An argument for a standardized method to record, measure, characterize, and compare captive animal soundscapes

Susan M. WISEMAN[1], Preston S. WILSON[2]

[1] Independent Researcher, USA

[2]The University of Texas at Austin

ABSTRACT

A small number of soundscape ecologists in North America, Europe and Australia are collaborating to develop international standards for their soundscape research (1). Acoustic studies of captive animal facilities have had widely differing goals, techniques, and results, and the type and accuracy of equipment is not always reported, making understanding of results difficult and direct comparisons impossible. To characterize an entire soundscape, multiple metrics are required. Schulte-Fortkamp (2) stressed the importance of interdisciplinarity to appreciate the broad roles of soundscapes, and the need for a common language. As interdisciplinarity increases, so does the need for standardization so researchers from any background can compare outcomes. Recording a soundscape can reveal important, previously unrecognised information about the experience of animals, particularly if sounds occur outside the range of human hearing or when staff are absent. This project sought to standardize a method whereby widely differing zoo and wildlife park soundscapes may be comprehensively recorded, measured, characterized, and compared. By seeking correlations between as many acoustic parameters as possible, and the health and well-being of the species held within each soundscape, greater understanding should ensue, leading to new considerations in animal care.

Keywords: Soundscape Ecology, Animal I-INCE Classification of Subjects Number: 56.3 Soundscapes

1. INTRODUCTION

Many animals depend less on sight than on their other senses for navigation, to interpret their environment, and to hunt or to avoid predators. For those that depend more on what they hear and what they smell, their "soundscape" and "scentscape" are vital, and are equivalent to a visually-oriented animal's "landscape". Yet few zoological studies examine the role of the soundscape (and even fewer examine the scentscape), apart from considering whether construction projects or crowd events are likely to disturb a specific species.

It is likely that the majority of zoos (as opposed to wildlife parks) are situated in or near urban environments. Natural and urban soundscapes manifest vastly different characteristics, one being chronic anthropogenic noise that frequently masks sounds essential to guiding natural behaviours. The World Health Organisation states that noise damages humans physiologically as well as psychologically (3). It may well impact other mammals similarly, particularly those heavily reliant on exceptionally sensitive hearing. For species that are disappearing from the wild due to poaching, habitat loss or other reasons, captive breeding may be the only hope of saving them from extinction. Yet a number of these species do not breed readily in zoos, so understanding and managing all conditions that negatively impact their health and well-being could be crucial to maintaining a broad gene pool or even species' survival.

Certain acoustic parameters such as vibration, impulse and fluctuating noise have been shown as particularly injurious to humans (3). One may expect factory farms such as indoor poultry producers to be loud in comparison to traditional outdoor farms. However although many zoos seem quiet to humans, could it be that unrecognized chronic injurious acoustic parameters exist within the hearing

[1] smwiseman15@gmail.com
[2] wilsonps@austin.utexas.edu

sensitivity of specific species, particularly for animals that hear infra- or ultra-sonically? Little is known about the hearing thresholds of many species, let alone their full audiograms. Are certain species held within soundscapes that may not be appropriate for them? A first step towards answering such questions could be to measure zoo and wildlife park soundscapes in such a way as to enable the identification and accurate comparison of specific acoustic parameters, then to correlate those measurements with the physiological and behavioural status of the animals living within those soundscapes to determine any patterns that might relate to a specific species' health, well-being or breeding success. In order to compare acoustic parameters at different facilities or time periods meaningfully, the soundscapes must be measured according to recognized standards and procedures.

2. BACKGROUND

2.1 Soundscape Ecology

While zoo acoustic studies have mainly measured noise levels and specific frequency bands, and bioacousticians mainly measure the vocalizations or an activity of an individual species, recent measurement of wild areas (including national parks) has highlighted soundscapes (4,5,6,7,8,9). These studies were undertaken by the relatively few teams of soundscape ecologists who have produced a number of useful techniques and are collaborating with soundscape ecologists in Europe and Australia to develop ISO international standards relating to soundscape research (1,10,11,12,13).

The soundscape is a fundamental component of landscapes (14). While most bioacousticians research at the species level, examining an entire soundscape reveals the spatial and temporal interaction of the acoustic environment with the physical and behavioural characteristics of organisms living within it. Krause explains that soundscape ecology is "based on the causes and consequences" of the geophony, biophony and anthrophony within a particular place, and of their inter-relationships (5,10).

Rachel Carson (15) and Bernie Krause (4) first documented how biophony indicates a habitat's health and provides good clues as to its age, level of stress and other valuable information. In his experience, a soundscape radically altered by anthrophony may never recover: Lincoln Meadow in the Sierra Nevada mountains of California was selectively logged in the late 1980s. Krause returns to re-record it every few years but even though it looks like it has recovered, the biophony (or lack of it) clearly indicates that ecologically the Meadow has never regained its original diversity, population density and vibrancy. Krause was the first to attempt to properly quantify the biological attributes of a soundscape (16), examining many sources of sound across different wild natural ecosystems and establishing new research techniques (7). Despite the simple equipment available in the 1980s, due to his accuracy of measurement and the regularity of his recording methods and analysis, he is able to meaningfully compare the results of over three decades of recordings of natural soundscapes in diverse parts of the planet. With today's far more sophisticated hardware and software, it is possible to far more readily calibrate and analyse results. Krause and researchers such as Fristrup and Pijanowski and their colleagues have since furthered techniques to record and measure natural soundscapes with increasing breadth and accuracy.

2.2 Impact of the Soundscape on Humans

E.O. Wilson suggested that the natural world is the most information-rich environment, not only for animals but also for humans (17). Schafer asserts that in contrast, urban soundscapes contain little acoustic information. This is a function of many factors, including ubiquitous masking noise, and the repetitive nature of machine-made sounds (18).

For more than fifty years, the World Health Organization (WHO) has published warnings about the most common impacts of noise on human health. The young (including foetuses), the elderly, and those in poor health suffer the most severe symptoms (19). Noise pollution has been shown to affect human physical, mental, and emotional well-being. Psychological annoyance, interference with verbal communication, sleep disturbance (including when a person does not consciously awaken), disruption of cognitive processes, short term to permanent hearing disorders, and interference with the cardiovascular and endocrine systems are the most frequent responses but they can in turn lead to other symptoms such as gastroenterological disorders and nutritional imbalance (20). Noise frequently attracts lower priority than other environmental considerations, hence there remain many opportunities for better noise control to create healthier human communities, let alone animal facilities.

Goines and Hagler (20) reported that more than 5000 citations in the U.S. National Library of Medicine relate to adverse health effects of noise. Even if a noise does not occur at a level harmful to the auditory system, it can still be perceived by the body (human or animal, whether awake or asleep) as a danger signal. While we may close or avert our eyes, we can't (without technology) close our ears. Twenty-four hour hearing is a survival mechanism shared by all animals. Even when people don't wake and don't think their sleep has been disturbed, their bodies tend to respond with "flight or fight" and other psychophysical responses as reflected by the central nervous system, and by hormonal and vascular changes that can have far-reaching short- and long-term consequences (21).

A more recently discovered impact of the soundscape is a link between the auditory sense and olfactory and taste sensations (22,23). The same food generally tastes quite different to people according to the frequencies and sound pressure levels (SPL) to which they are exposed while they eat. This can lead to different food choices and increased or decreased appetite, and thus long-term to a less than optimal diet.

2.3 Impact of the Soundscape on Animals

Nature is dominated by biophonic and geophonic sounds that are quickly absorbed by soil and vegetation (16). Krause's "niche hypothesis" states that the biophony of any natural place is measurably unique due to its creatures, vegetation, terrain and previous levels of disturbance, with various insects, birds, mammals and amphibians occupying their own bandwidths where there is no competition. Animals evolved to vocalize within available niches in the soundscape in order to be heard by others of their kind. They competed for and cooperated for bandwidth as much as for food and habitat (4,16,24,25). This makes pollution of the soundscape as critical as pollution of food and water, and helps explain why forcing wildlife into a strange habitat often fails—or can cause the demise of an original component of that habitat.

Ambient sound is a central component of natural habitats (26). It provides continuous information about and communication with conspecifics and other species, information about potential prey and predators, weather and changing environmental factors, the location of food sources, water and other resources, helps with navigation, and is essential to wildlife survival. From wild born to domesticated animals, there is no adaptation to stop their constant auditory surveillance. Yet wildlife, even endangered species, and captive animals are rarely factored into noise management.

Some animals are very sensitive to ground vibrations and use them as other animals use auditory waves, and for the same purposes. For animals like ungulates that use both auditory and ground vibration they seem to choose seismic vibration when communicating over long distances, particularly in times of stress or when locating distant members of their species. It is believed that rhinos and elephants communicate over enormous distances in this manner (27,28,29,30,31). Ground-burrowing animals like mole rats are particularly sensitive to tiny seismic vibrations that humans cannot detect, relying on these for navigation, to hunt, and to avoid predation. When these are masked by earth tremors – or by resource extraction, distant explosives, trains, or road traffic on uneven surfaces and especially on bridges – these animals are likely to become disoriented and vulnerable to predators that rely on sight rather than on sound or vibration (32).

Wild soundscape levels peak at times when birds and insects are most active but vary in range according to the habitat and species present. In savannah and even more in desert habitats, sound levels generally remain low apart from during storms and floods, or when a predator catches its prey – although even then many animals remain almost mute. In a study of habitat acoustics and primate communication, it was discovered that ambient noise levels rose in a rainforest habitat from 27 dB at 06:00 to 40 dB at 15:00 and in their riverine study area from 27 dB at 06:00 to 37 dB just an hour later. Dawn was significantly quieter in the savannah at 20 dB, but rose to 36 dB at midday due to wind (33).

Animals are known to respond to particular aspects of sounds, such as the spectral distribution of sound energy (34). Sound of various frequencies and amplitudes is an established tool that humans and non-human animals use to attract or to herd prey, to fight, or to ward off threatening approaches. Some sounds automatically instigate an animal's "fight or flight" response, either way altering their adrenalin levels, energy budget, and causing stress, which over a long period of repeated exposures can severely impact health. Sounds that are not direct threats, particularly unexpected sounds, often evoke similar responses and can alter health if they occur too frequently. This trait remains even in domesticated animals that have always lived in safe environments.

An increasing number of studies especially on urban wildlife, birds, and marine mammals exposed to human-perceived noise, show substantial changes in foraging and anti-predator behaviour, reproductive success, habitat selection, vulnerability, longevity, abundance and community structure (35). Glucocorticoid enzyme stress levels have also been correlated (36). Even benthic feeding lobsters have been shown to stop feeding or to flee the noise of small remotely-operated boats on the surface (37).

In addition to causing generalized stress, noise is believed to affect cetacean development and immune system health (38,39). Strandings and mortalities of beaked whales have in many cases been conclusively linked to noise events such as naval tactical sonars and seismic surveys, even when these were not considered loud enough to damage hearing. Thus even transient and localized acoustic impacts can have prolonged and serious population consequences (39). Marine mammals live in an "acoustic-dominant world", using sound as their primary means for interpreting and operating within their underwater environment (40). Chronic background noise for them would be like us living in a constant fog, with certain noises being the acoustic equivalent of a blindfold, completely masking vital information.

Brumm and Slabbekoorn (41) claim that communication is the foundation upon which all social relationships between animals are built. Since this is mostly acoustic, it can be considerably impaired by environmental noise. Some animals have evolved adaptations to counteract its masking effects, just as people have to shout or select different words to express themselves (42). When conspecifics cannot communicate due to masking of critical vocalizations, birds, primates, cetaceans, rodents, whales, and some other mammals have been observed to shift their vocalizations to another bandwidth, to alter their calls, to drop parts of their messages, and/or to vocalize louder. These efforts demand greater physical, emotional and intellectual energy which reduces their budgets for normal activities such as feeding or nursing. It appears that frequently they still fail to convey their message. This has added significance when community members miss urgent information such as the approach of predators, or in breeding selection where mating calls are a major component of partner attraction. Some species abandon nests or valuable feeding grounds, partners and prime habitats even due to "quiet" white noise (which masks all frequencies) such as air conditioners, or from occasional periodic noise such as aircraft overflights, trains, or recreational vehicles 10 km away. Birds with lower frequency calls abandon habitats exposed to low frequency noise (10,35,36,43,44). Since low frequencies travel such long distances, entire colonies are unlikely to find a suitable nesting place or habitat elsewhere as they are likely to come into conflict with existing residents or with others in search of a new habitat.

Researchers at the University of Missouri-Columbia reported that not only do animals respond to sound stimuli, plants produce chemical and physical defence mechanisms when exposed to recordings of insects munching on leaves, and can distinguish threatening sounds and vibrations from common but safe sources such as wind or water (45,46).

Natural soundscapes are dominated by biophony and geophony. Urban soundscapes are dominated by anthrophonies with very different physical and semantic characteristics. Absolute levels of sound generated by machinery are unparalleled in nature, which rarely produces similarly powerful amplitudes apart from a few immense waterfalls, earthquakes, massive storms, volcanic eruptions or natural disasters – all circumstances to be feared and to flee. Thus high amplitude machinery is likely to evoke some degree of a "fight or flight" response.

As noise impacts humans, it apparently influences non-human animals in very similar ways. Setting safe sound levels for humans is controversial (permissible levels in Europe and USA differ markedly), but far less is known about safe sound levels for other species. Clinical studies have revealed hearing loss in animals exposed to loud or chronic sound in laboratories, particularly in the young that are born there. Lab animals register blood pressure increases in response to noise, even during sleep or sedation (47). While some levels and frequencies have already been found unsafe, actual safe levels are generally unknown, and will vary from species to species. Despite ongoing research, the degree to which animals are being injured by modern soundscapes remains unknown, but there is sufficient evidence to indicate that this is an important issue which should be publicly acknowledged and further investigated.

2.4 Impact of the Soundscape on Captive Animals

Much remains unknown about the auditory sensitivities of species and thus about potential risks to their hearing. Yet captive animals are frequently exposed to high levels of unnatural noise at frequencies and pressure levels that would never exist in the wild. They are unable to "turn off" their hearing, and unable to flee the sound sources. They can't move past their confines to investigate the source of sounds to determine their meaning. In a 2003 study, it was noted that recordings played to a group of rhinoceros evoked distinct and repeatable behavioural reactions – sometimes curiosity, sometimes relaxation, sometimes aggravation, sometimes fear (48,49,50). In humans unrecognised, uncontrollable, worrying, or feared noises cause the greatest stress responses. This may well also be true for non-human animals. Species that suffer predation in the wild are especially prone to distress in response to unpredicted, high amplitude noise, even when kept safe lifelong in captivity (51). Captive, protected crows and mice act defensively at recordings of raptors (52).

Pet owners can testify that even domesticated animals try to flee unexpected, loud, or impulse sounds, and particular frequency ranges and vibrations – the same parameters that cause problems for humans. Many of the symptoms described by the WHO are evident in pets in earshot of loud vehicles or rifle ranges.

Equipment that saturates the ultrasonic soundscape includes computer monitors, closed-circuit security cameras, television and fluorescent lights. They produce constant ultrasonic hums. Sales et al. (53) reported that 24 of 39 pieces of common zoo equipment added over 60 dB of ultrasonic frequencies. Similar laboratory equipment has been found to produce in excess of 75 dB at over 60 kHz in closed, reflective environments (54), and cleaning equipment in combination with ventilation appliances have been measured at over 100 dB (53). High frequency reversing alarms are likely to cause physical pain to some species' ears. Alarms are generally mandated to exceed 90 or even 100 dB, depending on the state. Animals held in these captive spaces cannot escape the noise, nor are they likely to gain relief even at night. The degree to which their hearing has been compromised is generally unknown, let alone other physiological and psychological effects. The resultant lack of a normal baseline throws into question the applicability of laboratory animal testing.

2.5 Impact of the Soundscape on Zoo and Aquarium Animals

Despite the considerable attention that biologists and zoologists have focused on the audio-vocal behaviour of animals because the auditory sense is so critical to animal survival, much is unknown about the auditory ranges and sensitivities of most species and therefore, about the potential risks to their hearing. Yet most zoos produce high levels of unnatural noise at frequencies, pressure levels and durations that would never exist in the wild.

Aquariums are notorious for water pump, filtration and lighting noise that may not be obvious to viewers, but constantly saturate the soundscape of creatures that are almost totally reliant on their soundscape rather than on vision. Similarly, terrestrial animals with very limited vision such as the rhinoceros rely on their soundscape, so ambient sound pollution in a zoo can result in them straining to operate in a dense "fog" of noise.

Some zoos permit loud concerts, others are near public greenspace where fireworks displays can exceed 120 dB at numerous frequencies, but especially at low frequencies noted for causing distress in many species. Other common zoo sounds are lawn mowers and maintenance tools, small construction equipment, vehicles powered by various propulsion systems and with reversing alarms, pressure washers and floor scrubbers, and the continuous hum of air and water pumps, fans, air conditioners and heaters.

Some of the animals that hear ultrasonically include hummingbirds, rats and mice, prairie dogs, bats, squirrels, some species of fish, dolphins, orca, hamsters, canids and voles. Infrasonic detectors are known to include elephants, rhinoceros, giraffes, cassowaries, hippopotami, pigeons, tigers, chameleons, alligators, moles, prairie dogs (which have an exceptionally wide hearing range), and okapi. Many species remain to be tested to determine their hearing ranges and seismic sensitivity, so these lists are likely to increase.

3. ZOO SOUNDSCAPE ANALYSIS

In general zoo and aquarium soundscapes have received little detailed analysis, especially in the infra- and ultra-sonic ranges unless a target species was known to use spectrum extremes, such as bats and elephants. Factory farm and other agricultural arenas have received even less attention. Most zoo recordings have been of the animals themselves, rather than of their ambient surroundings.

Even when non-sonic ranges are considered, most hardware and software is optimized to operate within the human hearing bandwidth, and systems capable of accurately recording the entire spectrum are expensive, often poorly understood, or unavailable. In many studies, the accuracy of equipment above or below the sonic range has not been reported (or even assessed?).

A relatively few studies have recorded and correlated ambient zoo noise with the behavioural and occasionally the physiological responses of a target species or of individual animals. Documentation methods have varied in technique, resolution and duration. Often studies have been just a minor component of a wider focus – such as the search for a range of factors that can stress zoo animals, from the structure of their housing to the activities of zoo visitors.

The simplest acoustic review technique remains an established "scan and notate" observation method that requires the investigator to note the environment and the animals' behaviour at fixed time intervals or whenever a certain situation occurs (such as a certain sound). Usually a single investigator must adhere to a firm self-imposed methodology and definitions or the work will develop a subjective bias and notations will vary as the researcher/s fatigue or over time. Due to the concentration involved and the difficulty in standardizing interpretations and in sharing the workload, such studies tend to be of short duration and to seek a simple "present" or "absent" response, and to observe only a small number of animals at one time.

In order to be less subjective, some sort of data logger – usually a sound pressure level meter – can be utilized to determine ambient sound. These typically sample frequencies and sound pressure/amplitude, and may average these samples over a set period of time, for example over 30-second or one hour intervals. In many studies only amplitudes are recorded, not frequencies or any other parameters.

Ambient sound pressure levels are sometimes sampled as a reference when the main purpose of a study is to record something specific without the aid of a soundproof studio, such as in determining an animal's range of vocalizations or audiogram. Once it can be determined if the ambient noise frequencies directly overlap with the vocalization or with an intended sound stimulus, the risk of a possible masking effect can be assessed (55). Another common purpose of recording ambient zoo sound has been to assess noise disturbance to a specific species or individuals, particularly if the animals are endangered and do not breed well in captivity. This testing has most commonly occurred prior to and during zoo reconstruction periods.

A much longer and more sophisticated study was undertaken over four years at San Diego Zoo's Center for Reproduction of Endangered Species, focusing on a pair of Giant Pandas. This sought to determine whether short, loud bursts of noise were more disturbing than daily average levels, and whether frequencies were relevant to the pandas' behavioural and hormonal stress indices. The average noise amplitude was recorded across three bandwidths at least five days a week during various stages of the female's reproductive cycle, in conjunction with physical observations and hormonal tests. Only days of high or low ambient noise were included in the final analysis (56). At the end of four years of such monitoring, it was determined that anthropogenic noise can impact the Pandas' breeding and that ambient noise can have prolonged impact on stress indices. Behavioural distress resulted from even brief loud noise, especially while the female was in oestrus or lactating, while longer-lasting but even moderately loud noise resulted in more glucocorticoids being excreted. Loud low frequency noise had the greatest impact.

A similar method was used to assess the stress caused to another pair of Giant Pandas during the four-month construction of a new exhibit at the Smithsonian Zoo in Washington in early 2003. Sound levels were measured and the pandas' behaviour and cortisol levels were compared on construction days versus non-construction days. The mean amplitude each minute of the sampling periods was logged, resulting in levels from 30 to 110 LdB. The total amplitude over the entire broadband spectrum, as well as that of discrete frequency bands within the range of 516 Hz to 16 kHz were noted, then the data were averaged to produce a mean amplitude for each frequency of sound for each recording session. Again, these were correlated with the pandas' behaviour and hormone levels (57).

The only study that has examined zoo rhinos' sensitivity to noise appears to be a portion of the work on the Black Rhinoceros in U.S. zoos (58). Seventeen zoos were visited and sound levels were measured in the centre of each outdoor rhino enclosure four times for fifteen seconds prior to opening near dawn, twice during operating hours, and once after closing. Decibels were measured at their maximum and minimum sound pressure levels, and also their Leq. Frequency range was measured in eleven one-third octave-bands from 0 to 20 kHz. However they seem not to have studied infrasound at all, nor do they mention any sensitivity of their measuring equipment to the infrasonic range. Possibly due to the limitations of their sample size and sampling methods, this study did not produce statistically significant correlations but did indicate general trends that relate noise levels to early mortality, unnatural behaviour, diminished well-being, and diminished reproductive success. The authors recommended further research to investigate these trends.

The study excluded measures of mechanical equipment and/or sudden sharp changes in sound levels. Their interest was the overall chronic exposure of the rhinos to zoo noise, which they seem to have largely interpreted as visitor noise. However I would argue that mechanical and cleaning equipment is regularly used around zoos to move food and equipment and sharp, sudden noises like the clanging of chains and heavy metal gates occur on an hourly basis so should be considered part of the average ambient-sound load. When metal hits metal it can be extremely loud, and even at a distance a wide range of harmonics in a wide range of frequencies typically ensue, unlike anything heard in a wild soundscape.

4. THE PROBLEM

As discussed, natural soundscapes are information-rich and directly and indirectly essential to survival (17), being the basis of diverse essential behaviours (34). Urban soundscapes are anthrophonic and exhibit vastly different physical and semantic characteristics: reflections from hard geometric surfaces, multi-path propagation and reverberation, and often increased sound pressure levels, in addition to a far greater component of anthropogenic noise. Information is buried in the pervasive noise, much of which is infrasonic or ultrasonic, too low or too high for humans to perceive but well within the hearing range of other species. Urban zoos tend to be enveloped in these anthrophonic soundscapes, as are a number of other animal holding facilities. Does this matter? Do the soundscapes of facilities in which certain species are healthy and productive differ from soundscapes in which they do not?

While the literature demonstrates that sound studies have been undertaken within the zoo environment, they have largely focused on recording specific animals rather than the soundscape, or on absolute sound levels rather than on the characterization of the soundscape, and largely only within the (human) sonic bandwidth. The few studies that assessed ambient sound for captive animals generally related to periods of construction, or else to equipment operating within animal housing. None of these zoo studies attempted to describe the soundscape as a whole, particularly from the animals' viewpoint considering their auditory ranges and semantics. The panda studies were technically the most comprehensive and form a good basis to build on, and indicated that ambient noise does impact the behaviour and stress levels of those animals, particularly during oestrus and lactation. The single (but black) rhinoceros study compared the noise levels within a number of zoos, but sampled only for very short, non-consecutive periods and only when the recordists considered the sound environment to be "average". The results of that study did however indicate trends that require further research for full substantiation.

It is clear the soundscape can have a profound influence on humans and on animals both in the wild and in captivity. The factors that influence humans most, and are associated with stress and reproductive problems, include chronic noise, high amplitudes, low frequency and/or impulse noise, vibration, fluctuating noise, noise during sleeping periods, unrecognized sounds, and sounds that are likely to cause fear. The first three of these (the only parameters tested) were shown to affect the pandas. It is not yet apparent the degree to which these factors are present in most zoo or wildlife park environments, nor whether they correlate to a species' health. No study was found that compares soundscapes in such a manner.

5. MEASUREMENT

In order to answer the question of whether soundscapes of facilities in which certain species are healthy and productive differ from soundscapes in which they are less so, it was necessary to develop a reliable process by which a wide variety of soundscapes can be comprehensively measured pertinent to the way they are likely to be perceived by that species (59). Only if the recording, analysis and reporting are comprehensive and standardized, can the measurements from different locations be meaningfully compared. If activities at the facility alter between weekdays and weekends, or day and night, all must be recorded. Seasonal and other variations should be documented if possible. Since soundscapes are dynamic, the longer the recording period and the greater the number of activities sampled, the more accurate the results.

For this purpose, a project was developed to comprehensively record the soundscape of the Southern White Rhinoceros (Ceratotherium simum simum) at Fossil Rim Wildlife Center in north central Texas. Rhinos are very myopic and navigate any distance by sound and smell more than by sight, and vocalize in infrasonic to sonic frequencies. A total of three weeks of pilot studies were conducted from May to October 2013, culminating with nine days of continuous recording with a total of seven sonic microphones (capable of 10Hz to 23kHz), an array of ten low frequency sensors, a geophone, two cameras, and a weather station.

Even if a target species' audiogram has been conclusively described, it would be valuable to record from as low a frequency to as high a frequency as possible (ideally infrasonically to ultrasonically), but certainly from well below to well above the known audiogram's bandwidth to cater for any individuals that hear better than those originally tested for the audiogram, since the original animals' hearing may have been compromised due to age, disease, or acoustic or other environmental exposure of which previous researchers were unaware. Even if individuals in a holding were thought to be deaf, it would be important to measure all possible acoustic parameters since the animals may be able to discern information of which keepers are unaware, or the soundscape itself may have influenced other occupants which in turn may prove a factor, for example the presence or absence of bats, or certain birds or insects that can influence the well-being of the target species. Their presence might only be detected by the sound recordings.

If it is suspected that the species senses seismic vibration, that should also be measured. Even for species (like humans) that do not hear very low frequencies, studies have shown that low frequencies and vibration cause negative responses.

All sections of the holding which the animals can reach should be recorded, with cameras taking intermittent photos (perhaps one frame per minute, depending on the mobility of the animals concerned) to assess whether they move to any particular location in response to sound events (attraction or aversion) or whether there is a noticeable change in their behaviour, such as cessation of grazing or of an interaction. Photographs also disclose activities nearby such as traffic, visitor and maintenance activities. In the case of a large wildlife park enclosure, this may require several recorders, microphones and cameras. An array that enables beamforming would be a bonus. All equipment needs to be calibrated, including time references so any moment can be later investigated across any or all locations. It is also important to log weather from a station at the enclosure since awareness of changing conditions, in particular of wind speed and direction and precipitation, will greatly assist the interpretation of data and of the animals' behaviour.

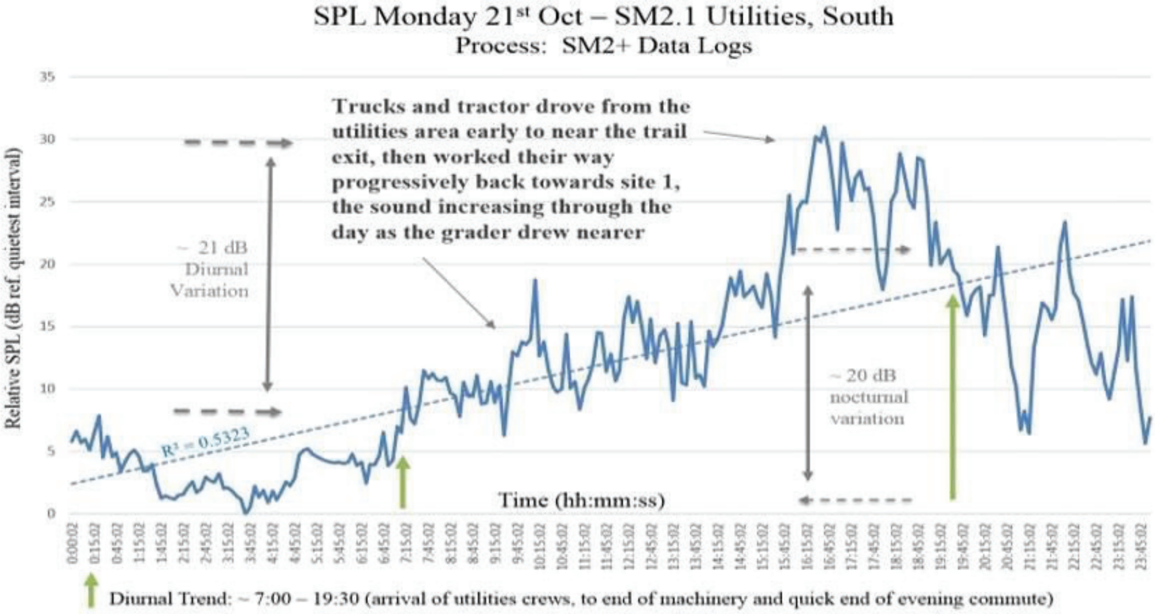
During the analysis, since it is not known which acoustic parameters (if any) may prove significant to the well-being of the animals in question, as many parameters as possible should be extracted from the recordings. Matlab or Raven Pro can identify entropy for example (the degree of disorder in a sound). Some parameters can be simply documented by listening to the sound recordings, then quantified. Other parameters may have to be calculated. Wherever possible, acoustic parameters known to cause distress to humans (such as chronic noise, high amplitudes, extreme frequencies, impulse noise, vibration, fluctuating noise, noise during sleeping periods, unrecognized sounds, and sounds that are likely to cause fear) should be examined since evidence indicates that animals may suffer similar responses to humans.

One limitation in our project was the computing power available, and thus the amount of data that could be processed in a reasonable time. With many microphones, continuous recording for over a week at fairly high resolution resulted in terabytes of data. The software programs Raven Pro Sound Analysis and Matlab proved to have limitations on the size of files they can process concurrently before becoming unstable. A novel aspect of comprehensive soundscape recording is that it addresses extremely wide bandwidths, resulting in an enormous amount of data to be measured, drawn, and processed in order to investigate an entire soundscape, as opposed to most projects' relatively narrow bandwidths, such as when recording the calls of a particular species. Other projects may analyse huge datasets, but most search in restricted bandwidths or are otherwise able to narrow down the amount of calculation that is necessary.

6. CHARACTERIZATION

Once the data was extracted, various forms of visualisation and characterisation took place, relevant to the facility and the species. Measures such as maximum, minimum and mean sound pressure levels, averages and standard deviations, diurnal and nocturnal variations and other factors were graphed and compared over varying time periods and activities, as seen in Figure 1. Periods identified included 24 hour cycles, dawn and dusk, feeding, workhours, while staff were cleaning or conducting particular maintenance chores, while visitors were in attendance, certain weather events, and predominant sleeping periods. Graphs were accompanied by sonograms of noteworthy sounds and by photographs and weather data.

When similar recordings, measurements and characterizations are compiled for other facilities holding the same species, additional patterns and contrasts will emerge.



Mean SPL Interval	Trendline	Minimum	Maximum	Diurnal Variability	Nocturnal Variability	Average	Standard Deviation
5 minutes SM2+data log	$R^2 = 0.5323$	0 dB at 3:40	31 dB at 16:40	~ 21 dB	~ 20 dB	12.1 dB	0.9

Figure 1 – An example of the sound pressure levels at the southern-most site of the white rhinoceros enclosure at Fossil Rim Wildlife Center, as tracked throughout one 24 hour cycle when the trail was being repaired. The SongMeter sensors nearest the Utilities buildings show increasing noise as the road crews worked steadily towards them throughout the day.

7. CONCLUSION

Since humans and other animals appear to share many physiological and psychological responses to sound, and various sounds are known to be either beneficial or detrimental to humans, a thorough investigation and understanding of the soundscapes in which animals are held could prove invaluable in furthering their health, well-being and productivity. This may prove particularly significant in supporting endangered species that do not traditionally breed well in captivity. Acoustic parameters known to be harmful to humans or to cause response in animals should be investigated in depth in each captive environment to determine whether they are present and whether they may be significant.

This project provides a method whereby a soundscape, not just certain aspects of an animal enclosure, can be recorded and measured in a more comprehensive manner than has been reported in the past, and in such a way as to identify how that soundscape may relate to the likely acoustic sensitivity of the animals within it. Natural habitats of the species may be similarly measured in order to establish desirable baselines to act as goals for captive facilities.

Once a wide variety of soundscapes for a particular captive species has been comprehensively measured and characterised according to a recognised standard, correlations between particular acoustic parameters and the behaviour, stress hormones and over-all health and well-being of the animals within each soundscape can be sought. If relationships are discovered, their acoustic environments could be modified to better suit the species concerned.

Apart from components of a soundscape being potentially harmful or healing, the soundscape can impart important information about the animals' experience that animal-care managers may be unaware of, particularly sounds outside the range of human hearing or sounds that occur when staff are absent, such as at night. This project offers a new standard by which captive environments may be measured and compared, and may lead to greater understanding of factors that may prove influential in animal care.

ACKNOWLEDGEMENTS

This project would not have been possible without the generous support of Fossil Rim Wildlife Center for permitting the project to proceed and taking an active interest in its progress. I give special thanks to my dissertation committee: Dr John Tiefenbacher and Dr Ron Hagelman, and especially to my acoustics adviser Dr Preston Wilson.

REFERENCES

1. Pijanowski BC, Farina A. Introduction to the special issue on soundscape ecology. Landscape Ecology. 2011;1-3.
2. Schulte-Fortkamp B. The challenge of interdisciplinarity in soundscape. J Acoust Soc Am. 2014; 135 (4): 2148.
3. World Health Organisation expert task force. Guidelines for Community Noise. 1999(4/19/2012):1-21.
4. Krause B. Loss of Natural Soundscape: Global Implications of Its Effect on Humans and Other Creatures Prepared for San Francisco World Affairs Council, 31 January 2001. 2001.
5. Krause B, Krause BL. Wild soundscapes: Discovering the voice of the natural world. Wilderness Press; 2002.
6. Krause B. Anatomy of the soundscape: Evolving perspectives. Journal Audio Engineering Soc. 2008; 56 (1-2): 73-80.
7. Krause B, Gage SH, Joo W. Measuring and interpreting the temporal variability in the soundscape at four places in Sequoia National Park. Landscape Ecol 2011:1-10.
8. Krause B. Sounds from The Great Animal Orchestra (Enhanced): Air. : Little, Brown; 2012.
9. McKenna MF, Mennitt DJ, Lynch E, Joyce D, Fristrup KM. Patterns in bioacoustic activity observed in US National Parks. J Acoust Soc Am 2013;134(5):4175-4175.
10. Pijanowski, BC, Farina A, Gage SH, Dumyahn SL, Krause BL. What is soundscape ecology? An introduction and overview of an emerging new science. Landscape Ecology. 2011;1-20.
11. Villanueva-Rivera, LJ, Pijanowski BC, Doucette J, Pekin B. A primer of acoustic analysis for landscape ecologists. Landscape Ecology. 2011; 26:1233-46.
12. Mennitt, DJ. Spatial variation of natural ambient sound pressure levels in Rocky Mountain National Park. J Acoust Soc Am. 2011; 129 (4): 2617.
13. Mennitt DJ, Sherrill K, Fristrup K. A geospatial model of ambient sound pressure levels in the contiguous United States. J Acoust Soc Am. 2014; 135 (5): 2746-64.
14. Farina A. Sonic patterns III: Sounds and vibrations from soils. Soundscape Ecology. 2014; 209-220.
15. Carson R. Silent Spring. Boston, MA: Houghton Mifflin; 1962.
16. Krause BL. Bio-acoustics: habitat ambience & ecological balance. Whole Earth Review. 1987.
17. Wilson EO. Biophilia. : Harvard Univ Press; 1984.
18. Schafer RM. The tuning of the world. Knopf; 1977.
19. World Health Organisation expert task force. Guidelines for Community Noise. 1999; (4/19/2012):1-21.
20. Goines L, Hagler L. Noise pollution: A modern plague. Southern Medical Journal. 2007; 100 (3): 287-94.
21. Babisch W. Guest editorial: Noise and health. Environmental Health Perspectives. 2005; 113 (113(1): A14–A15) (Jan 2005) (last accessed 17/5/2016).
22. Woods AT, Poliakoff E, Lloyd DM, Kuenzel J, Hodson R, Gonda H, Batchelor J, Dijksterhuis GB, Thomas A. Effect of background noise on food perception. Food Quality and Preference. 2011; 22 (1): 42-7.
23. Restaurant noise can alter food taste - Scientific American [cited 8/19/2014. 2014]. Available from http://www.scientificamerican.com/podcast/episode/restaurant-noise-can-alter-food-tas-10-10-18/ (last accessed 17/5/2016).
24. Krause BL. The Niche Hypothesis: A virtual symphony of animal sounds, the origins of musical expression and the health of habitats. Soundscape Newsletter, World Forum for Acoustic Ecology, Simon Fraser, Univ; 1993.
25. Krause B. Sounds from The Great Animal Orchestra (Enhanced): Air. Little, Brown; 2012.
26. Gray PM, Krause B, Atema J, Payne R, Krumhansl C, Baptista L. The music of nature and the nature of music. Science. 2001; 291 (5501): 52-4.
27. O'Connell, CE. Aspects of elephant behavior, ecology, and interactions with humans. 2000.
28. O'Connell-Rodwell C, Hart L, Arnason B. Exploring the potential use of seismic waves as a

communication channel by elephants and other large mammals. Am Zool. 2001;41(5):1157-1170.
29. O'Connell-Rodwell CE. Keeping an "ear" to the ground: seismic communication in elephants. Physiology (Bethesda). 2007; Aug;22:287-294.
30. Payne K. September 2010. Personal communication. Elephant Listening Project, Cornell University.
31. Drake N. Stealth percussionists of the animal world. Scientific American. 2011; Available from http://blogs.scientificamerican.com/guest-blog/2011/03/22/stealth-percussionists-of-the-animal-world/ (last accessed 17/5/2016).
32. Narins PM, Willi UB. The golden mole middle ear: A sensor for airborne and substrate-borne vibrations. Springer; 2012.
33. Waser PM, Brown CH. Habitat acoustics and primate communication. Am J Primatology. 1986; 10 (2): 135-54.
34. Pater LL, Grubb TG, Delaney DK. Recommendations for improved assessment of noise impacts on wildlife. The Journal of Wildlife Management, 2009;73(5):788-795.
35. Barber JR, Crooks KR, Fristrup KM. The costs of chronic noise exposure for terrestrial organisms. Trends in Ecology & Evolution 2010;25(3):180-189.
36. Creel S, Fox JE, Hardy A, Sands J, Garrott B, Peterson RO. Snowmobile activity and glucocorticoid stress responses in wolves and elk. Conservation Biology. 2002; 16 (3): 809-14.
37. Spanier E, Cobb JS, Clancy M. Impacts of remotely operated vehicles (ROVs) on the behavior of marine animals: an example using American lobsters. Marine ecology progress series. Oldendorf. 1994; 104:257-266.
38. Hildebrand JA. Anthropogenic and natural sources of ambient noise in the ocean. Marine Ecology Progress Series. 2009; 395 (5).
39. Weilgart LSWLS. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Canadian Journal of Zoology. 2007; 85 (11): 1091-116.
40. Grossman E. Noise reduced ocean habitat for whales. Scientific American. 22 Oct 2010.
41. Brumm H, Slabbekoorn H. Acoustic communication in noise. Advances in the Study of Behavior. 2005; 35: 151-209.
42. Brumm H, Voss K, Köllmer I, Todt D. Acoustic communication in noise: Regulation of call characteristics in a new world monkey. Journal of Experimental Biology. 2004; 207 (3): 443-8.
43. Radle, AL. The effect of noise on wildlife: A literature review. University of Oregon, Eugene: 2007.
44. Stone, E. Separating the noise from the noise: A finding in support of the niche hypothesis, that birds are influenced by human-induced noise in natural habitats. Anthrozoos: A Multidisciplinary Journal of the Interactions of People & Animals. 2000; 13 (4): 225-31.
45. Appel H. Plants Know the Rhythm of the Caterpillar's Creep. All Things Considered. 8 July 2014. http://www.npr.org/2014/07/08/329884061/plants-know-the-rhythm-of-the-caterpillars-creep (last accessed 17/5/2016).
46. Hsu C. Plants Fight Harder When Feeling Fear. Counsel&Heal. 2 Jul 2014. http://www.counselheal.com/articles/10324/20140702/plants-fight-harder-when-feeling-fear.htm (last accessed 17/5/2016).
47. Song S. Nighttime noise and blood pressure. Time Health. 13 Feb 2008.
48. Wiseman SM. Sound as an Enrichment for Southern White Rhinoceri. Unpublished. 2003.
49. Wiseman SM. The role of sound in the captive environment of rhinoceri. Proc AAG Annual Meeting 2009; 21-26 March 2009; Las Vegas, Nevada. 26/3/2009.
50. Wiseman S. Soundscape Enrichment for the White Rhinoceros (*Ceratotherium simum simum*). Proc DAGA 2016; 14-17 March 2016; Aachen, Germany. 17/3/2016.
51. Meyer-Holzapfel M. Abnormal behavior in zoo animals. Abnormal Behavior in Animals. 1968; 476-503.
52. Hauser MD, Caffrey C. Antipredator response to raptor calls in wild crows, corvus brachyrhunochos hesperis. Animal Behavior. 1994; 48 : 1469-71.
53. Sales GD, Wilson K, Spencer KEV, Milligan SR. Environmental ultrasound in laboratories and animal houses: A possible cause for concern in the welfare and use of laboratory animals. Laboratory Animals. 1988; 22: 369-75.
54. Milligan, SR, Sales GD, Khirnykh K. Sound levels in rooms housing laboratory animals: An uncontrolled daily variable. Physiology & Behavior. 1993; 53: 1067-76.
55. Stansbury AL. Behavioral in-air audiogram of two arctic fox (*Alopex lagopus*) at the Columbus Zoo. Western Illinois University; 2011.
56. Owen MA, Swaisgood RR, Czekala NM, Steinman K, Lindburg DG. Monitoring stress in captive giant

pandas (*Ailuropoda melanoleuca*): Behavioral and hormonal responses to ambient noise. Zoo Biology. 2004; 23 (2): 147-64.

57. Powell DM, Carlstead K, Tarou LR, Brown JL, and Monfort SL. Effects of construction noise on behavior and cortisol levels in a pair of captive giant pandas (*Ailuropoda melanoleuca*). Zoo Biology. 2006; 25 (5): 391-408.
58. Carlstead K, Fraser J, Bennett C, Kleiman DG. Black rhinoceros (*Diceros bicornis*) in US zoos: II. Behavior, breeding success, and mortality in relation to housing facilities. Zoo Biol. 1999;18(1):35-52.
59. Wiseman S. Measuring a soundscape of the captive Southern white rhinoceros (*Ceratotherium simum simum*). Proc INTER-NOISE 14; 16-19 November 2014; Melbourne, Australia. 18/11/2014. P.758.