS FOR DOLPHIN WELFARE

All actions to improve policy would be facilitated by easier access to information. This includes scientific information that is both understandable and synthesizable, and information on welfare policies of facilities or other countries. With more informed use of available data, better welfare criteria can be established. Access can be facilitated by making publicly available an online database discussed in Chapter 1 (dBpod). This searchable information interface, included with the submission of this dissertation, models a method to improve data accessibility and distribution and facilitates addressing disparities between research on cognition, sensory systems and behavior, and established welfare policy and best practices.

The state of dolphin welfare under human care is improving with greater information. Acoustic regulations, though limited, for wild populations are lacking for managed populations. Dolphin facilities are neither clearly noisier nor more acoustically sterile than wild sites, but differ qualitatively. The results are encouraging for the welfare of dolphins under human care because levels are unlikely to cause threshold shifts in hearing, and the levels of the construction and cleaning sounds at the dolphin facilities do not reach the levels of boat motor noise at the wild site. Facilities vary, and biophysical similarities to wild sites are good indicators of overall soundscape similarity, especially whether water is circulated naturally or with a pump system. Yet this evaluation approach is not a replacement for PAM. The central role of bioacoustics for dolphins means that PAM is a basic life support requirement along with water and food testing. Periodic noise is of highest concern, and PAM is needed to inform mitigation of noise from periodic sources. More widespread and long-term standardized monitoring, further research on habituation, preference, coupling and pool acoustics, implementation of acoustics training, standardization of measurements, and improved information access are needed.
Appendix A

dBPod Taxonomy - Descriptions and definitions of Taxonomy terms in Drupal for dBPod

For dBPod, Taxonomy terms are used in the organization and tagging of documents. Taxonomy is a module within Drupal for classifying content. Taxonomy terms are grouped by ‘vocabularies’ and enable content to be organized in specific ways.

For each document in dBPod, information is entered. Some of this information is unique to the document, such as the Title, and some information can be chosen from a list of possible choices, such as Species. The information that is chosen from a list is organized with taxonomy terms I established and are described below.

REFERENCE INFORMATION

DOCUMENT TYPE

Research Article = Article published in a scholarly, peer-reviewed, journal presenting primarily new research

Review Article = Article published in a scholarly, peer-reviewed, journal primarily summarizing/reviewing previous research

Book or Book Chapter = Document that was published in a book

Conference presentation = Document related to a conference presentation, which could be a published abstract or other content (e.g. slides/poster) from the conference

Government report = Document created by a government

Other Report = Document that is a report that wasn't created by a government or published in a peer-reviewed journal.

Legal document = Document such as a report, or legal proceedings, or review, that primarily discusses legal aspects and/or a particular case

Other = any document that does not fit the above categories

*Multiple selections possible*

*While it is possible to designate more than one category for Document Type, these situations should be rare. Usually a document should fit one of these categories much better than the others.*
BIOACOUSTICS FOR DOLPHIN WELFARE

DOCUMENT INFORMATION

POLICY

Enforceable = regulations that are legal / in place

Not enforced = e.g. guidelines, proposed regulations not yet enforceable

Multiple selections possible

RESEARCH

Hearing = The document discusses research on the hearing abilities (normal or loss of them) of the animals

Behavioral Response = The document discusses behavioral response (e.g. avoidance, non completion of tasks, etc.) by the animals to sounds (could be abiotic or biotic, opportunistic or in a controlled setting)

Physiological Response = The document discusses physiological response (e.g. threshold shifts, heart rate, respiration, hormones, etc.) by the animals to sounds (could be abiotic or biotic, opportunistic or in a controlled setting)

Model = The document discusses a model, such as, a model for hearing loss, extrapolations of research data, models for sound propagation, etc.

Mitigation = The document discusses one or more methods for lessening impact/responses to sounds/noise

Other = The document discusses some other type of research

Multiple selections possible

POPULATION INFORMATION

SPECIES

Choose “General Marine Mammals” if the document applies to marine mammals in general, not only the selected species, or if the species are not specified. Choose other if the document deals with a particular species not listed.

<table>
<thead>
<tr>
<th>General Marine Mammals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common bottlenose dolphin Tursiops truncatus</td>
</tr>
<tr>
<td>Indo-Pacific bottlenose dolphin Tursiops aduncus</td>
</tr>
<tr>
<td>Common Name</td>
</tr>
<tr>
<td>-----------------------------------</td>
</tr>
<tr>
<td>Commerson's dolphin</td>
</tr>
<tr>
<td>Chilean dolphin</td>
</tr>
<tr>
<td>Heaviside's dolphin</td>
</tr>
<tr>
<td>Hector's dolphin</td>
</tr>
<tr>
<td>Rough-toothed dolphin</td>
</tr>
<tr>
<td>Atlantic humpback dolphin</td>
</tr>
<tr>
<td>Indian humpback dolphin</td>
</tr>
<tr>
<td>Pacific humpback dolphin</td>
</tr>
<tr>
<td>Costero</td>
</tr>
<tr>
<td>Tucuxi</td>
</tr>
<tr>
<td>Burrurana dolphin</td>
</tr>
<tr>
<td>Atlantic spotted dolphin</td>
</tr>
<tr>
<td>Clymene dolphin</td>
</tr>
<tr>
<td>Pantropical spotted dolphin</td>
</tr>
<tr>
<td>Spinner dolphin</td>
</tr>
<tr>
<td>Striped dolphin</td>
</tr>
<tr>
<td>Short-beaked common dolphin</td>
</tr>
<tr>
<td>Arabian common dolphin</td>
</tr>
<tr>
<td>Long-beaked common dolphin</td>
</tr>
<tr>
<td>Fraser's dolphin</td>
</tr>
<tr>
<td>Atlantic white-sided dolphin</td>
</tr>
<tr>
<td>Dusky dolphin</td>
</tr>
<tr>
<td>Hourglass dolphin</td>
</tr>
<tr>
<td>Pacific white-sided dolphin</td>
</tr>
<tr>
<td>Peale's dolphin</td>
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<tr>
<td>White-beaked dolphin</td>
</tr>
<tr>
<td>Northern right whale dolphin</td>
</tr>
<tr>
<td>Southern right whale dolphin</td>
</tr>
<tr>
<td>Risso's dolphin</td>
</tr>
<tr>
<td>Melon-headed whale</td>
</tr>
<tr>
<td>Pygmy killer whale</td>
</tr>
<tr>
<td>False killer whale</td>
</tr>
<tr>
<td>Killer whale</td>
</tr>
</tbody>
</table>
### BIOACOUSTICS FOR DOLPHIN WELFARE

**Long-finned pilot whale** Globicephala melas  
**Short-finned pilot whale** Globicephala macrorhynchus  
**Australian snubfin dolphin** Orcaella heinsohni  
**Irrawaddy dolphin** Orcaella brevisrostris  
**Beluga whale** Delphinapterus leucas  
**Other**

*Multiple selections possible*

### REGION

<table>
<thead>
<tr>
<th>Region</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic Ocean</td>
<td>Wild pops or coastal in this region</td>
</tr>
<tr>
<td>Pacific Ocean</td>
<td>Wild pops or coastal in this region</td>
</tr>
<tr>
<td>Indian Ocean</td>
<td>Wild pops or coastal in this region</td>
</tr>
<tr>
<td>Southern/Antarctic Ocean</td>
<td>Wild pops or coastal in this region</td>
</tr>
<tr>
<td>Arctic Ocean</td>
<td>Wild pops or coastal in this region</td>
</tr>
<tr>
<td>North America</td>
<td>Managed pops in this region, and/or policy by governments in this region</td>
</tr>
<tr>
<td>South America</td>
<td>Managed pops in this region, and/or policy by governments in this region</td>
</tr>
<tr>
<td>Europe</td>
<td>Managed pops in this region, and/or policy by governments in this region</td>
</tr>
<tr>
<td>Asia</td>
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</tr>
<tr>
<td>Africa</td>
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<td>Australia</td>
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</tr>
<tr>
<td>Antarctica</td>
<td>Managed pops in this region, and/or policy by governments in this region</td>
</tr>
</tbody>
</table>

*Multiple selections possible*
WILD

Yes = The document discusses wild animals
No = The document does not discuss wild animals

Restricted to Yes OR No. Can leave blank if unclear/known.

MANAGED

Indoor = The document discusses managed animals in indoor environments (e.g. indoor aquarium pools)
Outdoor = The document discussed managed animals in outdoor environments (e.g. outdoor pools open to the elements)
Unknown = The document discusses managed animals, but it is unclear whether they are in outdoor or indoor facilities

Multiple selections possible

EXPOSURE TIME

This is a proxy for Acute / Chronic exposure which is defined differently by different people. To get around this, exposure time specifies the length of time of exposure to the particular sound. This could be in a controlled experimental setting, human activity assessment, or other type of controlled or not-controlled setting.
These are times related to the particular sound of interest / target sound.

Exposure time addresses the importance of Acute versus Chronic exposure. Acute and Chronic are defined differently by different people.
Exposure time is the time period over which exposures occur (as opposed to individual sound exposures such as a short sonar ping - the type of sound is addressed in Sound Properties)
This could be in a controlled experimental setting, human activity assessment, or other type of controlled or not-controlled setting.

<table>
<thead>
<tr>
<th>Duration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1 hr</td>
<td>Exposure to the sound = less than 60 minutes</td>
</tr>
<tr>
<td>&lt; 1 day</td>
<td>Exposure to the sound = less than 24 hours</td>
</tr>
<tr>
<td>persistent</td>
<td>Exposure to the sound is relatively constant, over multiple days +</td>
</tr>
<tr>
<td>unknown/other</td>
<td>Exposure time to the sound is unknown or does not fit the above categories</td>
</tr>
</tbody>
</table>

Multiple selections possible
## SOUND SOURCES

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shipping</td>
<td>Large-scale shipping</td>
</tr>
<tr>
<td>Offshore wind</td>
<td>Wind farms</td>
</tr>
<tr>
<td>Construction</td>
<td>Offshore projects e.g. platform building, pile driving, etc</td>
</tr>
<tr>
<td>Recreational boating / whale watching</td>
<td>Small-scale ‘shipping’</td>
</tr>
<tr>
<td>Military Sonar</td>
<td>Sonar from military operations or testing; including simulations in controlled experiments</td>
</tr>
<tr>
<td>Oil and Gas exploration / air guns</td>
<td>Sounds from exploration including air guns, and seismic exploration</td>
</tr>
<tr>
<td>Oil and Gas mining / drilling and extraction</td>
<td>Sounds from mining including from drilling and extraction processes</td>
</tr>
<tr>
<td>Other</td>
<td>A sound source not listed above</td>
</tr>
</tbody>
</table>

*Multiple selections possible*

## SOUND PROPERTIES

General characteristics of the sound. Used only in select circumstances; main reliance is on source.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upsweep</td>
<td>Sound frequency increases over the duration of the sound</td>
</tr>
<tr>
<td>Downsweep</td>
<td>Sound frequency decreases over the duration of the sound</td>
</tr>
<tr>
<td>Tonal</td>
<td>Non-continuous spectrum with different frequency components</td>
</tr>
<tr>
<td>Broadband, continuous</td>
<td>Sound pressure levels are spread continuously throughout spectrum</td>
</tr>
<tr>
<td>Impulsive</td>
<td>Short duration, with broad frequency content. Steep rises and sharp peaks in medium pressure; rapidly returns to static pressure. E.g. pile driving, explosions</td>
</tr>
<tr>
<td>Other</td>
<td>Sounds that do not fit any of the above categories</td>
</tr>
</tbody>
</table>

*Multiple selections possible*
BEHAVIORAL CONTEXT

What are the animals doing while being exposed to the sound?

<table>
<thead>
<tr>
<th>Behavior</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foraging</td>
<td>Animals are seeking and/or eating food</td>
</tr>
<tr>
<td>Breeding</td>
<td>Animals are engaged in mating-related behaviors</td>
</tr>
<tr>
<td>Migrating</td>
<td>Animals are traveling long distances</td>
</tr>
<tr>
<td>Socializing</td>
<td>Animals are interacting within/between groups</td>
</tr>
<tr>
<td>Human Interaction</td>
<td>Dolphins are participating in activities with humans, e.g. training sessions, swim-with-dolphins programs, whale watch boat activities, feeding</td>
</tr>
<tr>
<td>Traveling</td>
<td>Animals are traveling short distances</td>
</tr>
<tr>
<td>Resting</td>
<td>Animals are not active</td>
</tr>
<tr>
<td>Other</td>
<td>Animals are involved in a behavior not listed above</td>
</tr>
<tr>
<td>Unknown</td>
<td>Behavioral context is not known</td>
</tr>
</tbody>
</table>

Multiple selections possible

RESPONSE TYPE

What type of response do the animals exhibit, or is being investigated, regulated or discussed?

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Behavioral</td>
<td>Response involves change in activity of the dolphin(s). Includes movement such as approach or avoidance behaviors, and vocalizations</td>
</tr>
<tr>
<td>Physiological</td>
<td>Response involves physiological change, such as hearing loss, heart rate, blood evaluations</td>
</tr>
<tr>
<td>Mortality</td>
<td>Response involves death of the animal</td>
</tr>
<tr>
<td>Other</td>
<td>Some other kind of response</td>
</tr>
<tr>
<td>Unknown</td>
<td>Response type is not known</td>
</tr>
</tbody>
</table>

Multiple selections possible
Appendix B

Dolphin Bioacoustics Policy Online Database (dBPod)

Find documents about the effects of sound on dolphins and related policy at
dbpod.graciass.net
Appendix C

Supplemental Audio Files

For each spectrogram graph, there is an accompanying audio wav file.

**Chapter 2: Supplemental Audio 2.1-2.22**

2.1 Deployment 2 #6492 (August 8, 2012, 24:00)
2.2 Deployment 1 #8651 (February 20, 2021 17:30)
2.3 Deployment 2 # 9124 (September 4, 2012, 10:00)
2.4 Deployment 1 #6335 (January 27, 2012, 14:30)
2.5 Deployment 1 #17458 (May 22, 2012, 11:15)
2.6 Deployment 2 #1820 (June 20, 2012, 08:00)
2.7 Deployment 2 #6077 (August 3, 2012, 16:15)
2.8 Deployment 2 #9123 (September 4, 2012, 09:45)
2.9 Deployment 1 #1835 (December 11, 2011, 17:30)
2.10 Deployment 1 #13 (November 22, 2011, 18:00)
2.11 Deployment 1 #54 (November 23, 2011, 04:15)
2.12 Deployment 1 #196 (November 24, 2011, 15:45)
2.13 Deployment 1 #232 (November 25, 2011, 00:45)
2.14 Deployment 1 #165 (November 24, 2011, 08:00)
2.15 Deployment 1 #2392 (December 17, 2011, 12:45)
2.16 Deployment 1 #8651 (February 20, 2012, 17:30)
2.17 Deployment 1 #70 (November 23, 2011, 08:15)
2.18 Deployment 1 #3757 (December 31, 2011, 18:00)
2.19 Deployment 1 #11784 (March 24, 2012, 08:45)
2.20 Deployment 2 #2983 (July 2, 2012, 10:45)
2.21 Deployment 2 #4120 (July 14, 2012, 07:00)
2.22 Deployment 2 #8847 (September 1, 2012, 12:45)

**Chapter 3: Supplemental Audio 3.1 - 3.12**

3.1 Riviera Maya #572 (September 30, 2014, 11:00)
3.2 Xel Ha #109 (September 25, 2014, 15:15)
3.3 Interactive Aquarium #760 (October 2, 2014, 10:00)
3.4 Xel Ha #267 (September 27, 2014, 06:45)
3.5 Xcaret #430 (September 28, 2014, 23:30)
3.6 Xcaret #367 (September 28, 2014, 07:45)
3.7 Riviera Maya #547 (September 30, 2014, 04:45)
3.8 Xel Ha #57 (September 25, 2014, 02:15)
3.9 Xcaret #410 (September 28, 2014, 18:30)
3.10 Riviera Maya #538 (September 30, 2014, 02:30)
3.11 Interactive Aquarium #639 (October 1, 2014, 03:45)
3.12 Interactive Aquarium #647 (October 1, 2014, 05:45)
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bioacoustics and astrophysical particles detection, Ettore Majorana Foundation and Centre for Scientific Culture (Erice, Sicily) School of Ethology - 30th workshop.


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Literature Cited Chapter 3


