MASTERARBEIT | MASTER'S THESIS

Titel | Title

Conservation research towards an acoustic monitoring system for African elephants (Loxodonta africana)

verfasst von | submitted by

Viktoria Staufer BSc

angestrebter akademischer Grad | in partial fulfilment of the requirements for the degree of

Master of Science (MSc)

Wien | Vienna, 2025

Studienkennzahl lt. Studienblatt | Degree programme code as it appears on the student record sheet:	UA 066 879
Studienrichtung lt. Studienblatt | Degree programme as it appears on the student record sheet:	Masterstudium Naturschutz und Biodiversitätsmanagement
Betreut von | Supervisor:	Mag. Dr. Angela Stöger-Horwath Privatdoz.

Abstract (English)

The decline of African elephant *(Loxodonta africana)* populations is alarming and mainly driven by poaching, climate change, habitat loss, and human-elephant conflict (HEC). One potential solution to mitigate HEC is the development of an acoustic early-warning system. This system was developed to help communities living within elephant home ranges avoid unexpected confrontations with approaching elephants by acoustically and visually identifying their presence and sending warnings to nearby human settlements. Elephants produce rumble calls containing elements in the infrasonic range that convey acoustic information up to several kilometres away, making them a suitable system for acoustic monitoring even when elephants are not visible. The main aim is to explore the presence of social cues in elephant rumbles that may be further incorporated into the early-warning system initiated by Zeppelzauer et al. (2015) and Zeppelzauer & Stoeger (2015), to provide crucial information that can help mitigate human-elephant conflict. The automatic recognition of elephant vocalizations necessitates comprehensive ground truth, demanding an extensive dataset rich in information about context and caller. The focus of my thesis was to collect data from a novel elephant population to enhance the variety of the existing dataset.

Data were collected in the Marataba Contractual National Park within the Marakele National Park, South Africa. The thesis focused specifically on whether the sex of a caller can be distinguished based on acoustic cues of the rumbles. In addition, this study also explored whether rumbles produced by male elephants could indicate if the individual was in the male-specific hormonal state called “musth”. The results demonstrate that the acoustic features of rumbles can be used to determine the sex of the caller. The acoustic properties of social rumbles generated by males in musth are indistinguishable from those of males not in musth. Musth rumbles, characterized by a specific structure, occur solely when males are in the state of musth. Nevertheless, the limited sample size requires additional research to validate the latter.

This study represents the first investigation of the vocal communication of the elephant population in the Marakele National Park. The data collected and the finding of presence of social information in the acoustic structure of elephant rumbles can contribute to the refinement of the early-warning system by enhancing the algorithm's training for more effective area-wide monitoring. This promising approach could enable humans to take timely precautions, potentially decreasing human-elephant interactions in shared home ranges.

Key words: elephants, human-elephant conflict, acoustic-monitoring, early-warning system, conservation, species protection

Zusammenfassung (Deutsch)

Der stetige Rückgang der Populationen von Afrikanischen Elefanten *(Loxodonta africana)* ist besorgniserregend und wird durch Wilderei, Klimawandel, Lebensraumverlust und den daraus resultierenden „human-elephant conflict“ (HEC) vorangetrieben. Eine mögliche Lösung zur Linderung des Konflikts zwischen Menschen und Elefanten, ist die Entwicklung eines akustischen Frühwarnsystems, welches der lokalen Bevölkerung, die in der Nähe von Elefanten leben, helfen könnte, unerwartete Konfrontationen zu vermeiden. Elefanten eignen sich besonders gut zur akustischen Überwachung, da ihre tieffrequenten Laute, die sogenannten „Rumbles“ über mehrere Kilometer hinweg wahrnehmbar und detektierbar sind. Das Hauptziel dieser Arbeit war es, Daten zu sammeln und zu analysieren, um zur Weiterentwicklung des von Zeppelzauer et al. (2015) und Zeppelzauer & Stoeger,(2015) entwickelten Frühwarnsystems beizutragen. Die automatische Erkennung von Elefantenvokalisationen erfordert einen umfassenden Basis Datensatz, welcher reich an Informationen über den Kontext und den Rufenden ist. Das Ziel meiner Arbeit war es, Daten von einer neuen Elefantenpopulation zu sammeln, um die Vielfalt des bestehenden Datensatzes zu erweitern. Die Feldarbeit wurde in Marataba Contractual National Park im Marakele National Park, Südafrika durchgeführt. Die folgende Arbeit konzentrierte sich insbesondere darauf, ob das Geschlecht eines Rufenden anhand akustischer Merkmale der Rumbles unterschieden werden kann. Darüber hinaus wurde untersucht, ob Rumbles von männlichen Elefanten darauf hinweisen können, ob sich das Individuum in dem männchen-spezifischen Hormonzustand namens „Musth“ befindet. Die Ergebnisse zeigen, dass die akustischen Merkmale der Rumbles genutzt werden können, um das Geschlecht des Rufenden zu bestimmen. Die akustischen Eigenschaften der sozialen Rumbles, die von Männchen in Musth erzeugt werden, sind jedoch nicht von jenen von Männchen nicht in Musth zu unterscheiden. Musth-Rumbles, die durch eine spezifische Struktur gekennzeichnet sind, treten ausschließlich dann auf, wenn sich Männchen im Musth-Zustand befinden. Dennoch erfordert die begrenzte Stichprobengröße weitere Forschung, um die letztgenannten Ergebnisse zu bestätigen. Diese Studie stellt die erste Untersuchung der vokalen Kommunikation der Elefantenpopulation im Marakele-Nationalpark dar. Die erhobenen Daten und die Erkenntnis über die Präsenz sozialer Informationen in der akustischen Struktur der Elefantenrumbles können zur Verbesserung des Frühwarnsystems beitragen, indem der Algorithmus für eine effektivere, flächendeckende Überwachung besser trainiert wird. Dieser vielversprechende Ansatz könnte es ermöglichen, rechtzeitig Vorsichtsmaßnahmen zu ergreifen, was potenziell zu einer Verringerung von Mensch-Elefant-Interaktionen in gemeinsamen Lebensräumen führen könnte.

Schlüsselwörter: Elefanten, Human-elephant conflict, akustisches Monitoring, Frühwarnsystem, Naturschutz, Artenschutz

Acknowledgements

I would like to take this opportunity to express my sincere thanks to all those who have contributed to the completion of this thesis. Without their support, this work would not have been possible.

First of all, I would like to express my deepest gratitude to Dr. Angela Stöger, my supervisor, who always helped me, stood by my side with advice and support when I needed it and trusted me to find my way. I wouldn't be where I am today if I hadn't taken part in your lecture during my bachelor's degree and fallen in love with the world of elephants and bioacoustics. I am so grateful that I had the opportunity to encounter wild elephants and countless other animals in South Africa and to push my own limits. Through this master's thesis and the opportunities, I was given by my supervisor, I was able to learn so much that I will probably benefit from my whole life. A thousand thanks Angela!

Secondly, I would like to thank my friend, best field-partner, statistic expert and co-supervisor Vesta Eleuteri. Thank you, Vesta, for overcoming all the obstacles with me in South Africa, teaching me so much, and spending so much of your precious time helping me navigate the highs and lows of statistics, always encouraging me along the way. I also want to thank the whole team at Marataba who welcomed us 'elephant ladies' with open arms, taught us all the tips and tricks to survive in the bush and helped us with all the small and big car problems. Thank you for the incredible opportunity to do our research and be in this incredibly beautiful place. I would also like to thank Kathi Prager and Sophie Steinwenter you two are one of the smartest and most helpful persons I have ever met, and I hope we will have many more adventures together.

Furthermore, I would like to thank all the professors of my studies who have inspired me and taught me so much. I am incredibly grateful for all the experiences I had during my master’s and for all the wonderful people I got to meet.

A heartfelt thank you goes to my partner Chrisi and my family, who consistently support me through all my highs and lows, celebrate my successes, and lift me up when I need it. Your unwavering love means the world to me. I also want to express my gratitude to all my friends, who always lend an ear, offer their help, and stand by me when I need them most.

Lastly, I want to thank all the elephants of the world, and especially the Marataba elephants. I have fallen deeply in love with these fascinating gentle giants and am endlessly captivated by their wonder.

Table of contents

List of tables

List of figures

1. Introduction

1.1 Human-Wildlife-Conflict and Conservation aspects

The Elephantidae family was once widespread across the Asian and African continents, but in the 19th and 20th centuries various factors led to a massive decline of elephant populations and today elephants are only found in parts of Asia and sub-Saharan Africa (Alex, 2017; Blanc et al., 2007; Calabrese et al., 2017; Douglas-Hamilton, 1987; *IUCN SSC African Elephant Specialist Group | IUCN*, 2023) (Fig. 1). A significant factor in the decline of elephant populations was the extensive poaching in the 1970s and 1980s, which reduced elephant numbers from 1.3 million to approximately 600.000 (Barnes et al., 1998; Douglas-Hamilton, 1987).

The ivory ban implemented by CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) in 1989 has helped limiting the ivory trade and decreasing poaching rates. However, today elephants continue to face numerous threats, such as habitat loss and fragmentation, ivory poaching and persecution from humans following crop raiding incidents (Armbruster & Lande, 1993; Barnes, 1999; Nelson et al., 2003; Nyhus et al., 2000; Parker & Graham, 1989; Sukumar, 1991).

According to the IUCN (International Union for Conservation of Nature and Natural Resources), the current elephant population is estimated at approximately 415.428 ± 20.111 individuals, based on the most recent survey (Blanc et al., 2007). Botswana and Zimbabwe have the largest populations of African savanna elephants (*Loxodonta africana*) holding 47% of the whole continental population (Blanc et al., 2007; Caughley et al., 1990; Chase et al., 2016). Current elephant population numbers are of concern for many ecologists, conservationists, scientists, and private individuals alike. Elephants are a keystone species, playing a crucial role in structuring both plant and animal communities (Shoshani, 1993). Long-term studies have further demonstrated that elephants have a significant influence on their environment and its biodiversity (Coverdale et al., 2016; Fritz, 2017; Kohi et al., 2011; Sekar et al., 2017). They help maintain forest and savanna ecosystems, creating diverse habitat mosaics that support rich biodiversity (Fritz, 2017; Haynes, 2012). Additionally, elephants contribute to ecosystem diversity through their role in seed dispersal (Blake et al., 2008; Dudley, 2000). These megaherbivores prevent savannahs from becoming overgrown with bushes, and their dung serves as an effective natural fertilizer for the soil (Coverdale et al., 2016; Fritz, 2017; Kohi et al., 2011; Sekar et al., 2017). Elephants are also called "ecosystem engineers" because they form pathways in the savannah and forest ecosystems for other animals to wander. During periods of drought, elephants can track down underground springs and then dig for them, also benefitting other animals (Haynes, 1991, 2012).

Elephants are long-lived, social animals, and their survival depends on regular migration over large distances to search for food, water, and social and reproductive partners (Sukumar, 1991; Vancuylenberg, 1977; White & Ward, 2010). As the largest living land mammals, elephants have substantial requirements for food and water. They consume approximately 150 kilograms of foliage and drink 190 liters of water each day (Sukumar, 1991; Vancuylenberg, 1977; White & Ward, 2010). To meet these needs, elephants must roam over vast areas. On average, a herd of African savannah elephants covers a home range from 11 to 500 square kilometres per year (Shannon et al., 2006; Thomas et al., 2008).

However, despite being crucial for the maintenance of biodiversity, elephants may have detrimental effects on ecosystems. Habitat loss leads elephants to live in fragmented or confined areas where they often have insufficient space available (Höft & Höft, 1995; Swanepoel, 1993; Tchamba, 1995). In these areas elephants may reach unsustainable densities that may lead them to destroy too many trees and bushes (Höft & Höft, 1995; Swanepoel, 1993; Tchamba, 1995). Living in a fragmented landscape also means that elephants live close to local communities, with whom they compete for the land, water, and food available (Barnes et al., 1998; Blanc et al., 2007; Wynyard, 2019). This leads elephants to often raid people's fields to feed on their crops, which is part of a larger, more complex conflict known as the human-elephant conflict (HEC) (Nelson et al., 2003; Santiapillai et al., 2010; Shaffer et al., 2019; Smith & Kasiki, 1999). Male elephants, in particular, are frequently involved in conflicts with humans and raid their fields. Therefore, more research is needed to address this issue (Baotic & Stoeger, 2017; Graham et al., 2010; Santiapillai et al., 2010; Smith & Kasiki,1999; Zeppelzauer & Stoeger, 2015).

HEC has been defined as "*any and all disagreements or contentions relating to destruction, loss of life or property, and interference with rights of individuals or groups that are attributable directly or indirectly to elephants*" by the Kenya Wildlife Service, (1994) (Smith & Kasiki, 1999). In addition to habitat loss and habitat fragmentation also the traditional migratory corridors of elephants get disrupted, forcing them into closer proximity with human communities and leading to more frequent and severe conflicts over space and resources. These conflicts result in various consequences ranging from crop collapses to loss of both human and elephant lives (Barnes et al., 1998; Calabrese et al., 2017, 2017; Graham et al., 2010; Leimgruber et al., 2003; Parker & Graham, 1989; Western et al., 2009).

People have coexisted with elephants for thousands of years, but a lot of things changed in the last decades and are still changing. In addition to poaching and habitat loss, climate change poses emerging threats to elephants, because with rising temperatures, changes in rainfall patterns and longer periods of draught, the animals are forced to navigate across large areas to find enough food and water to survive. This environmental stress can exacerbate the existing HEC as elephants wander into agricultural lands in search of food and water (Barnes et al., 1998; Blanc et al., 2007; Wynyard, 2019).

The human-elephant conflict is a highly complex and interdisciplinary issue that impacts not only human safety and elephant survival but also the health of ecosystems and biodiversity. This is because there is a strong connection between socio-economic and ecological factors. For instance, in a lot of African countries many people depend on small-scale farming and therefore if elephants destroy their fields, endanger their food supply and cause economic damage (e.g. destroy fences and wells) they can seriously affect the livelihood of the people and communities (Nelson et al., 2003; Osborn, F.V. & Parker, G.E., 2002; Shaffer et al., 2019). Thus, this conflict is exacerbated by a series of direct and indirect negative interactions between humans and elephants. These negative interactions often lead to the local population having a lower regard for the animals and the protected areas, which has potentially serious negative effects on the species and the environment (De Boer & Baquete, 1998; Nyhus et al., 2000). The consequences include increasing poaching and the further decline of elephant populations (R. E. Hoare, 1999; Shaffer et al., 2019). A multi-faceted approach is needed if humans and elephants are to peacefully coexist. The conflict must be minimised by reducing the costs to humans and increasing the benefits of living with elephants. This can be done by transforming elephants from a threat to an economic asset (Santiapillai et al., 2010; Shaffer et al., 2019). The involvement, participation and help of the local population is essential for the conservation and protection of elephants (Osborn, F.V. & Parker, G.E., 2002). As O'Connell-Rodwell et al. (2000) said: "*community involvement is crucial in creating sustainable solutions that benefit both humans and elephants*" (O'Connell-Rodwell et al., 2000).

The longstanding and ongoing conflict between humans and elephants has led to the creation of various strategies aimed at preventing and reducing these conflicts. Balancing the needs of elephants, human communities, and the environment is crucial to conserving elephant populations and minimising negative impacts on people (R. Hoare, 1995; Nelson et al., 2003; Nyhus et al., 2000; Shaffer et al., 2019; Tchamba, 1996). Traditional techniques for managing conflicts, for example, include local practices such as shouting, lighting fires, beehive fences, using noisemakers to scare elephants away or repellent methods as chilli odours (Nelson et al., 2003; Niskanen, 2006; Nyhus et al., 2000; Shaffer et al., 2019). These methods can be effective in certain situations but may not address the underlying causes of the conflict. Disturbance methods, like loud noises and bright lights, are also used to frighten elephants but can be disruptive and might not offer long-term solutions. Physical barriers, such as electric fences and trenches, are also often used to keep elephants out of human settlements. While these barriers can be effective, they are expensive to construct and maintain for local communities. Economic strategies such as compensation payments can provide financial refunding for damage caused by elephants, helping to mitigate negative feelings and foster coexistence (Nelson et al., 2003; Niskanen, 2006; Nyhus et al., 2000; Shaffer et al., 2019).

Wildlife utilization schemes, which allow communities to benefit from eco-tourism or the legal sale of elephant-related products, can create a positive relationship with elephants and provide economic incentives (Adams & Hulme, 2001; Nelson et al., 2003; Shaffer et al., 2019; Spierenburg, 2002). Additionally, effective land use planning, such as zoning human activities away from elephant habitats and establishing buffer zones, is also considered promising (Young & Van Aarde, 2011). One of the most advanced conservation concepts is to create corridors between core areas to facilitate the natural movements of elephants and restore migration routes (Young & Van Aarde, 2011). All these approaches require collaboration and a thorough understanding of elephant behaviour to be successful (Adams & Hulme, 2001; Nelson et al., 2003; Shaffer et al., 2019; Spierenburg, 2002).

In extreme cases, problematic elephants may be killed, though this practice is controversial and can worsen conflicts. Translocation, which involves relocating elephants to less populated areas, is another strategy, but is costly and often fails to resolve conflicts completely (R. Hoare, 1995, 2015; Nelson et al., 2003; Shaffer et al., 2019). Methods such as exclusion, deterrence, translocation, selective culling, and compensation have been implemented, yet they fail to tackle root causes like habitat fragmentation and resource competition (Fernando et al., 2005; Gubbi, 2012; R. Hoare, 2015; Shaffer et al., 2019). For instance, culling has been shown to harmfully reduce animal numbers, separating families and disrupt their long-term social behaviour and cognitive abilities (Shannon et al., 2013). Elephants from disturbed populations are less able to assess social threats and lose important decision-making and learning opportunities due to the loss of experienced matriarchs (McComb et al., 2001a; Shannon et al., 2013). These disruptions significantly affect the survival and well-being of individuals within complex social structures. The loss of social bonds leads to behavioural abnormalities in elephants, such as excessive aggression and, in extreme cases, attacks on other species. Such behavioural changes may further exacerbate negative interactions with humans (McComb et al., 2001a; Shannon et al., 2013).

Beyond addressing immediate issues, long-lasting solutions require site-specific management and strategic landscape-level plans (Fernando et al., 2005; Gubbi, 2012; R. Hoare, 2015; Shaffer et al., 2019).

The recently published paper "Integrating a 'One Well-being' Approach in Elephant Conservation: Evaluating Consequences of Management Interventions", offers a holistic perspective on elephant conservation (Van De Water et al., 2024). This approach aims to balance animal, human, and environmental well-being, addressing the interconnected impacts of conservation strategies. Elephant management interventions are often implemented to prevent human-wildlife conflict and protect biodiversity. However, these interventions can have many consequences across different dimensions (Menton et al., 2020; Otero et al., 2020; Van De Water et al., 2024). The "One Well-being" framework helps to assess these impacts comprehensively by categorising them into “direct intentional”, “direct unintentional”, and “indirect consequences”. This framework was applied to 12 elephant management strategies in South Africa, using data from 3.306 cases. The analysis revealed that while direct intentional consequences, such as planned management actions, were largely beneficial, direct unintentional and indirect consequences were frequently harmful. This highlights the need for conservation strategies that are balanced and integrated, considering all dimensions of well-being. The authors concluded that effective human-elephant conflict mitigation requires a combination of traditional methods, modern techniques, and comprehensive planning. By implementing adaptive and holistic strategies, it is possible to improve coexistence and promote elephant conservation while ensuring the well-being of all stakeholders involved (Van De Water et al., 2024).

To conclude, there are various approaches, including traditional methods and modern strategies, to strive for a peaceful coexistence between humans and animals. But many of these conservation programs, however, rely on technical innovations, such as autonomous early-warning and monitoring systems that can detect elephants over a wide area and monitor their migration patterns. It is also essential for conflict avoidance that when elephants approach human settlements, people are warned in a timely manner and can take precautions (Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

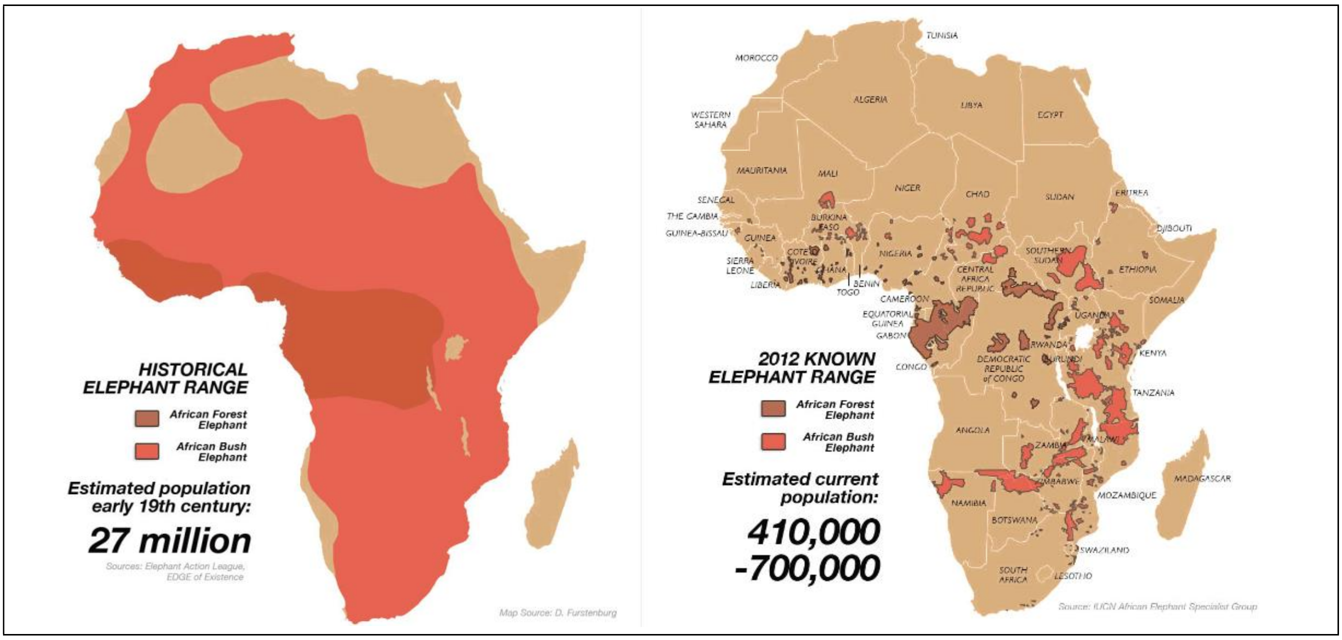

Figure 1: Maps of the historical and modern range of African elephants (Alex, 2017; IUCN SSC African Elephant Specialist Group | IUCN*, 2023).*

1.2 Communication and Acoustic Research

Elephants are long-lived, possess large brains, and have a highly complex social system (Bates, 2020; Plotnik & Jacobson, 2022). Consequently, they have developed a sophisticated communication system that engages all sensory modalities. However, this study will focus on acoustic signals because, unlike visual signals, they are omnidirectional and can effectively maintain group cohesion over long distances and in dense habitat (McComb & Reby, 2009; Poole et al., 1988a). The focus on acoustic communication of elephants is particularly relevant for the acoustic early-warning system, which will be discussed in more detail in Chapter 1.3.

For highly social animals like elephants, acoustic communication is particularly crucial. It conveys essential information not only about body size, age, sex, and fitness but also about the location of other individuals, state of arousal, and behavioural context (McComb & Reby, 2009; Poole, 2011b; A. S. Stoeger et al., 2011). For instance, a study by Stoeger et al. (2014) demonstrated that it is possible to distinguish age groups of African elephants based on acoustic parameters. These acoustic cues of social information are vital for the complex, so called fission-fusion society elephants live in (McComb et al., 2001a; McComb & Reby, 2009; Poole, 2011a; A. S. Stoeger et al., 2014).

Females live in matriarchal societies, using vocalizations to strengthen their bonds, maintain the herd's social dynamics, coordinate over long distances, and ensure survival and reproductive success by facilitating mating, alerting to threats, and promoting group cohesion (Langbauer, 2000; McComb et al., 2001a; Soltis, 2010, 2013; Wemmer, 2008). While females remain in their natal family, males disperse around the age of 14 and often form male-only coalitions and companionships (O'Connell-Rodwell et al., 2011, 2024). The majority of studies of elephant acoustic communication are on females, with little research on male elephant vocalizations (Baotic & Stoeger, 2017; O'Connell-Rodwell et al., 2011, 2024). Male elephant vocalizations are believed to be primarily related to intra-sexual dominance and reproduction (Poole JH., 1994). However, previous studies have shown evidence sexual dimorphism in the vocal behaviour of elephants (Baotic & Stoeger, 2017; O'Connell-Rodwell et al., 2011; Poole JH., 1994). Males vocalise less frequently than females (Baotic & Stoeger, 2017; O'Connell-Rodwell et al., 2011; Poole JH., 1994). Baotic & Stoeger (2017) conducted the only study to date that identified sexual dimorphism in the acoustic features of social rumbles in elephants (Figure 2). Therefore, sexual dimorphism in elephants is not only observable in physical traits like body size, tusks, and skull structure but also in vocalizations. These acoustic differences, influenced by body size, vocal fold anatomy, and hormonal factors such as testosterone, enable reliable identification of sexes through their vocalizations (Baotic & Stoeger, 2017). Male rumbles, for example, exhibit lower fundamental frequencies and distinct acoustic patterns compared to females. Such vocal differences are vital in social and reproductive contexts, aiding communication and mate selection within their complex social systems (Baotic & Stoeger, 2017; O'Connell-Rodwell et al., 2011; Poole JH., 1994).

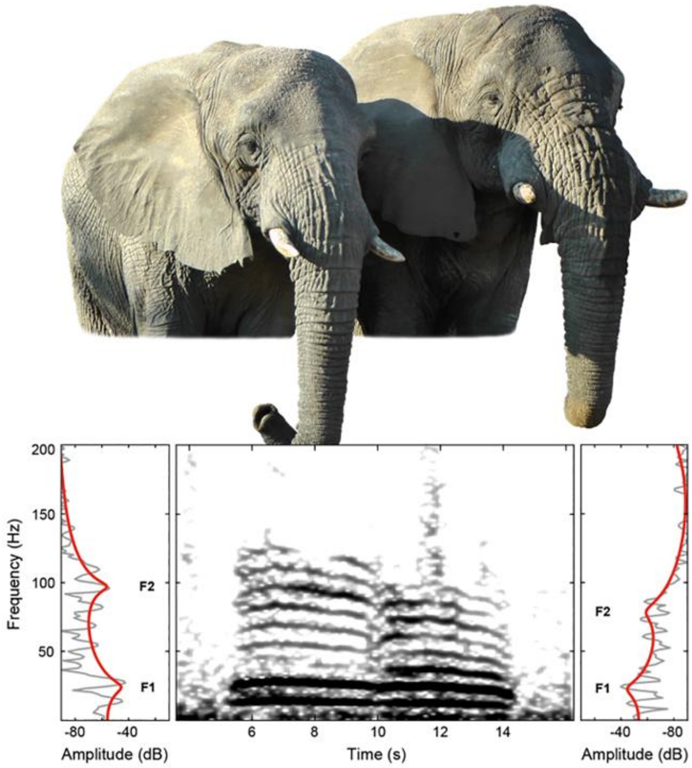

Figure 2: A spectrogram and a power spectra provide an example-comparison of a social rumble of a female (left) and a male (right), indicating formant positions (Baotic & Stoeger, 2017).

As discussed above, African savannah elephants are very social and vocalize frequently to stay in contact with their herd, mostly through the low-frequency 'rumble,' which is the most common call type in elephant communication (Soltis, 2010). Current findings show that African savannah elephants can produce many structurally different sounds, such as the low-frequency rumbling, the high-frequency trumpeting, the shouting, roaring and many other calls. Three independent studies (with individuals from different sex and age groups) concluded, that elephants can produce 8 to 10 different types of calls (Berg, 1983; Leong et al., 2002; Stoeger-Horwath et al., 2007). It has also been shown that elephants have a very high degree of vocal plasticity and are therefore often able to combine calls (Pardo et al., 2019; Poole et al., 2005; A. S. Stoeger & Manger, 2014). Furthermore, it has been demonstrated that African elephants are able to imitate sounds, are capable of vocal learning and develop individual mechanisms to produce idiosyncratic sounds (Poole et al., 2005; A. S. Stoeger et al., 2021; A. S. Stoeger & Manger, 2014).

At this point, it should be noted that mature male elephants in 'musth', a hormonally induced state marked by increased aggression, dominance behaviour, and reproductive activity, are known to produce 'musth-rumbles' (Poole, 1987). This type of rumble is unique among elephant vocalizations, characterised by repeated pulsations resonating in the nasal passages and overlaid on harmonic frequencies (Poole, 1987, S. 198, 1999; Poole JH., 1994). Similarly, females produce 'oestrous-rumbles' during their reproductive phase (Poole et al., 1988a). It is presumed that both musth-rumbles and oestrous-rumbles are used to signal or assess the behavioural and physiological status of potential sexual partners and rivals (Ganswindt et al., 2005a; Soltis, 2010).

At the beginning of elephant vocalization research, it was unclear for a long time, how elephants produce their harmonically rich, low-frequency rumbles with infrasonic components. It was not until 1986 that Payne et al. demonstrated, that Asian elephants indeed produce sounds inaudible components to humans, within in the infrasonic range (Payne et al., 1986). The spectrum of human hearing ranges from 20 Hz to 20.000 Hz (ref). In relation to this, sounds below 20 Hz are referred to as "infrasound," and sounds above 20.000 Hz are termed "ultrasound" (Beranek LL., 1988). Payne et al. (1986) described that Asian elephants can produce fundamental frequencies of 14 to 24 Hz. Additionally it has been confirmed, that the low-frequency rumbles are sounds that can be explained by the "source-filter theory", which means that elephant rumbles follow the same basic principles as human speech (Herbst et al., 2012).

Based on the source-filter theory, most vocalizations produced by mammals originate from the larynx and are then filtered by the supra-laryngeal vocal tract (Titze, 1994). The frequency of the source signal (the fundamental frequency f0) is determined by the dimensions, mass and tension of the vocal folds (Titze, 1994, 2011). As the source signal passes through each successive segment of the vocal tract (which acts as the "filter"), where resonances appear due to its morphology, it selectively amplifies specific resonant frequencies (formants) (Titze, 1994). There is a universal correlation between body size and vocal tract length within vertebrates: longer vocal tracts produce and the more closely spaced are the formant frequencies. In the larynx, the fundamental frequency of vocalizations is determined by the size of the vibrating tissue such as their size, length, and tension, rather than active control over vibration speed. According to the MEAD mechanism, these vibrations are passive and driven by airflow from the lungs, with the tension of the vocal folds playing a role in fine-tuning the resulting frequency (Herbst et al., 2012). The ability of elephants to produce very low-frequency sounds not only brings advantages in mating and aggressive behaviour but also in long-distance communication, as the infrasonic calls can potentially travel over several kilometres (Fitch, 2004; Langbauer et al., 1991; Payne et al., 1986). Langbauer et al. (1991) and Larom et al. (1997) have demonstrated through playback experiments that elephants respond to specific calls and can discriminate between individuals at distances of up to 2 km (Poole, 1999). At night, acoustic communication can extend over greater distances due to temperature inversions, potentially reaching up to 10 km. However, for recognizing individual animals, this distance is usually much shorter (McComb et al., 2003)

Although elephants, like other terrestrial mammals, use the myoelastic-aerodynamic (MEAD) mechanism for rumble production, they have an exceptionally long nasal vocal tract (proboscis) compared to their oral vocal tract (Herbst et al., 2012; A. S. Stoeger, Heilmann, et al., 2012). Studies using sound visualisation have demonstrated that elephants modify their vocal pathway from oral to nasal rumbles depending on the situation, leading to significant variations in the formant structure of their sounds (Soltis, 2010; Stoeger et al., 2012).

Elephant rumbles are characterised by a rich harmonic structure and low frequencies that fall within the infrasonic range, yet the upper harmonics can be heard by humans (Soltis, 2010). Current scientific understanding suggests that these calls serve multiple purposes, ranging from facilitating social interactions at close range to enabling communication and coordination over long distances (Poole et al., 1988a; Poole 2011).

It might be that low-frequency sounds evolved in elephants because they provided a critical advantage for communication over sight and smell in dense forests, their dominant habitat until late in their evolution (Garstang, 2004; MacFadden, 1997; Shoshani, 1998). This adaptation enabled elephants to maintain contact with conspecifics over long distances, a feature that continues to be vital for their survival in savannahs today (Fitch & Hauser, 2003; Garstang, 2004). Beyond its natural role in communication, this evolutionary trait also holds great potential for modern conservation efforts. Low-frequency vocalizations are invaluable for monitoring elephant populations, even in dense forests, and for mitigating human-elephant conflict (HEC), a major threat to the survival of these animals (Garstang, 2004; Zeppelzauer & Stoeger, 2015). Acoustic monitoring systems have already proven effective in estimating the population of African forest elephants *(Loxodonta cyclotis)* and show promise for application with African savannah elephants (Garstang, 2004; Poole, 2011b; Thompson, 2010; Thompson et al., 2010; Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

1.3 Acoustic Monitoring and Early-Warning System

Acoustic monitoring systems have been used for years in many different countries and with different species. This method serves as a non-invasive way to measure and monitor sound-producing species (Digby et al., 2013; Drakshayini et al., 2023; Knight et al., 2017; Sharma et al., 2023; Zeppelzauer & Stoeger, 2015). It can be used in a wide variety of fields, which are discussed in the following chapter.

As mentioned in Section 1.1, humans are expanding further into natural habitats, leading to increased landscape fragmentation and more frequent encounters between humans, African elephants, and other wildlife. This issue is prompting worldwide efforts to find solutions for peaceful co-existence. One promising approach is acoustic monitoring systems, which are being developed not only to monitor animal populations but also to warn the local human population in a timely manner when wild animals are approaching (Frommolt, 2013; Wall et al., 2014; Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

The method of acoustic pattern recognition has already demonstrated significant potential, particularly in the development of automated procedures for recognising sound-producing animals (Frommolt, 2013; Teixeira et al., 2019; Wrege et al., 2017). In recent years, there have been substantial advancements in environmental monitoring, especially in wildlife observation. Acoustic sensors such as Autonomous Recording Units (ARUs), Hydrophones, Microphones or Seismic Sensors now play a crucial role in measuring and documenting the presence and activities of animals (Knight et al., 2017; Teixeira et al., 2019). These technologies are essential for research and the protection of various species, providing invaluable data to support conservation efforts (Frommolt, 2013; Teixeira et al., 2019; Wall et al., 2014; Wrege et al., 2017). There is also the field of ecosystem monitoring, where acoustic data is used to monitor the condition and biodiversity of ecosystems such as forests, marine areas or savannahs (Borden & Flory, 2021). Additionally, there is substantial research in the field of noise measurement. In urban areas, acoustic monitoring is conducted to measure ambient noise and assess its impact on wildlife and humans. This data is crucial for planning noise protection measures if necessary (Hao et al., 2024; Panda et al., 2022). For instance this topic has gained considerable media attention in recent years due to evidence that birds and other wildlife in urban environments, where anthropogenic noise pollution is high, tend to vocalise more loudly or shift their frequency range (Hao et al., 2024; Panda et al., 2022).

It should be mentioned here, that the first acoustic monitoring of animals was carried out on marine mammals such as whales (*NOAA Ocean Exploration*, 2024). Hydrophones (underwater microphones) were used to record and study the characteristic calls and songs of whales. These techniques allow researchers to study cetacean behaviour, migrations and population dynamics. Passive acoustic monitoring (PAM) is increasingly being used as whales are often easier to hear than to see. PAM is not only used to study and count marine mammals, but also helps to mitigate the negative impacts of human activities such as shipping traffic, sonar and offshore exploration (Au & Hastings, 2008; Richardson et al., 1995; Zimmer, 2011). In recent decades, human activities have made the oceans significantly louder, which affects, for example cetacean communication. The noise from ships and sonar disrupts the whales' orientation, foraging and social interactions. PAM is being used to understand these impacts and foster development of solutions. These monitoring techniques document the presence and behaviour of whales and analyze the noise sources and their intensity (Au & Hastings, 2008; Zimmer, 2011). Through such technologies such as PAM researchers can better understand how whales react to noise and develop measures to minimise the negative effects. This is crucial for the protection and conservation of cetaceans in increasingly noisy oceans (Au & Hastings, 2008; Richardson et al., 1995; Zimmer, 2011).

For over twenty years, wildlife acoustics have been used by field researchers to estimate the population size and abundance of various species, particularly in birds and marine mammals. This technique has also been applied to species like tigers *(Panthera tigris)*. Tigers, like African savanna elephants, are severely affected by habitat fragmentation and poaching and are classified as endangered according to the IUCN (*The IUCN Red List of Threatened Species*, 2021). Similar to African savannah elephants, tigers can communicate over long distances, making them highly suitable for acoustic monitoring (Walsh et al., 2010). In the "Prusten Project", for example, tiger vocalizations are recorded using automated recording units (ARUs) and analyzed to attribute sounds to sex and age as well as specific individuals, helping to estimate population sizes (Holmes et al., 2014; Palminteri, 2015). This method is crucial for monitoring tigers in dense forests where visual identification is difficult. Knowing the number and location of individual tigers is vital for conservation efforts, as it informs decisions about which areas to protect. Understanding the population dynamics of wild tigers aids in directing resources, such as funding and rangers, to key areas to combat poaching and protect these regions from negative human impacts (Holmes et al., 2014; Palminteri, 2015). For example, microphones can also be used to detect the sounds of poachers (e.g., poachers moving through the area, gunshots, or chainsaws used for illegal logging activities) (Garstang, 2004; Palminteri, 2015; Walsh et al., 2010).

African savannah elephants, as discussed in Chapter 1.2, have complex social structures and highly developed communication behaviour (Garstang, 2004; Langbauer, 2000; Soltis, 2010, 2013; Wemmer, 2008). In the context of acoustic research on elephant behaviour and especially in the search for solutions to combat HEC, the question arises, whether elephants are a suitable species for acoustic monitoring. To answer this question comprehensively, several important aspects must be considered. Firstly, elephants communicate using a variety of vocalizations, especially the low frequency rumble, which allows acoustic systems to detect and analyze them over long distances (Berg, 1983; Garstang, 2004; Leong et al., 2002; Stoeger-Horwath et al., 2007). This in turn makes it possible to warn the local population at an early stage so that they can react in a timely manner and take appropriate measures (Zeppelzauer et al., 2015). Secondly, elephants live in social groups and use vocalizations to mediate contact and coordinate movements, which means that their communication and movement patterns can be theoretically tracked through acoustic monitoring. Thus, changes in behaviour or certain call patterns can indicate threats or changes in their environment, which is very relevant information for nature and species conservation (Langbauer, 2000; Payne et al., 2003; Soltis, 2010; A. S. Stoeger et al., 2011; Wemmer, 2008). Overall, these points indicate that elephants' biological and social characteristics make them ideal for the use of acoustic monitoring and early-warning systems that can support both conservation and human population protection (Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

Biologists, computer scientists and mathematicians from Austria *(Mammal Communication Group; Austrian Academy of Sciences, Acoustics Research Institute; University of Applied Sciences, Media Computing Group; Vienna University of Technology Institute for Software Technology and Interactive Systems)* are actively involved in pioneering such a system. The main objective is to develop a non-invasive monitoring system that can recognise elephants by means of acoustic and subsequently also visual signals (Zeppelzauer et al., 2013, 2015; Zeppelzauer & Stoeger, 2015). For an acoustic monitoring and early warning system to succeed, it must robustly and automatically recognise elephant vocalizations under natural field conditions. In order for elephant sounds to be recognised automatically and, above all, to be robust and safe in relation to various noise sources in the respective environment, a lot of data had and still has to be collected under natural field conditions. Zeppelzauer et al.'s (2015) method showed promising results and outperformed existing approaches, recognising elephant rumbles reliably and accurately. The basic acoustic detection system, using data from a group of semi-captive elephants, achieved an 88.2% detection rate but showed a false-positive rate of 24.4%, demonstrating both its promise and the need for further refinement (Zeppelzauer & Stoeger, 2015). In comparison, other methods such as spectral template matching had high false positive rates (78.6 %) (Zeppelzauer & Stoeger, 2015). Additionally, the team has explored the extent of what can be achieved with visual recognition. The developed visual recognition algorithm segments video images and uses colour models to distinguish elephants from the background. The algorithm is robust against occlusions and can reliably detect elephants even in challenging environments recorded at the Addo Elephant National Park (Zeppelzauer & Stoeger, 2015). The visual component of the early warning system is also relevant because, for example, males often do not vocalise as much as female groups, making the acoustic system alone potentially insufficient for a reliable detection (Baotic & Stoeger, 2017; O'Connell-Rodwell et al., 2011; Poole JH., 1994). Different modalities are important, so if they are missed acoustically, they can be traced visually (Zeppelzauer & Stoeger, 2015).

The envisioned elephant early warning and monitoring system by Zeppelzauer & Stoeger (2015) consists of three modules: the input, the processing, and the output module, as shown in Figure 3. First, there is the input module, which comprises various sensors that collect different data from the environment. The sensor input can be highly multimodal, including acoustic sensors (individual microphones or microphone arrays for directional measurements, which are used to determine the location and direction of sound source) and various visual sensors such as video cameras and thermal cameras. The input module collects data from these sensors to provide information for analysis. Next is the processing module, which is responsible for processing the data from all the sensors, undergoing acoustic and visual detection analysis. The processing module is crucial for interpreting the sensor data and extracting meaningful information from it. For training the processing module, it is important to collect a lot of data under natural field conditions, because the more data the system receives and can analyze, the more robust the early warning system becomes (Zeppelzauer & Stoeger, 2015). Lastly, there is the output module, which provides the results of the analyses conducted in the processing module, which can include detected elephant presence, behaviour, or movements. The output module may generate early warning messages. Additionally, the outputs from the processing module serve as input for higher-level tasks in the analysis layer, enabling further in-depth analysis and interpretation of the data (Zeppelzauer & Stoeger, 2015).

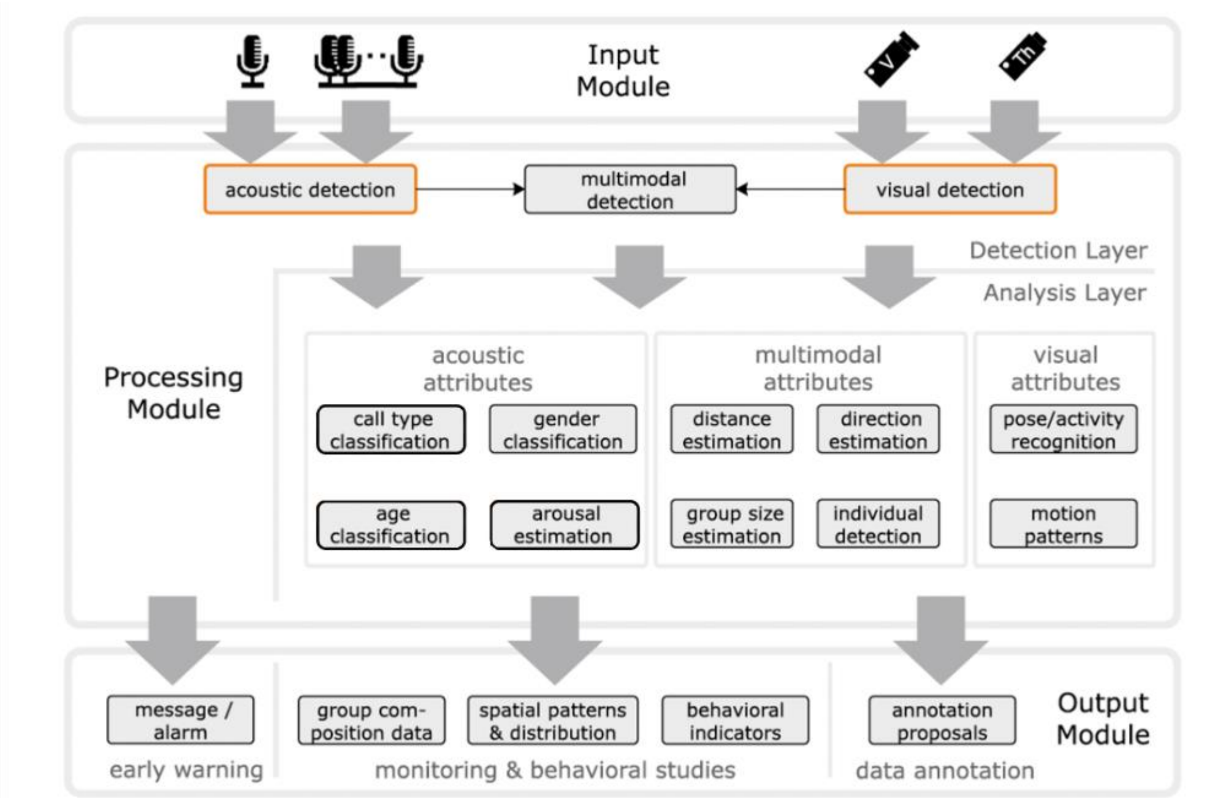

Figure 3: An overview of the envisioned elephant early warning and monitoring system discussed in Chapter 1.3 (Zeppelzauer & Stoeger, 2015).

To develop a reliable system, many factors play a role and there are some challenges that still need to be addressed. Signal enhancement techniques, such as those introduced by Zeppelzauer and colleagues (2013), are essential for improving detector performance in noisy environments. Additionally, robust algorithms and machine learning models for acoustic signal detection and species identification need further development and implementation (Frommolt, 2013; Zeppelzauer et al., 2013; Zeppelzauer & Stoeger, 2015).

Overall, a lot of substantial fundamental work is required, such as the research conducted by Stoeger et al., (2014) on age group estimation of African elephants or the studies on sex dimorphism in rumbles (Baotic & Stoeger, 2017; Poole JH., 1994; Stoeger et al., 2014).

One of the most important work packages to establish a functioning system capable of automatically detecting calls is the annotation of the data, as this provides the ground truths. Through this process, empirical evidence provided through an observer is added into the system. Through this data, the system learns to distinguish between human-made noises, for example vehicle noise, other animal sounds, and elephant sounds (Zeppelzauer et al., 2013). The environment from which the data originates and in which the system is trained plays an important role as well, as each environment has its own specific background noises. It is also crucial to consider the environment, knowing whether it is characterised by many noise sources or remains rather quiet, helps decide whether the focus should be more on visual or acoustic cues. In summary, the more data is collected and provided to the system, the more it learns and improves (Zeppelzauer et al., 2013, 2015; Zeppelzauer & Stoeger, 2015).

One of the biggest challenges for computer scientists and bioacousticians currently, is the automatic recognition of animal vocalizations, for example elephants have high variability and vocal creativity in their vocalizations (A. S. Stoeger et al., 2021; A. S. Stoeger & Manger, 2014). Recent research by Pardo, Lolchuragi, et al. (2024) revealed that vocalizations within a species can vary significantly in structure, from the individual level to the population level. Their study found clear evidence of distinct vocal patterns among individuals and populations, as well as more subtle differences among social groups. These findings demonstrate the need to study and collect data from diverse populations to effectively train acoustic monitoring systems (Pardo, Lolchuragi, et al., 2024; Zeppelzauer & Stoeger, 2015).

The automated analysis of animal vocalizations is gaining increasing research attention as a non-invasive method to study and monitor wildlife. Technologies like machine learning and remote sensing show significant promise in automating species identification, habitat mapping, and population tracking. By integrating artificial intelligence with remote sensing data, these systems can classify calls, monitor endangered species, and enable proactive measures to protect habitats and mitigate human-wildlife conflicts (Drakshayini et al., 2023; Zeppelzauer et al., 2013, 2015; Zeppelzauer & Stoeger, 2015).

In conclusion, long-term and large-scale field tests are now necessary to evaluate the actual performance of the system in different real-world scenarios, identify potential weaknesses, and address them. This is precisely the goal pursued by Zeppelzauer & Stoeger (2015) in implementing the acoustic early warning system, which is urgently needed for nature and species conservation as well as human protection (Zeppelzauer et al., 2013, 2015; Zeppelzauer & Stoeger, 2015).

1.4 Research Questions and Hypothesis

This thesis aims to explore the intraspecific communication of African elephants, with a specific focus on their vocalizations and behaviour of the Marataba elephant population. Using acoustic data collected in South Africa, the study seeks to contribute to and the enhancement of a further the acoustic monitoring system for African elephants (Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015). The goal is to support the work by adding data of an elephant population that has not been recorded before, and by increasing knowledge about the information that is encoded in in elephant vocalizations.

I initially analyzed and described the vocal behaviour of the elephant population in Marataba, concentrating on the behavioural context of males and females within herds, while also examining background noise and its masking effect on vocalizations, which is relevant for autonomous detection (discussed in Chapter 1.3).

The primary objective of my research was the annotation, analysis, and comparison of female and male rumbles, as determining demographic information, including the sex of approaching individuals, is crucial for local communities and the early-warning system. This thesis presents a comparative analysis of social rumbles produced by African elephants, comparing the findings with those of Baotic & Stoeger (2017)

This leads to my first hypothesis:

1. Significant differences exist in the acoustic parameters of rumbles between male and female elephants within the Marataba population.

Another focus was on the comparison of rumbles from bulls not in musth and bulls in musth. Especially when bulls are in musth, they show increased aggressive behaviour, posing an even greater danger to humans and their settlements (Ganswindt et al., 2005a; Graham et al., 2010; Poole JH., 1994; Santiapillai et al., 2010; Smith & Kasiki, 1999).

Previous studies (Poole JH., 1994) have documented demonstrating that musth males produce a display that includes a characteristic musth rumbles, yet relatively little is known about the vocal behaviour of males in general. For example, there has been no mention of their use of social rumbles during this state (Baotic & Stoeger, 2017; Ganswindt et al., 2005b; Poole, 2011b; Poole et al., 1988a; Poole JH., 1994; Soltis, 2010; A. S. Stoeger & Baotic, 2016a). This leads to my second hypothesis:

2. Are musth rumbles a reliable acoustic indicator of an elephant's hormonal state?

I aim to investigate into the vocal behaviour of bulls, if musth-bulls can deliberately control their vocalizations and if their musth status can be identified from the acoustic parameters. I will compare the acoustic differences in a descriptive manner as a first step towards conducting a comprehensive study to determine whether normal rumbles and musth rumbles convey information about the individuals' hormonal state.

2. Methods

2.1 Study site and study subjects

Data was collected in the Marataba Contractual National Park (-24.342587, 27.585978), a 2.000-hectare privately managed section of the Marakele National Park in South Africa's Limpopo Province (Fig. 4).

Marataba is home to a variety of wildlife, including the Big Five: lions, leopards, rhinos, elephants, and buffalo. Additionally, visitors can find cheetahs, hippos, giraffes, zebras, and numerous bird species. The management of Marataba National Park is dedicated to sustainable conservation practices. The park operates under a philosophy of balancing wildlife preservation with community involvement and eco-tourism. Efforts are made to protect endangered species and their habitats while promoting education and awareness among visitors. The park also collaborates with local communities to ensure that conservation efforts benefit both the environment and the people living in the area (*Marataba*, 2020).

Figure 4: Location of Marataba, our study region in South Africa (Staufer, 2024).

At the time of our data collection there were around 400 elephants in the park, including 83 identified males and 17 family groups (A-Q). The family sizes ranged from 5 to 23 individuals.

To accurately identify individual elephants, we utilized identity kits (ID kits) created by Vesta Eleuteri and a team of volunteers. This comprehensive identification tool was developed during 2018 and 2019 specifically for the Marataba Conservation Team, providing a reliable resource for distinguishing between different elephants within the park (Figure 5).

In identifying elephants, so-called Key ID features are used, which include: "LT = Left Tusk," "RT = Right Tusk," "LE = Left Ear," and "RE = Right Ear." These refer to distinctive characteristics of the ears or tusks. Additionally, the age class and body size are considered. For instance, the individual HFF1 in Figure 5 belongs to Age Class B, corresponding to an age between 15 and 40 years (Figure 5).

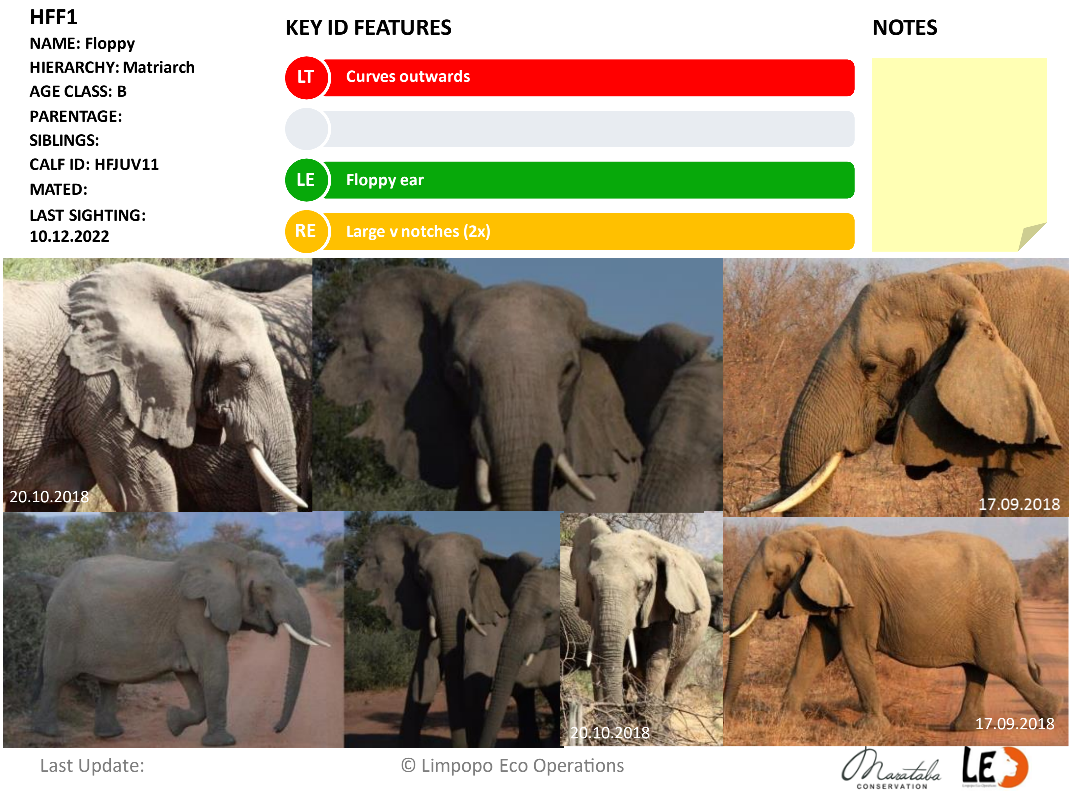

Figure 5: Example for an ID-Kit of the elephant "HFF1" of the Herd F, made by Vesta Eleuteri.

2.2 Data collection

Data collection employed in this study encompassed audio recordings, video recordings, behavioural observations, and elephant monitoring data. I focused to collect diverse recordings of wild elephants, including factors such as varying environmental conditions, recording distances, types of vocalizations, behavioural contexts, age groups, and sex in order to document the overall communicative behaviour and pattern of this specific elephant population.

Data were collected between October 2022 and December 2022 from a Land-Cruiser vehicle provided to us by the park, with the assistance of Vesta Eleuteri, a PhD student at the Mammal Communication Group and Department of Behavioural and Cognitive Biology, University of Vienna.

Recording sessions were conducted every day from sunrise (6am) to sunset (7pm) with usually a one-hour break around midday. Recording distances were consistently maintained between approximately 10-60 meters to avoid disturbing the elephants while ensuring high sound quality and visibility.

Due to the lack of data on the collared elephants, we had to actively search for elephants every day within the park. Given the park's vast size, lush vegetation, and complex topography, locating individual elephants and herds was sometimes challenging. Even when we successfully located a family or a group of males, we frequently lost sight of them in the dense habitat, complicating data collecting.

Audio recordings were made following the methodology of Stoeger et al. (2014), using an omnidirectional Neumann KM 183 microphone (modified to capture frequencies down to 5 Hz) and a Rycote windshield. The microphone was connected to a Mix pre-6 Sound Device Recorder. The recording device was mounted on a tripod attached to the car. Simultaneous to the audio recordings we also collected video recordings with a Panasonic HC-VXF1 camcorder in 4k Ultra HD quality. This is helpful for synchronising and analysing the acoustic and visual data with the field notes.

I also collected detailed field notes on observed behaviour and descriptive information for each recording. I noted the following variables and information:

- Date and time
- File number of recording
- Location of the elephants
- Approximate distance from microphone
- Weather conditions (temperature, clouds, wind)
- Individuals or groups present (group size)
- Estimated age group (how many infants, calves, juveniles, subadults and adults)
- Identification of vocalizing individual
- Identification of call type (for example: rumble, must-rumble, trumpet, roar,..)
- Sex of the vocalizing individual
- Behaviour of vocalizing individual (Table 1)
- Behaviour of overall group (which activities for example: feeding, drinking, travelling, sparring…) (Table 1)
- Overall context in which a vocalization happened (for example if a male harasses a female…) (Table 1)
- Musth/no musth (if males were present)

Table 1: Description of the Behavioural Contexts (Eleuteri, in preparation).

Context name	**Description**
Affiliation	An individual affiliates with another one in general (usually included tactile behaviours: hugging with trunk, touching temporal glands, touching mouth, touching genitals (which also convey chemical info)). Greeting is only if individuals have just met. But put this when not sure whether greeting.
Little Greeting	An individual greeting another after they had been separated for a while. Description of greeting behaviour: J: A Rumbling greeting exchange between members of an elephant family in which one (usually older and female) approaches another (usually younger, in parallel and from behind). Typically, the approaching elephant gives a Little-Greeting-Rumble and the elephant being approached, responds by Head-Raising, Ear-Lifting and sometimes Backing-Towards the approaching elephant and gives a Little-Greeting-Rumble in return. Often both individuals engage in Head-Raising and Ear-Lifting and may Social-Rub and Ear-Brush against one another or otherwise touch one another or greet Trunk-to-Mouth.
Greeting Ceremony	An individual taking part in a group greeting. Description of Greet-cerem by J: During a Greeting-Ceremony members of a family or bond group may rush to meet one another while emitting loud, modulated, throaty Greeting-Rumbles, and, sometimes, Social-Trumpets and Roars. The elephants raise their heads, lift and spread their ears, secreting Temporin profusely. As they meet, they flap their lifted ears rapidly, while still Rumbling, Trumpeting and Roaring. Rubbing together they may stand in parallel, or face-to-face, and while holding heads high, Open-Mouth-to-Open-Mouth they may click their tusks together and entwine trunks. As the greeting continues, they may back into one another, Pirouetting, Urinating and Defecating.
Defensive	An individual bunches together with others or protects an individual after hearing or seeing a threat.
Agonistic	An individual is attacking or mock charging another elephant (if attack is to another species note it in comments).
Consortship	A male follows a female allegedly in oestrous and spending time together.
Digging	An individual is digging the ground with their tusks.
Drinking	One or more individuals are drinking water. Refers to the broader context of a group drinking at a water source. Social interactions such as vocal exchanges (contact calls), physical contact, or coordinated movements may occur.
Dusting	An individual is dusting himself with dry soil.
Bathing	An individual is bathing, splashing, submerging in a water hole or river.
Feeding	An individual or more browsing or grazing. If they move in between feeding patches while doing so it´s still feeding. Social interactions such as vocal exchanges (contact calls), physical contact, or coordinated movements may occur.
Listening	An individual listening and not engaging in any other behaviour. When elephants listen, they suddenly stop moving, raise their ears and feel the ground with their feet (sometimes having one foot up with just the front touching the ground). Subtle change in tension in body posture differs it from resting.
Mud bathing	An individual is wallowing in mud or covering themselves with mud.
Musth	Advertisement behaviours specific to males in musth towards any sex: musth stance and walk. Put this context for any advertisement signals done by males in musth.
Suckling	A mother/allomother suckling her calf.
Sucking	A calf sucking from a mother/allomother.
Play social	An individual is playing in general with another one (if sparring, put sparring, see definition below).
Play solitary	An individual playing by himself, including playing with objects.
Play social in water	An individual is playing with another one in water.
Sparring	An individual is sparring with another one: can include pushing, tusking, entwining trunks, tusks while front facing each other. Usually done from subadulthood and has a dominance affirmance component.
Resting	An individual is not engaged in any of the other active contexts like traveling, feeding etc and is relaxed either standing up or lying down (do not confuse with listening as when listening it´s a sudden freezing or tension in posture as described above). An individual can flap his ears as a thermoregulation strategy and move a bit their trunk while resting.
Post copulation behaviour	The behaviour of an individual after she/he copulated. E.g., a female calls, is very excited and touches the male´s penis, rubbing with the male she mated with (and viceversa for male).
Mating pandemonium	The behaviour of elephants approaching individuals after they mated where they vocalize, display, defecate, urinate, touch genitals etc.
Sex	An individual has sex or reproduces sexual behaviours with another one of the opposite sex. For example, if a male mounts a female or a female does.
Socio-sexual behaviour	An individual reproduces sexual behaviours towards an individual of the same sex: mounting, showing erect penis etc (could be signs of dominance).
Swimming	An individual swimming in a river. Different from bathing in that they actually travel by swimming.
Traveling	An individual is locomoting.
Other	Another behaviour not listed.
Unclear	When it´s unclear which behaviour it is.
Unknown	When it is unknown which behaviour it is.

Before data collection, categories for the age of elephants were established. We utilized the following categories: infant, calf, juvenile, subadult, and adult (A. S. Stoeger et al., 2014) (Figure 6).

As we frequently collected data from male groups with different ages and sizes, we try to distinguish when young bulls or old bulls vocalised and divide them into 3 categories. These are not official age categories, they were only used to help us in the field. We used the additional age categories: 'Young adult' (15-25 years old), 'Medium adult' (25-35 years old), and 'Old adult' (>35 years old), based on physical features and available ID kits.

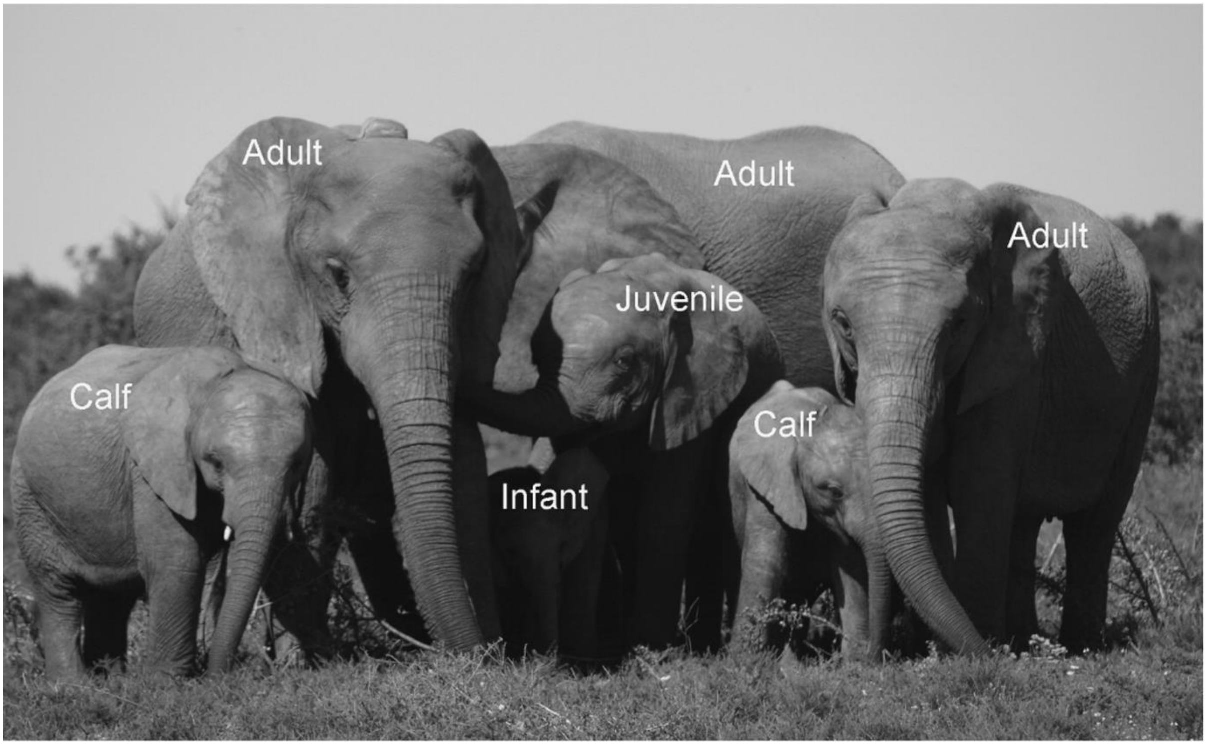

Figure 6: Example of an elephant group at the Addo Elephant National Park showing the age-group categories: infant, calf, juvenile and adult (A. S. Stoeger et al., 2014).

Categories used for sounds were defined prior to data collection, referring to the categories defined by Leong et al. (2003), Moss et al. (2011), Soltis et al. (2005), Stoeger-Horwath et al. (2007). We employed the following categories: rumble, must_rumble, trumpet, croaking, roar, noisy, mixed and tonal_roar, bark, grunt, snort, feeding_noise, fart, and unclear (Table 2).

Table 2: Definitions of used call type categories.

Call type	Definition
Rumble	Rumbles are harmonically rich, voiced sounds with fundamental frequencies near the infrasonic range. These low-frequency, tonal vocalizations serve social functions such as coordinating spatial dynamics, movement, and maintaining contact (Poole, 2011b).
Musth rumble	A musth rumble is a distinctive vocalization produced by male elephants during the heightened sexual and aggressive period known as musth. This rumble is characterised by a pulsated, low-pitched tonal quality with significant overlaying noise. These calls can vary significantly in length and pulsation among different males (Poole, 2011b).
Trumpet	Trumpets are loud, high-frequency sounds generated by a forceful expulsion of air through the trunk. Typically produced in distress or high-arousal situations, they are medium to high-intensity vocalizations characterized by frequency modulation and varying harmonic structures (Poole, 2011b; A. Stoeger, 2020).
Croaking	Croaking is an orally emitted, pulsatile and harmonic sound and is often associated with sucking water or odors into the mouth (Soltis, 2010; A. S. Stoeger et al., 2021).
Roar	Graded sounds that range from tonal to chaotic, typically emitted in distress or high-arousal situations (A. Stoeger, 2020).
Noisy roar	A noisy roar is characterized by the absence of harmonic elements, resulting in a rough or harsh sound quality, were the fundamental frequency varies (Stoeger-Horwath et al., 2007).
Bark	The bark is a short, primarily noisy call produced by a single burst of overpressure in the vocal cavities. Elephants open their mouths wide when making this sound. The bark's brief duration and transient nature are consistent, though there is some variation in its fundamental and dominant frequencies (Stoeger-Horwath et al., 2007).
Grunt	Grunts are very soft, barely audible from over 20 meters away, and are produced with the mouth almost closed. (Stoeger-Horwath et al., 2007).
Snort	The snort is a non-tonal sound produced by a forceful burst of air through the trunk. It has a consistent structure but shows some variation in frequency characteristics, with peak frequencies reaching up to 1500 Hz. The sound lasts between 0.2 to 1.2 seconds, and its dominant frequency remains consistent throughout its range (Berg, 1983; Stoeger-Horwath et al., 2007).
Unclear	When it's unclear if it was a vocalization or not.

To identify which individual is vocalizing, it is best to observe and listen to the group of elephants without earphones. It is also easier to identify a vocalizing individual in calm contexts as browsing or feeding where the elephants are widespread in an area, and you can identify where exactly the sound comes from. The use of earphones, which are connected to the microphone, is helpful to verify if the microphone is recording properly and to locate the elephants, as the low-frequency rumbles are often audible even when the elephants are not yet visible.

To accurately identify which individuals were vocalizing, we observed their behaviour and body posture. Body postures such as an open mouth, specific body postures, or ear flaring can be indicative of vocalizations. The precise identification of vocalizing individuals predominantly focused on adult elephants, as our data were limited to existing ID kits, which sometimes lacked identification information for infants and calves. However, we often encountered infants, calves, and juveniles during recordings, and in such cases, we made detailed notes regarding descriptive data, family affiliations, and gender (if possible). During data analysis, video footage was compared with the audio recordings to further identify vocalizing individuals. This method proved particularly useful in instances of choruses or overlapping vocalizations, where focusing on a single individual might have been challenging. This approach allowed for more precise identification and analysis of vocalizing individuals post hoc.

In addition to collecting acoustic and behavioural data, we also gathered monitoring data, which was subsequently used to enhance the existing ID kits. We collected data on date, time, video time, latitude, longitude, area in the park, number of individuals present, group composition, herds present, ID of individuals, activity of the individuals and video recordings of distinctive features, such as ear patterns and tusk characteristics, to add individuals to the existing monitoring ID kits.

2.3 Data entry and analysis

2.3.1 Data annotation

Data was annotated using the field notes and the software STx (Version 5.0.6) (Balasz P. & Noll A., 2000). The software STx is used for acoustic analysis and comes from the Acoustic Research Institute of the Austrian Academy of Sciences (Balasz P. & Noll A., 2000). I further worked with a template customised and adapted to my data using the software Notepad++ (version 8.4.9) (Don Ho, 2003).

The first step was to load all the data into the software and adjust the parameter settings for the signal analysis and the spectrograms. To be able to analyze different sounds, three signal analysis spectrograms were created. A 'High Frequency' spectrogram *(Settings: fit amplitude spectrum, frequency range: 0-1000Hz, amplitude: range=-80dB.-50dB (30dB), frequency scale: Hz, weighting: none)* preset was created for high-frequency sounds such as trumpeting, a 'Rumble' spectrogram *(Settings: fft amplitude spectrum, frequency range: 0-200Hz, amplitude: range= 65dB.-35dB (30dB), frequency scale: HZ, weighting: none)* was created for low-frequency sounds such as 'Rumbles' and one for 'Overview' *(Settings: fft amplitude spectrum, frequency range: 0-250Hz, amplitude: range=-70dB.-40dB (30dB), frequency scale: Hz, weighting: none)*. An example for an 'Overview' spectrogram of a sound file is shown in Figure 7, where a few 'rumble' sounds can be seen, as well as some noise in the beginning and at the end of the recording. An example for the finished STx template, with all the parameters I used is shown in Figure 8, here I selected a single rumble of the male EM08 (Figure 8).

The next step was to use the spectrograms, field notes and video recordings to find the individual sounds and enter all the collected information into STx. Each sound was given an ID-number, and the duration was determined. Further for each single sound, information about the caller (such as gender and age), the social context, behaviour and present individuals were noted (Figure 8).

We always distinguished between 'single_vocalization' and 'multiple_vocalization'. For 'multiple_vocalization' there were the categories 'combination', 'overlapping' and 'chorus' as well as 'unknown' or 'unspecified'. A 'single_vocalization' is referring to a single, distinctive call by one individual. The call-category 'combination' was applied when a single individual produced multiple vocalizations of different call types, for example a roar-rumble or a rumble-roar-rumble (Pardo et al., 2019). A 'overlapping' vocalization is if more than one individual vocalizes and the vocalizations overlap each other. 'Chorus' describes the case in which several individuals vocalise and these sounds overlap.

After the annotation, all the metadata were exported into an Excel list using a custom-made script. The single sound files were exported as .wav files. The script was also set to add 1 second before and after each sound, facilitating the subsequent acoustic analysis which was carried out in Matlab, following the customized semi-automatic sound analysis tool of Zeppelzauer & Stoeger (2015). The last step is to select the 'output directory' and save the data in XML format.

I annotated a total of 636 recorded vocalizations using STx and with the help of the Excel list I conducted a descriptive data analysis, providing a good overview of my data: After gaining this overview about sample sizes for calls per category for sex, call type, age groups (defined in Figure 6.), behavioural context and sound quality, I was also able to consider which sounds to use for further acoustic analysis. The sound quality was classified into five categories, ranging from 1 to 5. Category 1 represented high-quality vocalizations that were clearly detectable on the spectrogram, while category 5 indicated vocalizations that were not easily discernible.

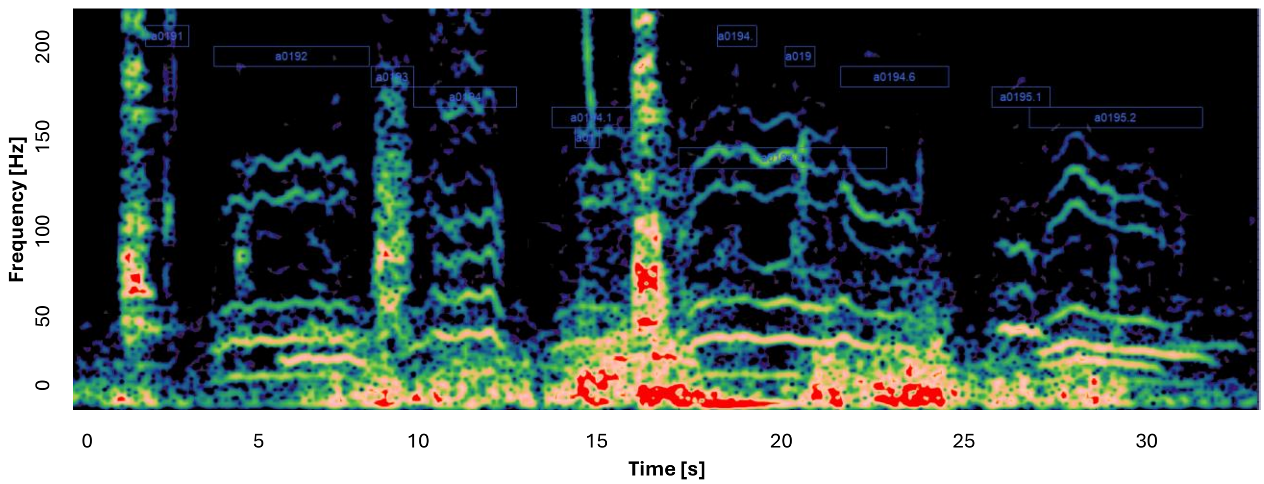

Figure 7: Screenshot of a Spectrogram.

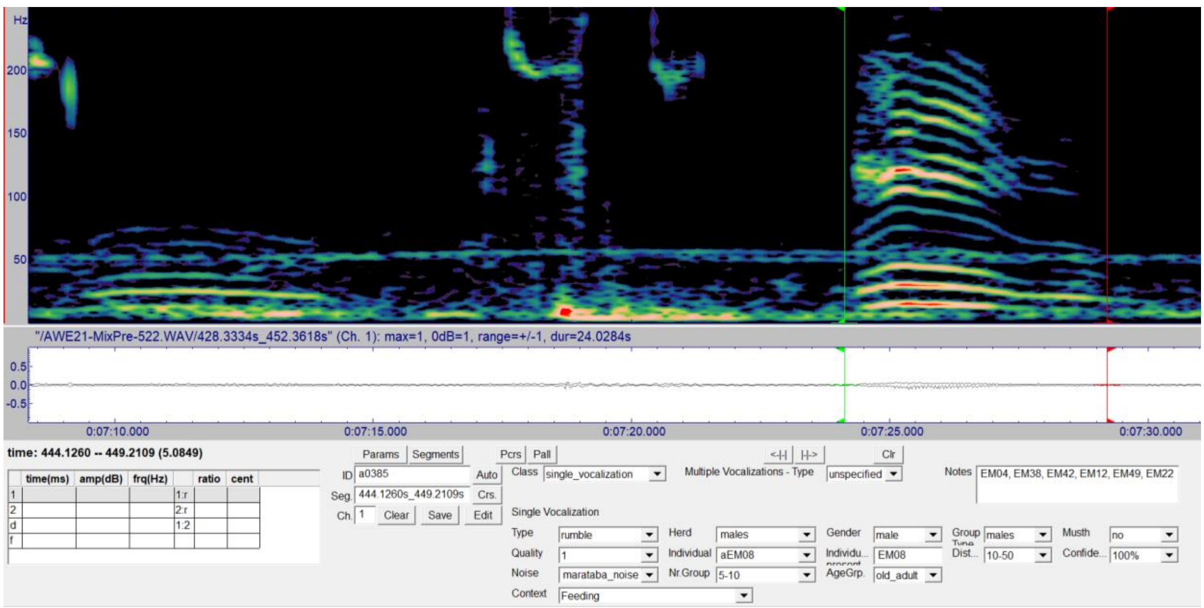

Figure 8: Screenshot of the STx template used for annotating elephant vocalizations.

Since distinguishing between elephant sounds and other noises is crucial for the development of an early-warning system, this work also involved annotating the noise present during vocalizations. It is important to differentiate, for example, between sounds from generators, wind turbines, or vehicles, which can also produce noises in the infrasonic range. A reliable differentiation between elephant sounds and those from other animals is also essential. Therefore, for the further development of the early-warning system, it is imperative to identify and annotate these sounds so that the system can learn to distinguish between them.

2.3.2 Acoustic analysis

Since this is the first study to describe the Marakele/Marataba elephant population both acoustically and behaviourally, I will provide a detailed analysis of the descriptive data for the population. For the acoustic analysis of the data and to test the hypothesis regarding sex differences and musth-non-musth social rumbles, I annotated rumbles, because these low frequency vocalizations are the most relevant for the development of an acoustic early warning system.

I chose 103 rumbles from females (quality 1-4) and 52 rumbles of males (quality 1-4). Furthermore, I wanted to take a closer look at the sound structure of rumbles from males in musth, rumbles from males not in musth, and musth-rumbles from males in musth. For this I selected high-quality recordings. This comparison will help to determine whether there are recognisable differences in the vocalizations and structures of the calls of the males depending on their hormonal state.

<u>The three categories (in males) I compared are:</u>

1. Rumbles of males not in musth (36 calls)
2. Rumbles of males in musth (22 calls)
3. Musth rumbles from males in musth (3 calls)

I excluded vocalizations with sound quality 5, as it was often not possible to recognise the fundamental frequency (f0) in these sounds, for example if there was too much noise, or the individual was too far away. The selected data was subsequently extracted from STx and saved as .wav files using a custom-made script for further analysis.

For data analysis of the fundamental frequency and first harmonic, I used a customized Contour Annotation Tool in the Matlab software (Zeppelzauer & Stoeger, 2015) and for the formant analysis I used the software STx (Version 5.0.6) (Balasz P. & Noll A., 2000). I followed the methodology of Stoeger et al. (2014) as well as Zeppelzauer & Stoeger (2015). The tool in Matlab calculates a Fourier spectrogram, the frequency range that was used in this study was 0-400Hz with a frame size of 300ms and a step size of 40ms, but it was possible to change these settings manually, depending on the structure and frequency of the individual call. Figure 10 illustrates an example using this spectrogram range to better identify the fundamental frequency in a rumble produced by EM08, an adult male. The tool also allows for manual labelling of frequency contours within the provided spectrogram, thereby enabling the annotation of contours using predefined labels such as 'fundamental frequency', first harmonic' 'second harmonic' and so on (A. S. Stoeger et al., 2014) (Figure 10).

In my study, I focused on analysing the fundamental frequency (F0) and the first harmonic (F1). For both, I used the same method, manually labelling the frequency contours as demonstrated in Figure 9. The figure illustrates how the analysis was conducted in Matlab, where I manually selected the fundamental frequency (black line) and the first harmonic (blue line) by carefully tracing the spectrogram. I then analyzed the formants (Formant 1 and Formant 2) of the selected rumbles (Figure 11). In the literature the predicted formant locations, for female African elephants, are Formant1 = 35.0 Hz and Formant2 = 105.0 Hz, based on an estimated vocal tract length of 2.5 m (Soltis, 2010). Generally, in savanna elephant vocalizations, only the first two formants are consistently present (McComb et al., 2003; Soltis et al., 2009, 2014).

Once all the data had been analyzed, I exported the metadata to Excel. The resulting variables were following: Formant1; Formant2; COFM; JitterFactor; FreqVariabilityIdx; InflectionFactor; FinishFreq; MinFreq; MaxFreq; MeanFreq; FreqRange; PeakByMeanFreq; MeanByMinFreq; PeakFreqLoc; MinFreqLoc; Duration; StartSlope; MiddleSlope; FinalSlope; StartFreq; MidFreq; TimeMinMax; mean1stThird; mean2ndThird; mean3rdThird; medianFreq. A detailed explanation of these variables is shown in table 3.

Table 3: Description of the acoustic parameters used for analysis (Stoeger & Baotic, 2016).

Acoustic parameter	**Description**
Absolute frequency parameter	
Start, mid, finish frequency	Fundamental frequency at the start, at the middle, and at the end of the rumble (Hz).
Min and max frequency	Lowest and highest measured frequency of the fundamental (Hz).
Mean frequency	Calculated as average frequency across the fundamental.
Median frequency	Divides the distribution into two equal halves.
Range frequency	Difference between the highest and lowest frequencies.
Peak/Mean frequency	Ratio of the peak frequency to the mean frequency of a signal.
Mean/Min frequency	Ratio of the mean frequency to the minimum frequency of the signal.
Mean1st, 2nd and 3rd Third	Mean fundamental frequencies of first, second, and third part of the sound segment (Hz).
Temporal parameter	
Duration	Temporal distance of rumble measured in seconds (s).
Min and max frequency loc	Location of the minimum and maximum frequency on the fundamental contour (s).
Time Min/Max	Temporal distance between min and max frequency (s).
Shape and contour parameters	
COFM - Coefficient of frequency modulation	Calculated variable that represents the amount and magnitude of frequency modulation across a rumble, computed by summing the absolute values of the difference between sequential frequencies divided by 10,000.
Jitter Factor (Mitani and Brandt 1994)	Calculated variable that represents a weighted measure of the amount of frequency modulation, by calculating the sum of the absolute value of the difference between two sequential frequencies divided by the mean frequency. The sum result is then divided by the total number of points measured minus 1 and the final value is obtained by multiplying it by 100.
Frequency variability index (Mitani and Brandt 1994)	Calculated variable that represents the magnitude of frequency modulation across a rumble, computed by dividing the variance in frequency by the square of the average frequency of a rumble and then multiplying the value by 10.
Inflection factor	The inflection factor refers to a measure that indicates the point at which the curvature of the frequency contour changes, helping to identify shifts or bends in the signal's frequency trajectory.
Start, middle, and final slope	Frequency 40-Frequency 20)/(Time 40-Time 20) (Frequency 60-Frequency 40)/(Time 60-Time 40)
Filter-related features	
Formant 1	First spectral peak of the LPC smoothed spectrum in the range of 0 to 500 Hz (model order 8)
Formant	Second spectral peak of the LPC smoothed spectrum in the range of 0 to 500 Hz (model order 8)

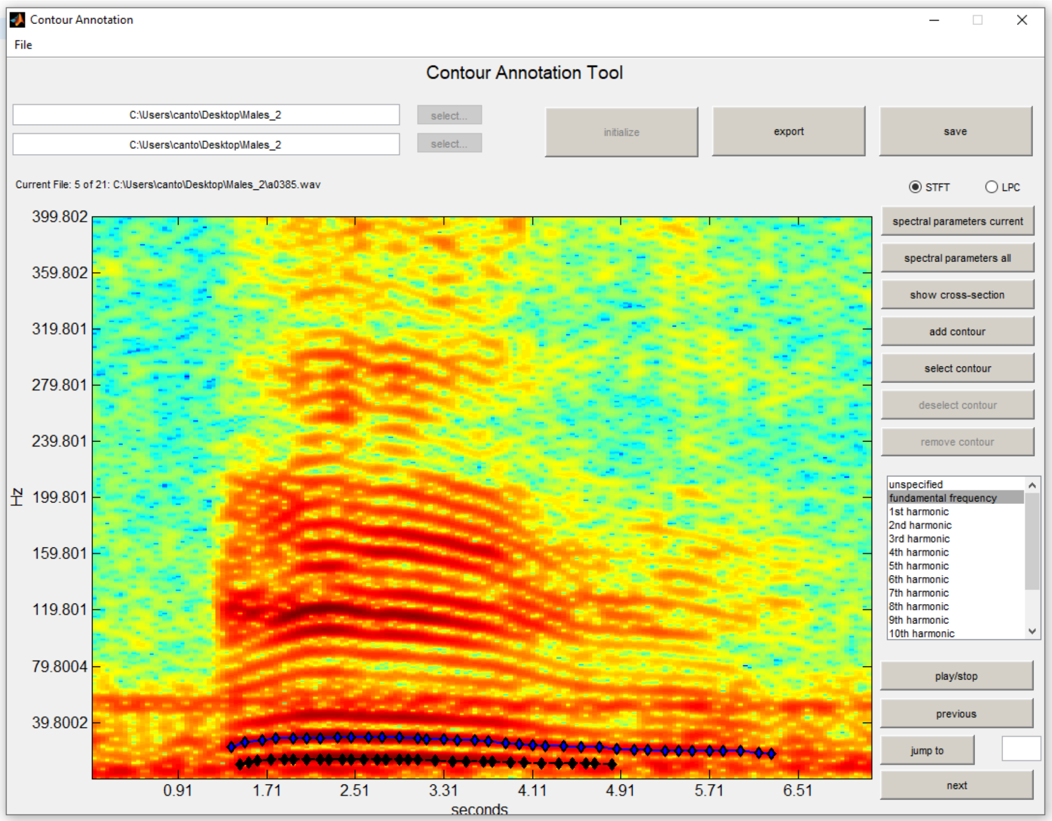

Figure 9: An example of the Analysis of Fundamental Frequency (f0) and First Harmonic (f1) of a Male Rumble using Matlab.

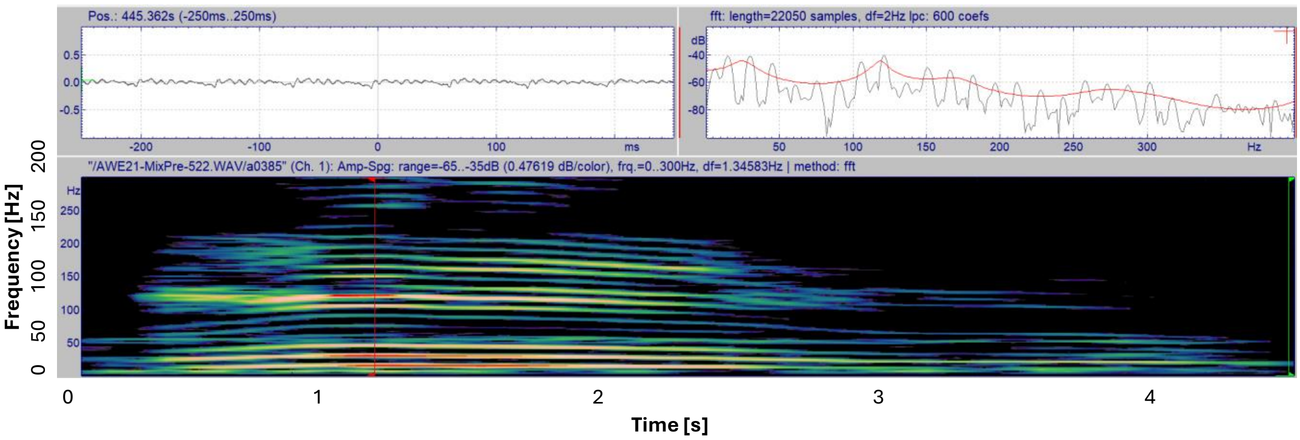

Figure 10: Example of the Analysis of the Formants of a Male Rumble using STx.

2.3.3 Statistical analysis

The statistical analysis was conducted using R Studio (version 1.4.1106) with the MASS, caret, MVN, biotools, and ggplot2 packages (R Core Team, 2021). The analysis included N=103 rumbles from 13 female African savannah elephants and N=52 rumbles from 16 male African savannah elephants. The statistical approach I used followed the analysis Baotic & Stoeger (2017) used in their study with modifications based on my dataset. Acoustic analyses focused on first harmonic parameters, as these contained the highest number of datapoints compared to fundamental frequency measures.

To test for sex differences in rumbles, I initially performed a MANOVA (Multivariate Analysis of Variance), to identify if there is a significant difference between female and male African savannah elephants in single acoustic parameters. For the MANOVA I selected parameters, based on the variables that in (Baotic & Stoeger, 2017) study were significantly discriminating genders. The selected parameters were: Formant.1, Formant.2, COFM, JitterFactor, MeanFreq, FreqRange, PeakFreqLoc, MinFreqLoc, MidFreq, TimeMinMax.

The MANOVA results indicated a significant overall effect of gender on acoustic parameters. Therefore, I followed up with a posthoc univariate ANOVA to identify which of the used variables are significantly contributing to the sex differences. I then continued with a Discriminant Function Analysis (DFA), specifically a Linear Discriminant Analysis (LDA), including all the acoustic measures to assess whether the differences identified by the MANOVA were sufficient to discriminate between male and female vocalizations.

Before fitting the model, assumption testing was performed to ensure the validity of the analysis. Multivariate normality was assessed using the Henze-Zirkler test. Univariate normality was examined using the Anderson-Darling test. Additionally, homogeneity of covariance matrices was tested using Box's M test, indicating a violation of homoscedasticity. Since log transformations did not improve the normality of the data, the original variables were retained for analysis. To address homoscedasticity violations, a Quadratic Discriminant Function (QDA) could have been considered, however, the limited sample size restricted its application. Nevertheless, the LDA was considered appropriate for this dataset due to its robustness to such violations, particularly when working with small sample sizes.

Classification analysis was conducted with a Linear Discriminant Function Analysis and a MANOVA to determine if there were significant differences between sexes based on acoustic parameters. I used the "lda()" function from the MASS package in R (R Core Team, 2021). The dataset was split into an 80% training set and a 20% test set to validate the model. The model was trained on centered and scaled acoustic variables, and posterior classification probabilities were computed. Cross-validation was used to assess accuracy. To visualize the results, discriminant function scores were plotted using the ggplot2 package (R Core Team, 2021).

For the statistical analysis of the second hypothesis regarding acoustic differences in male rumbles during musth, the dataset included N=21 rumbles from males in musth, N=37 rumbles from males not in musth, and N=3 musth-specific rumbles from males in musth. Due to the small and imbalanced sample sizes, statistical tests could not be performed reliably. Instead, descriptive statistics (means and standard deviations) were calculated for each group to provide a preliminary examination of possible difference (Table 9).

3. Results

3.1 Descriptive Analysis

Table 4 summarizes the number of different call types recorded from the elephants, along with information on whether the specific caller was identified.

Overall, I recorded 636 calls across various call type categories, with the identities of 243 of these calls known. The most common call type was the ‘rumble,’ with 349 recorded vocalizations, of which only 116 were from 29 different known individuals. Most the unknown rumbles were made by females, who often roam in large herds making it challenging to identify the exact caller. Additionally, many female subadults, juveniles and calves had not yet been indexed, so data on their ID was unavailable (Table 4).

Table 4: This table shows the number (N) of calls and indicates whether the identity of the caller was known.

Call type	N of recorded calls	ID of caller known
Rumble	349	116
Musth Rumble	4	4
Trumpet	60	4
Croaking	116	113
Roar	28	3
Noisy roar	0	0
Bark	1	1
Grunt	7	0
Snort	31	3
Unknown	40	
Sum	636	243

Noise: The most common noise, with 278 instances, was the typical 'Marataba noise,' which included bird calls, wind, cicadas, and other insects. Additionally, there were many recordings of 'Talking humans' with 117 instances. Some recordings also included cars, planes, generator noise, and water. Nonetheless, all this data is important and can contribute to the improvement of a potential early warning system (Table 5).

Table 5: This table lists the number (N) of the most common noise-types that have been recorded.

Type of Noise	N of recorded noise
Marataba noise	278
Generator	1
Car	25
Plane	4
Talking humans	117
Water	62
Unspecified	25
Sum	512

In the course of data collection, I was able to record a diverse array of vocalizations from elephants across different age groups, which is crucial for the acoustic monitoring of elephant populations. The majority of the recordings were obtained from adult individuals, with a particular emphasis on adult males and female matriarchs. As a result, the dataset includes a substantial number of calls from adult elephants (Table 6). Specifically, we recorded 5 calls from young adult males, 35 from medium adult and 191 calls from old adult males. In total, 636 calls were recorded (Table 6).

Table 6: This table lists the number (N) of the age groups of recorded vocalizations.

Age Group	**N of recorded calls**
Infant	5
Calf	22
Juvenile	3
Subadult	0
Adult	202
Young adult	5
Medium adult	35
Old adult	191
Unknown	173
Sum	636

Table 7 shows the vocal behaviour of elephants across 29 different contexts, based on the dataset of 636 recorded calls (Table 7). Drinking (154 calls) and Feeding (143 calls) were the most common contexts for vocalizations, both of which frequently occurred in social settings where elephants interacted vocally and physically. While these contexts may not be inherently social, vocalizations likely serve to maintain group cohesion and coordination during these activities. However, it should be noted that more than 89 calls in the 'Drinking' context were recorded from a solitary individual. These calls belonged to the 'croaking' category, which was only documented in two individuals (Table 7).

‘Traveling’ (127 calls), ‘Greeting Ceremonies’ (23 calls) and ‘Little Greeting’ (21 calls) also featured prominently. Vocalizations during ‘Play Social’ (32 calls), ‘Play Social Water’ (28 calls), ‘Bathing’ (29 calls), and ‘Mud Bathing’ (7 calls) highlight the role of communication during playful interactions. Most of the calls in playful interactions were from calves, subadults, and males. On one occasion, we observed a sexual interaction between a ‘medium adult’ male and an adult female. In this context, 27 calls were recorded, as many individuals of the herd vocalised simultaneously. The contexts ‘Sparring’ (10 calls) and ‘Musth’ (4 calls) involved only males, and we did not observe any ‘Sparring’ contexts involving females. For contexts such as ‘Affiliation’, ‘Consortship’, or ‘Defensive’, no recorded calls were available.

Table 7: This table lists the number (N) of the contexts of recorded vocalizations.

Context	N of recorded context
Unknown	18
Affiliation	0
Reassurance	2
Little_Greeting	21
Greeting_Ceremony	23
Defensive	0
Agonistic	6
Consortship	0
Digging	0
Drinking	154
Dusting	0
Bathing	29
Feeding	143
Listening	0
Mud_bathing	7
Musth	4
Suckling	0
Play_social	32
Play_solitary	0
Play_social_water	28
Sparring	10
Resting	4
Post_copulation_behavior	0
Mating_pandemonium	0
Sex	27
Socio_sexual_behavior	0
Swimming	0
Traveling	127
Dominance	0
Sum	636

3.2 Call types

I recorded a total of nine different call types and as shown in Figure 12, the most frequently recorded call type was the 'rumble,' with 349 recorded vocalizations from more than 40 known and unknown individuals. Elephants use the low-frequency rumble to stay in constant contact with each other, which aligns with my observations. The elephants of Marataba rumbled in various contexts, such as 'Feeding,' 'Traveling,' 'Greeting,' and 'Drinking' (Table 7).

The second most common vocalization was ‘croaking,’ with over 100 recorded calls. Most of the ‘croaking’ sounds were collected from a male elephant identified as EM08, I also documented this call type from another male individual. The individuals mostly produced this sound in the context of ‘Drinking’ or ‘Resting’. It's important to note that croaking appears overrepresented in the figure due to repeated recordings of the same individual producing this vocalization. To clarify, the number of individuals recorded for each vocalization type is indicated next to the bars. A truly representative result would require at least four different individuals for each call type, which in my dataset only applies to the categories snort, grunt, roar, trumpet and rumble (Figure 11).

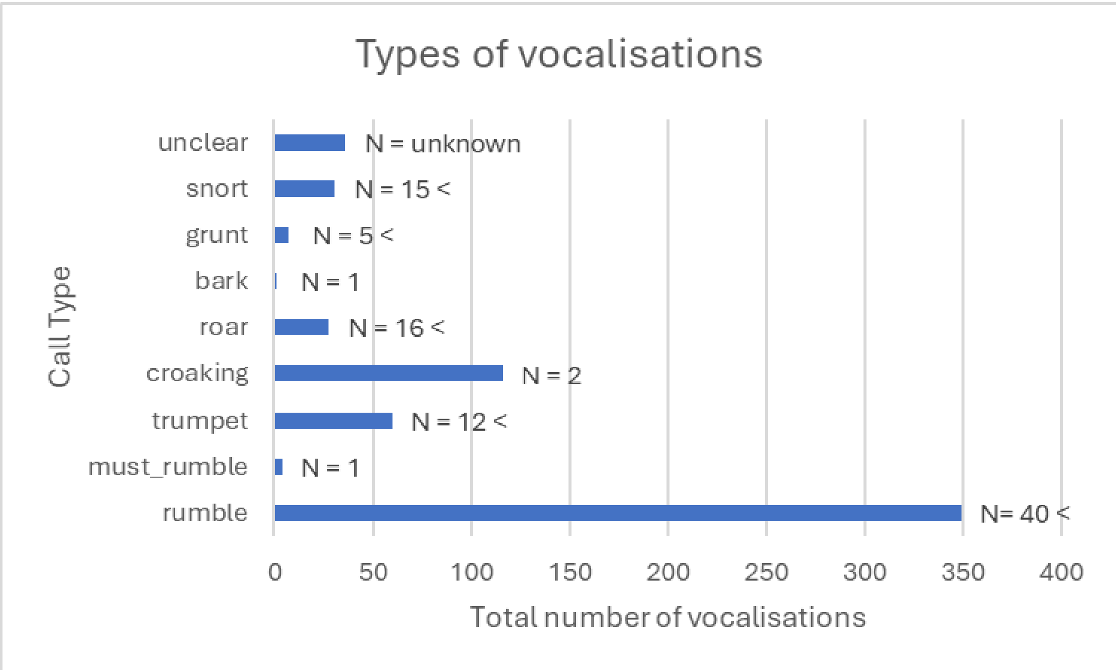

Figure 11: The absolute numbers of the different sound categories with N = number of individuals who produced the call type.

3.3 Female-Male Rumble Comparison

To investigate the differences between female and male African savannah elephants, I employed various statistical techniques. In the following sections, I will present the results of these analyses. I included vocalizations from 73 recordings of unidentified females, 10 recordings of unidentified males, 32 recordings from identified females, and 43 recordings from identified males in the statistical analyses. In total, the dataset comprised 103 rumbles from 13 different female individuals and 52 rumbles from 16 different male individuals.

The initial step in testing my main hypothesis, whether there are statistically significant differences in the acoustic parameters of rumbles between male and female elephants, involved performing a MANOVA on selected acoustic parameters for both sexes.

The results of the MANOVA indicated a statistically significant effect of sex on the acoustic parameters, Wilks' Lambda = 0.696, $F(10, 144) = 6.290$, $p < 0.001$. The residual degrees of freedom were 153. Significance was determined using the conventional alpha level of 0.05, and the highly significant p-value ($p = 5.8e-08$). As the MANOVA showed a significant result, I followed up with a post hoc ANOVA to discriminate which of the used variables significantly contributed to sex differences and found the following 6 significant variables: Formant.1, Formant.2, COFM, JitterFactor, MeanFreq, MidFreq.

To evaluate whether these differences were sufficient for classification, a Discriminant Function Analysis (DFA), specifically a Linear Discriminant Analysis (LDA), was conducted. Prior to model fitting, assumption testing was performed. The Henze-Zirkler test for multivariate normality revealed a violation ($HZ = 5.465$, $p < 0.001$), and the Anderson-Darling test for univariate normality also showed significant deviations ($p < 0.001$) for all six acoustic parameters, with positive skewness and high kurtosis (Table 8). Additionally, the Box's M test for homogeneity of covariance matrices yielded a significant result ($p < 2.2e-16$), indicating a violation of homoscedasticity. Despite these assumption violations, the LDA was deemed appropriate due to its robustness in small sample sizes.

Table 8: Test for Multivariate Normality.

Variable	Univariate Normality Test (A-D Statistic)	p-value	Normality	Mean	Std. Dev.	Skewness	Kurtosis
Formant.1	2,4481	<0.001	NO	29,27	5,59	1,15	4,31
Formant.2	27,5394	<0.001	NO	124,4	93,59	10,72	124,39
COFM	1,9694	<0.001	NO	0,0011	0,00058	1,1	1,93
JitterFactor	2,2594	<0.001	NO	1,63	0,73	1,29	3,15
MeanFreq	1,9916	<0.001	NO	29,06	5,11	0,36	1,74
MidFreq	2,0546	<0.001	NO	30,06	5,32	0,52	1,76
Multivariate Normality Test	Henze-Zirkler	5,46	NO				

The model was trained using the transformed dataset with centered and scaled acoustic variables. Prior probabilities of classification were based on the observed proportion of male and female vocalizations in the dataset (female: 66.4%, male: 33.6%). The LDA model was trained using an 80% training set and a 20% test set. The classification model correctly assigned 83% of vocalizations to the correct sex, demonstrating that the selected acoustic parameters provided a strong basis for distinguishing between male and female rumbles.

The discriminant function coefficients indicated that Mean Frequency (-1.794) and Mid Frequency (1.541) had the highest contributions to sex differentiation, followed by Formant.2 (-0.639) and Formant.1 (-0.494). COFM (-0.159) and Jitter Factor (-0.203) had smaller but still notable effects. A positive discriminant coefficient suggests that higher values of the corresponding acoustic feature are associated with female vocalizations, whereas a negative coefficient indicates a stronger association with male vocalizations. The results indicate that Mean Frequency was the most influential feature in discriminating between the sexes, with a stronger contribution than other acoustic measures.

To further confirm the validity of the DFA/LDA results, an additional MANOVA was conducted using only the six significant DFA variables. The MANOVA assessed whether the acoustic features significantly differed between male and female vocalizations. The results of Wilks' Lambda test indicated a statistically significant effect of sex on the acoustic parameters (Wilks' $\lambda = 0.816$, $F(6,148) = 5.573$, $p < 0.001$), confirming that the acoustic measures used in the classification model contributed significantly to the observed sex differences.

The discriminant function scores histogram (Figure 12) illustrates the distribution of male and female rumbles along the discriminant axis. Female rumbles, which are presented in red are predominantly clustered around positive values, whereas male rumbles presented in blue, are more frequently found in the negative range. The visual representation aligns with the statistical results, indicating that the acoustic variables used in this analysis successfully differentiate between sexes. Overall, the results indicate that male and female vocalizations exhibit significant acoustic differences, that these differences can be effectively used for classification with high accuracy.

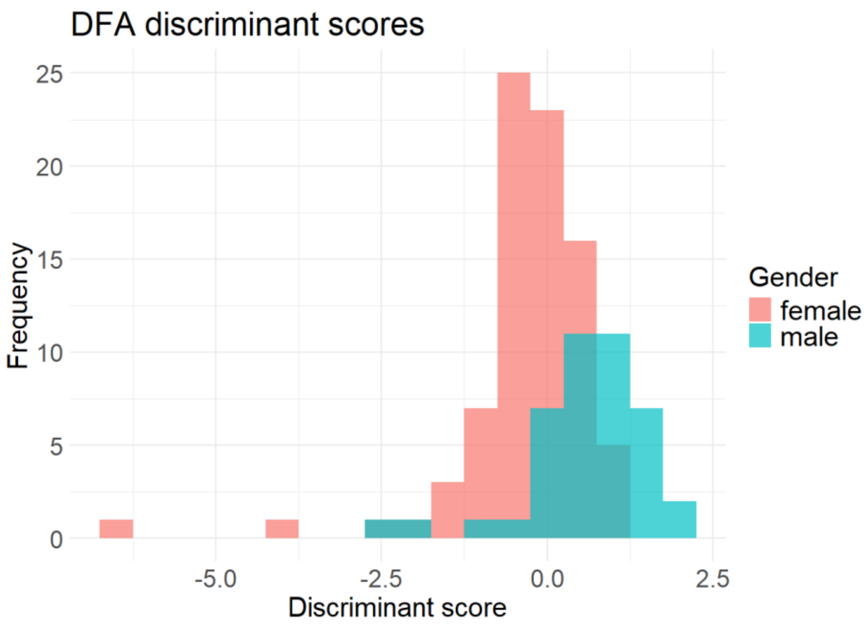

Figure 12: DFA Discriminant Scores.

In addition to the statistical analysis, I aimed to visualize the differences between male and female rumbles. As depicted in Figure 13, three example rumbles from both females and males reveal that male rumbles occur at lower frequencies compared to female rumbles. This visual representation complements the statistical findings by showing the distinct acoustic patterns between females and males (Figure 13).

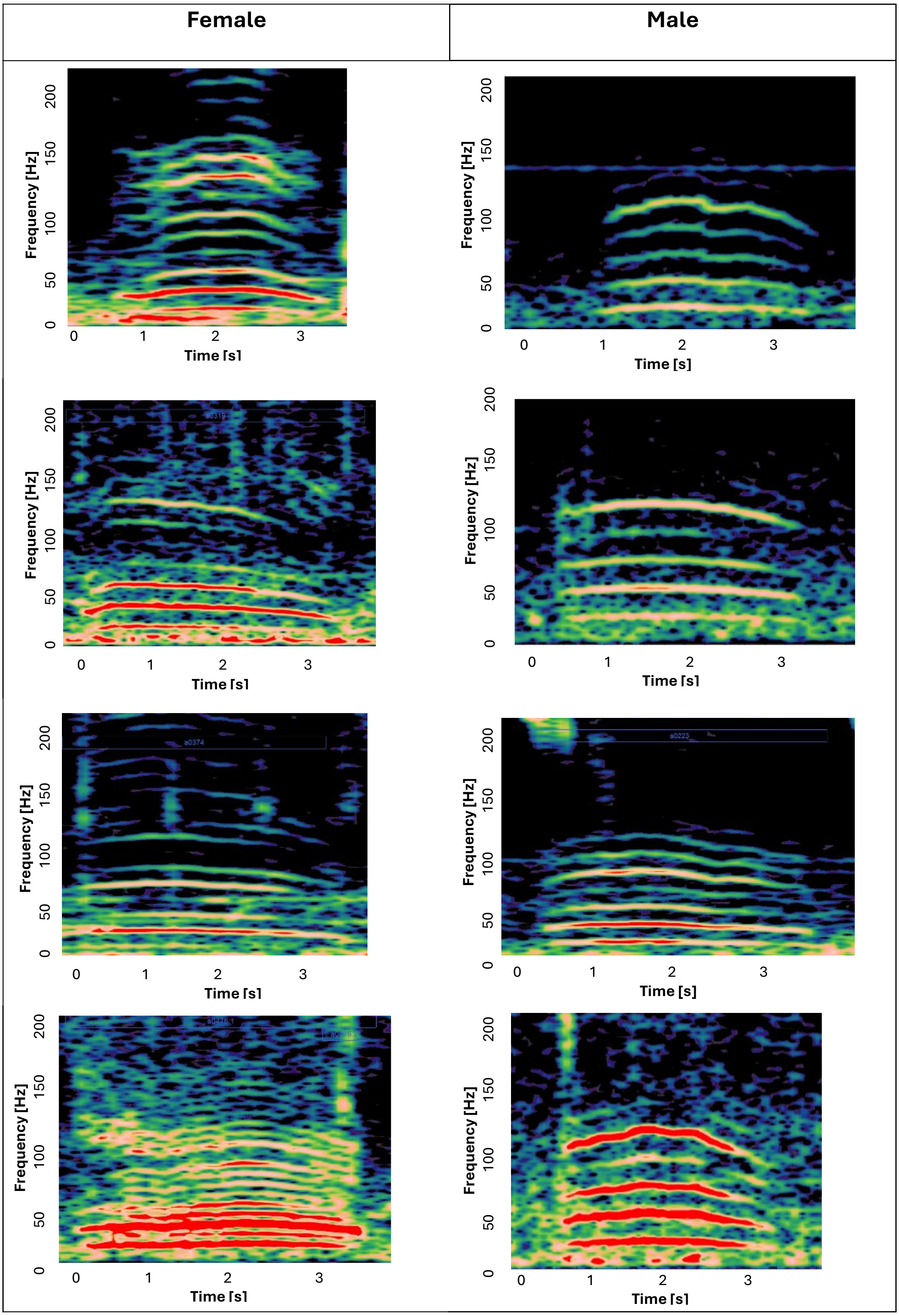

Figure 13: Visual Comparison of Female (Left) and Male (Right) African Elephant Rumbles, Plotted in STx.

3.4 Comparison of Male Rumbles

My final focus was to test whether males in musth and males not in musth produce acoustically different social rumbles. Similar to the comparison of female and male rumbles, I will focus on parameters related to the first harmonic. Many data points for the fundamental frequency were excluded due to their lack of clear visibility in numerous vocalizations. It's important to note that, for this analysis, I only calculated the means and standard deviations. This is because I intended to compare three categories but lacked sufficient data in each to conduct a statistical analysis that would yield significant and robust results.

I have created a table (Table 9) with all the calculated values, as well as a figure (Figure 16) that, using example vocalizations, shows what a rumble from a male in musth, a male not in musth, and a musth rumble can look like (Figure 16). For instance, in the filter-related parameter Formant 1, the mean frequency of rumbles from males not in musth was 26.65 Hz (SD ± 5.12 Hz), while rumbles from males in musth had a mean of 24.84 Hz (SD ± 2.91 Hz). In contrast, musth-specific rumbles from males in musth exhibited a lower mean of 15.18 Hz (SD ± 1.78 Hz). The mean duration and standard deviations were 3.58 ± 1.27 seconds for rumbles from males not in musth, 3.38 ± 1.18 seconds for males in musth, and 3.32 ± 2.04 seconds for musth-specific rumbles (Table 9).

Table 9: Comparing the mean and standard deviation (SD) of source-and filter-related acoustic parameters between the male categories.

Source-related parameters	Mean ± SD		
Absolute frequency parameters (Hz)	**Rumble Male not in Musth (N= 36)**	**Rumble Male in Musth (N= 22)**	**Musth Rumble Male in Musth (N= 3)**
Start F1	25,97 ± 4,95	27,55 ± 7,97	17,13 ± 6,28
Middle F1	28,98 ± 4,95	31,65 ± 8,57	23,87 ±2,78
Finish F1	25,29 ± 4,98	28,03 ± 8,91	24,80 ± 5,52
Min F1	25,43 ± 4,62	26,25 ± 8,05	17,13 ± 6,28
Max F1	29,78 ± 5,34	32,42 ± 8,61	26,18 ± 4,39
Range F1	5,34 ± 2,86	6,27 ±2,44	8,93 ± 2,55
Mean F1	27,93 ± 4,68	30,42 ± 8,30	22,36 ± 4,32
Median F1	28,29 ± 4,55	31,00 ± 3,99	22,87 ± 3,99
Mean 1s tThird	27,86 ± 4,73	29,98 ± 7,99	19,45 ± 4,82
Mean 2nd Third	28,80 ± 4,77	31,46 ± 8,51	23,10 ± 3,57
Mean 3rd Third	27,13 ± 4,99	30,14 ± 8,08	24,69 ± 4,87
Max F1/Mean F1	1,07 ± 0,05	1,06 ± 0,02	1,17 ± 0,03
Mean F1/Min F1	1,15 ± 0,09	1,18 ± 0,09	1,48 ± 0,23
Temporal parameters(s)			
Duration	3,58 ± 1,27	3,38 ± 1,18	3,32 ± 2,04
Min F1 Location	0,50 ± 0,48	0,35 ± 0,45	0,00 ± 0,00
Max F1 Location	0,37 ± 0,19	0,45 ± 0,26	0,82 ± 0,17
Time Minimum to Maximum	0,56 ± 0,20	0,60 ± 0,23	0,82 ± 0,23
Shape and contour parameters			
Coefficient of Frequency Modulation (COFM)	0,001 ± 0,001	0,001 ± 0,0001	0,001 ± 0,001
Jitter Factor	1,31 ± 0,58	1,35 ± 0,49	2,69 ± 0,67
Frequency Variability Index	0,04 ± 0,10	0,04 ± 0,03	0,15 ± 0,08
Inflection Factor	0,21 ± 0,10	0,24 ± 0,07	0,05 ± 0,04
Start Slope	3,42 ± 3,63	3,74 ± 2,75	3,91 ± 2,38
Middle Slope	-0,29 ± 2,67	0,53 ± 2,45	2,95 ± 2,10
Final Slope	-2,50 ± 2,31	-3,12 ± 2,67	3,66 ± 3,78
Filter-related parameters (Hz)			
Formant 1	26,65 ± 5,12	24,84 ± 2,91	15,18 ± 1,78
Formant 2	85,07 ± 16,05	77,64 ± 11,02	38,48 ± 1,74

The following figure (Figure 15), highlights the findings, calculated in table 9. Shown are three boxplots, that illustrate the frequency distributions of the mean frequency of three categories of male elephant rumbles: "Rumble_Male not in Musth," "Rumble_Male in Musth," and "Musth Rumble_Male in Musth" (referring to the first harmonic). For each category, the minimum, mean, and maximum frequencies are presented, providing insights into how these conditions affect the acoustic properties of the rumbles (Figure 15).

"Rumble_Male not in Musth" has a median frequency of about 25 Hz, with an interquartile range (IQR) of 20 Hz to 30 Hz and includes outliers at 10 Hz and 40 Hz. The mean frequency is around 27 Hz. "Rumble_Male in Musth" also has a median frequency of 25 Hz, a slightly broader IQR from 22 Hz to 32 Hz, and no outliers. The mean frequency is higher at 30 Hz (Figure 15).

The "Musth Rumble_Male in Musth" category, however, exhibits a different pattern. This category has a lower median frequency of 20 Hz, with an IQR from 17 Hz to 25 Hz, and no outliers. The mean frequency is around 22 Hz and in contrast to the other categories shows a pulsated structure (Figure 15).

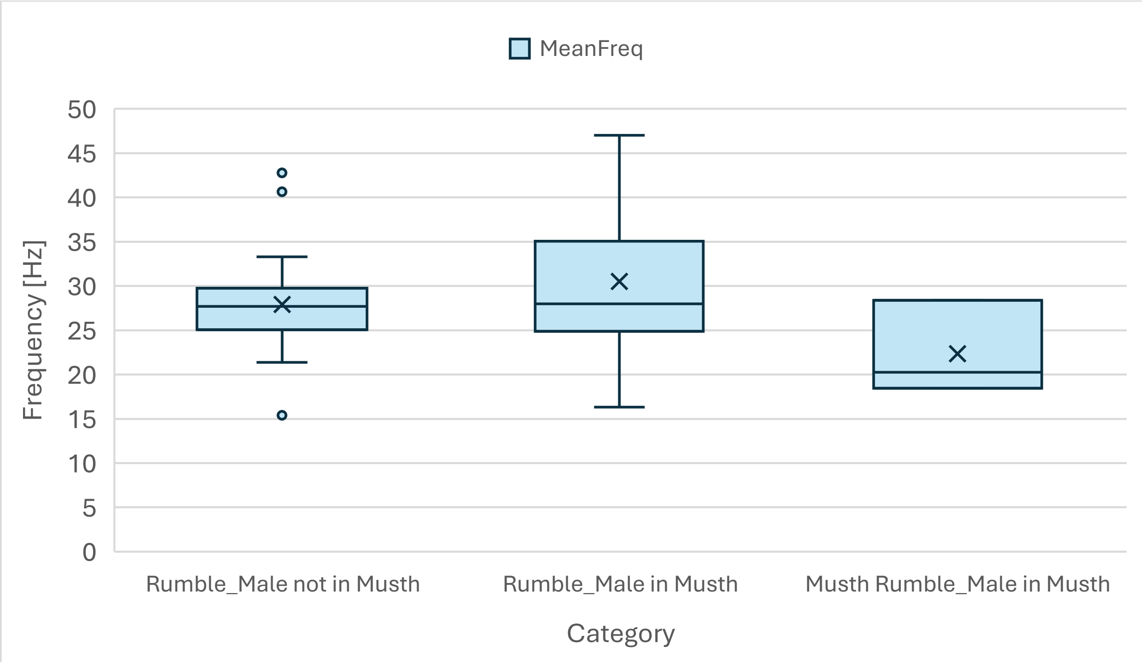

Figure 14: Boxplots of the three categories (Rumble_Male not in Musth; Rumble_Male in Musth and Musth Rumble_Male in Musth) created using the mean frequency of all the datapoints.

To further illustrate the analogy and the differences among the three categories, I created the following figure (Figure 16), which includes three examples for each category. Here, it is visible that the rumbles of the two categories 'in musth' and 'not in musth', appear very similar, while the musth rumbles shows noticeable differences. The musth rumbles are deeper and display a pulsated structure in the fundamental frequency (black) as well in the first (blue) and upper harmonics. These observations align with the results presented in Table 9 and Figure 15 (Figure 16).

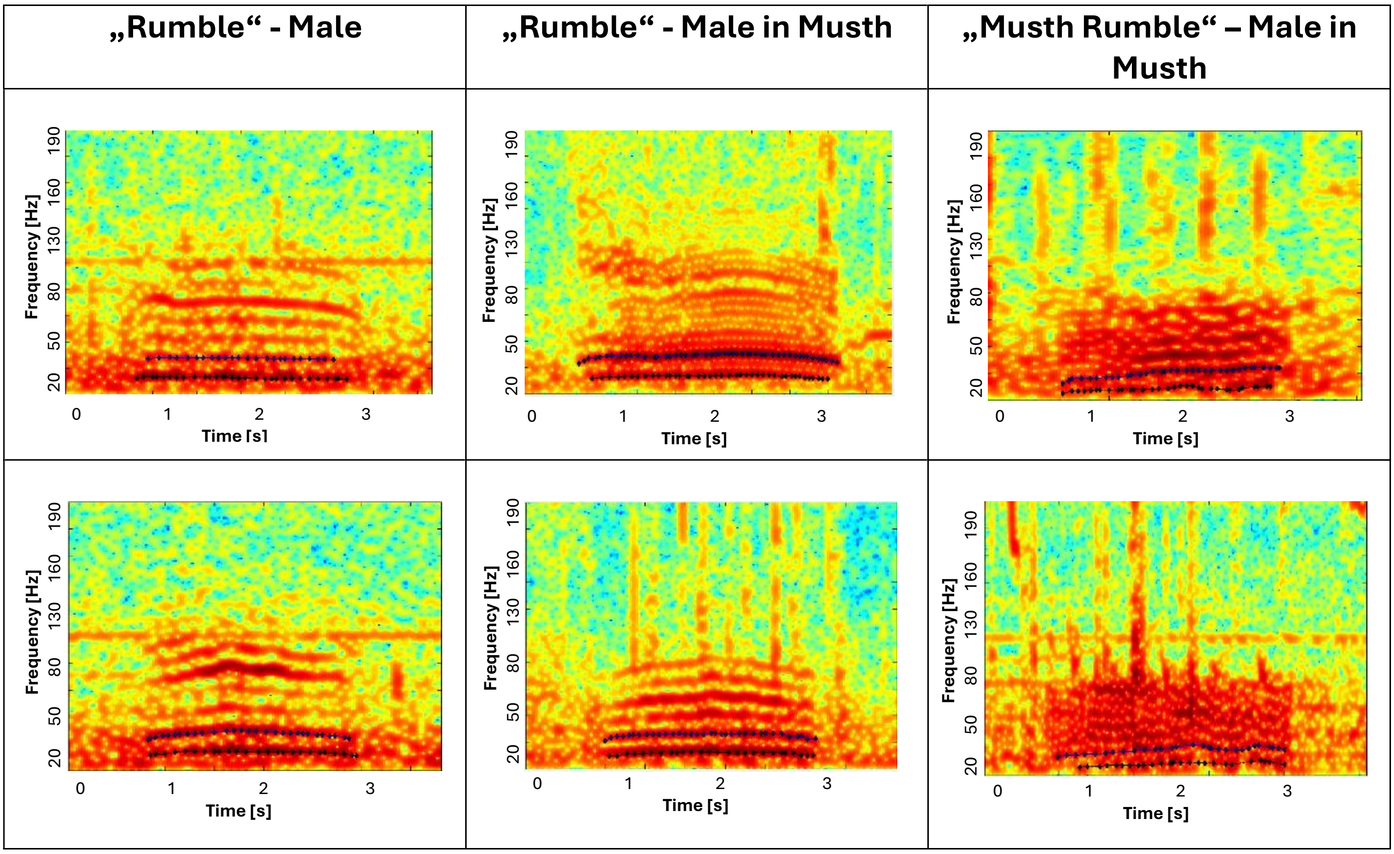

Figure 15: Visual Comparison of the three categories "Rumble_Male not in Musth"; "Rumble_Male in Musth" and "Musth Rumble_Male in Musth" plotted in Matlab.

4. Discussion

This thesis aimed to support the acoustic monitoring and early-warning system established by Zeppelzauer (2015) and Zeppelzauer & Stoeger (2015) by describing the vocalizations of the African elephant population in Marataba, in the Marakele National Park. The study specifically examined the acoustic differences between female and male elephant rumbles, and between rumbles from males not in musth and those in musth. Furthermore, a descriptive analysis was conducted, as all gathered and analyzed data, such as the behavioural contexts in which the recorded elephants communicated, the presence of noise, and collected information on age, gender, and group composition, are essential for the early-warning system discussed in the following chapters.

This thesis provides an initial acoustic and behavioural description of the Marataba elephant population. The descriptive data, consisting of 636 recorded calls across various call types and contexts, offers preliminary insights into the vocal behaviour within this population. The data collected and analyzed includes information on sex differences, 29 different behavioural contexts, data on males in musth, different noise sources and insights on call types and their acoustic structure.

4.1 Descriptive Analysis

4.1.1 Identification of individuals

During data collection and annotation process, we successfully identified the caller in 243 out of 636 calls. We were able to identify 193 calls from males and 50 from females. Recognising individual callers in elephant populations is crucial for understanding their behaviour, social structure, and improving conservation strategies. By identifying specific individuals, researchers can track movement patterns, monitor changes in group composition, and assess the stability of social bonds over time. This information helps determine whether vocalizations are used in specific contexts, such as maintaining group cohesion, mother-offspring communication, or to signal distress. Additionally, long-term monitoring of identified individuals provides insights into population dynamics, allowing conservationists to detect disruptions caused by habitat loss, poaching, or human-wildlife conflict. Such detailed knowledge is essential for developing conservation strategies that align with the social structures and ecological needs of elephant populations (O'Connell-Rodwell et al., 2023).

Our ability in identifying many individuals was due to two key factors. First, we utilized an ID kit developed by Vesta Eleuteri and a team of volunteers, which familiarised us with the animals before our fieldwork, simplifying the task of identifying callers. Second, the relatively low number of individuals present during most recordings made it easier to localise the callers. However, without such an ID kit or when many individuals are present, localising callers becomes challenging, resulting in the loss of valuable information.

The difficulty in identifying vocalizing animals, especially under natural field conditions with large groups and unknown individuals, highlights a significant challenge in acoustic monitoring. This limitation underscores the need for more comprehensive and consistent monitoring efforts to improve the accuracy of vocal data. Accurate identification of callers is crucial for conservation efforts and the development of early-warning systems, as it provides critical data about individual elephants (O'Connell-Rodwell et al., 2023).

For example a study by O'Connell-Rodwell et al. (2023), explored African elephant communication methods, including the significance of individual-specific calls. This paper discusses the application of Laser Doppler Vibrometry (LDV) to identify individual callers within elephant vocalizations. LDV allows researchers to determine who initiates and responds to calls within a group, offering insights into decision-making processes (for example “let’s go” rumbles), communication dynamics and leadership structures. Another paper by Pardo et al. (2024) reveals that African elephants use name-like calls to address one another, with each call being individually specific and not merely imitations. This ability to identify the call recipient suggests sophisticated social interactions and precise communication. While identifying individual callers alone is not sufficient to guide relocation or rehabilitation decisions, it can be a valuable tool alongside other factors such as social networks, kinship structures, and group dynamics. Understanding individual vocal recognition may support efforts to maintain social bonds and group cohesion in conservation planning. Additionally, understanding individual-specific communication can aid in monitoring the well-being of elephants, both in the wild and in captivity. Changes in an elephant’s vocal behaviour, for example reduced vocal activity or shifts in acoustic structure may indicate stress, illness, or social isolation. By studying these vocal patterns researchers and conservationists can gain insights into the health and emotional state of individuals, contributing to more effective management and conservation strategies (O’Connell-Rodwell et al., 2023; Pardo, Fristrup, et al., 2024; Shannon et al., 2013).

4.1.2 Noise

The most common noise, recorded in Marataba with 278 instances, was the typical ‘Marataba noise,’ which included calls of various birds, wind and insects. Additionally, there were many recordings of ‘Talking humans,’ which should be minimised in future data recordings, although in some cases it is unavoidable as we had to coordinate our recordings and data collection. Other noise sources included running water, as well as recordings of cars and in some areas also of a generator of nearby lodges. The descriptive analysis highlights the crucial role of annotating noise recorded in Marataba for the development of an effective early-warning system. A monitoring system must be capable of detecting elephant vocalizations out of environmental and anthropogenic noise sources specific to the area, some of which producing frequencies in the infrasonic range (Zeppelzauer et al., 2013).

Despite the effectiveness of the early-warning system in real-world conditions, with diverse noise sources, challenges persist. To this date the false positive rate is still too high, for example because of interferences from environmental noise and variability in elephant calls. This highlights the importance of collecting, annotating, and analysing more data to optimise the system and minimize false detections (Zeppelzauer et al., 2013).

Furthermore, comparing different populations, such as those in Marataba and for example in Addo Elephant National Park, where anthropogenic noise levels vary, could provide valuable insights into how noisy environments impact system performance. Such comparisons may reveal the need for customised adaptations in different settings (Zeppelzauer et al., 2013). In general, studying and monitoring multiple populations in terms of behaviour, acoustic behaviour and noise in which the population lives is crucial for effective conservation measures and comparisons between populations. It is essential to ascertain whether elephants are vocally active or silent in specific contexts to determine whether to prioritize visual or auditory cues in that setting (Fritz, 2017; A. S. Stoeger, Heilmann, et al., 2012; Zeppelzauer et al., 2013, 2015).

To conclude, the system's ability to detect and adapt to new types of noise is essential for improving accuracy and minimising false positive detections. Including diverse noise data and refining detection algorithms will enhance the system's robustness and reliability. Further research is necessary to refine the system's robustness and accuracy, ensuring its effectiveness across diverse and noisy environments (Zeppelzauer et al., 2013).

4.1.3 Behavioural contexts

The last aspect of the descriptive analysis was the evaluation of the various observed contexts. The most frequently recorded vocalization contexts in Marataba were 'Drinking,' 'Feeding,' and 'Travelling'. These activities often took place in social settings, where elephants interacted both vocally and physically. This suggests that vocalizations play a crucial role in facilitating communication during common contexts such as drinking or feeding, which are consistent with findings from previous studies. In her chapter titled 'Behavioural situations of Elephant Acoustic Communication,' Poole (2011) defines the diverse contexts and explains the acoustic behaviour of elephants. Poole (2011)' chapter states that elephants use vocalizations to stay in constant contact and employ contact calls in various contexts to maintain communication. These calls help keep family members connected and coordinated, and can be used to communicate over distances of up to 2 kilometres (Langbauer et al., 1991; McComb et al., 2003; Poole, 2011b).

Another very common interaction observed during my data collection was "Little Greeting" and "Greeting Ceremony". Greeting is considered a strongly affiliative behaviour that strengthens social bonds, but it is not the only vocal behaviour that strengthens bonds. Physical contact is also very common during social interactions, as greetings or when family members reunite after separation and playful interactions, which were often observed between younger and male elephants (Eleuteri et al., 2024; Moss et al., 2011; Poole, 2011b; Poole & Granli P. K, 2004).

Elephants live in complex fission-fusion societies, where interactions occur within and between families and bond groups. Vocal signals are crucial for maintaining group cohesion and coordination (McComb et al., 2001b; Poole, 2011b; Poole JH., 1994; A. S. Stoeger et al., 2014). This is especially important in their matriarchal societies, as communication plays a crucial role in maintaining social cohesion and ensuring group coordination (McComb et al., 2003; O'Connell-Rodwell et al., 2024). Vocalizations strengthen herd bonds, enhance social dynamics, and assist in spatial coordination over long distances. Specific vocalizations, such as rumbles and trumpets, are used to reinforce social bonds through affiliative interactions, including mother-offspring communication, greeting ceremonies, and coordinated movements within the herd. Therefore, vocalizations are found in many behavioural contexts (McComb et al., 2001b; Poole, 2011b; Poole JH., 1994; A. S. Stoeger et al., 2014).

4.2 Call repertoire

4.2.1 Rumbles

The findings of this study reveal a diverse number of vocalizations within the Marataba population, referring to the categories defined by Leong et al. (2003), Moss et al. (2011), Soltis et al. (2005), Stoeger-Horwath et al. (2007). Among the nine identified call types, the 'rumble' was the most frequently recorded, with 349 occurrences. This aligns with existing literature that found that the rumble is the most commonly produced call, used, beside others, to maintaining constant contact within herds (Moss et al., 2011; Poole et al., 1988b; Soltis et al., 2005, 2005; Stoeger-Horwath et al., 2007). The observations made during data collection confirm that elephants use rumbles in various situations such as 'Feeding,' 'Traveling,' 'Greeting,' and 'Drinking', supporting the notion that rumbles serve multiple social functions (Moss et al., 2011; Poole, 2011b).

As mentioned in the introduction, elephants are particularly suitable for acoustic monitoring and subsequently for acoustic early warning systems. Because the rumble is the most common sound and can be detected over 2 kilometres (Langbauer et al., 1991; McComb et al., 2003), elephants can be detected over long distances and the local population can be warned in a timely manner when elephants are approaching (Langbauer et al., 1991; McComb et al., 2003; Soltis et al., 2014; Zeppelzauer & Stoeger, 2015).

Rumbles play multifunctional roles in elephant communication. One of the primary functions is as contact calls. Contact rumbles are used by closely bonded but spatially separated females to coordinate movements and facilitate reunions, which is critical for maintaining social cohesion within elephant groups (McComb et al., 2003; Soltis, 2010; Soltis et al., 2005). Additionally, both male and female elephants produce rumbles that serve as mate attraction calls (Poole JH., 1994). These rumbles communicate the reproductive state of the caller to potential partners, playing a crucial role in their reproductive behaviour (Moss et al., 2011; Poole et al., 1988a; Poole JH., 1994).

It has been shown that the structural variations in rumbles can convey important information about the individual's identity or the reproductive state (Poole et al., 1988a; Soltis et al., 2005; A. S. Stoeger & Baotic, 2016a). Furthermore, rumbles can reflect the emotional state of the caller, with different structural variations indicating different emotions such as stress, excitement, or calmness (Soltis et al., 2005, 2014).

A study by Soltis et al. (2014) demonstrated, that elephants vocalise and react differently to different threats. The Samburu pastoralists in northern Kenya live alongside African elephants and compete for resources, for example water. Experiments show that elephants produce alarm calls when they hear the voices of Samburu men. These alarm calls lead to alertness, escape behaviour and vocalizations (rumbling, roaring and trumpeting), with rumbling being the most common and having higher and more variable frequencies (Formant 1 and Formant 2 compared to control rumbles). Further when this recorded alarm calls were presented to other individuals, they too showed vigilance and flight behaviour. However, the "Samburu alarm rumble" differs acoustically from the "bee alarm rumble", where only the Formant 2 increases. Both alarm calls lead to different behavioural reactions. For instance, elephants respond with vigilance and flight to both, but only to bee stimuli with head shaking. Overall, the results show that threatening stimuli lead to alarm calls with increased fundamental frequencies and formants in elephants. Therefore, acoustic cues can increase vigilance and escape behaviour, as elephant alarm calls distinguish between different threats and indicate the degree of urgency of the threat (Soltis et al., 2014).

The studies abovementioned show that further investigating elephant vocal communication is important as it provides insight into the emotional state of the caller, which is extremely relevant for acoustic monitoring systems. Understanding the emotional cues in elephant vocalizations allows for more accurate interpretations of their behaviour. For instance, distinguishing between a calm, relaxed elephant and one that is stressed or frightened can provide valuable information for local communities. This differentiation enables the community to respond appropriately, people would potentially react differently if a stressed individual were approaching or a relaxed. Furthermore, having this information and knowing about the emotional state of elephants is crucial for future conservation efforts. If a conservation team receives data indicating that a herd is exhibiting signs of nervousness or fear could signal the presence of poachers. This early-warning system would enable conservationists to take swift action to protect the elephants, enhancing the effectiveness of anti-poaching measures (Soltis et al., 2014; Teixeira et al., 2019; Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

4.2.2 Vocal creativity

The second most common vocalization recorded during data collection was 'croaking,' with over 100 instances. It should be mentioned that most 'croaking' sounds were recorded from one male elephant (EM08), although another unidentified male individual also produced this call. The presence of similar 'croaking' sounds from a female elephant named Mongu at the Schönbrunn Zoo in Vienna, documented during my bachelor thesis in 2021, suggests that this vocalization may not be restricted to a single population or gender (Staufer, 2021).

Since 'croaking' was not found in the defined call types of Leong et al. (2003), Moss et al. (2011), Soltis et al. (2005), Stoeger-Horwath et al. (2007), it was initially assumed that the discovery of the 'croaking' call type underscores the vocal plasticity and creativity in elephant communication.

However, after a detailed literature search, it was found that other researchers have also recorded this type of sound. In his study, Leong et al. (2003) found that the "croak" call type does not resemble any of the previously mentioned vocalizations. In his study, she also listened to the sounds and found that these sounds were acoustically different and were recorded by more than one individual. In his case, 71 croaks were recorded from four identified and four unidentified individuals (Leong et al., 2003). The observations of Leong et al. (2003) also align with my research, because both noted that croaks usually occurred in a repeated series of two or three croaks and were often associated with sucking water into the trunk. It was also noted that other scientists have made this observation, such as Joyce Poole in Amboseli National Park in Kenya (J. Poole, pers. comm; Leong et al., 2003). Another paper describing the vocalization 'croak' is Soltis (2010), who noted that croaks were only found in adults, which also agrees with our observations. A paper by Stoeger et al. (2021) on vocal creativity also identified the vocalization known as 'croaking' among several individuals. This sound was characterised as an orally emitted, pulsatile, and harmonic vocalization. Although 'croaking' sounds from different individuals have not yet been directly compared, it is assumed that their acoustic features are similar based on available spectrograms and sound samples (Leong et al., 2003; Soltis, 2010; Stoeger et al., 2021).

Stoeger et al. (2021) states, that vocal creativity refers to the ability of elephants to produce new and unique sounds. Vocal learning and creativity are very special because it is a rare skill among terrestrial mammals. These abilities enable elephants to modify their vocalizations based on experience and adapt them to diverse contexts and environments. This flexibility allows elephants to mimic a variety of sounds and plays a crucial role in maintaining social bonds and communication within their complex fission-fusion societies. Their vocal learning is further supported by advanced cognitive and neurological capabilities, including memory, imitation, and problem-solving (Poole et al., 2005; Stoeger et al., 2021).

Elephants achieve this creativity through individualized sound production techniques, where they often manipulate non-phonatory structures like the trunk or the mouth. For example, high-frequency sounds can be generated by closing one nostril at the trunk tip while inhaling air through the other, inducing nasal tissue vibrations. Similarly, low frequency 'throb' sounds are produced by contracting specific muscle groups, to create pulsating noises. Elephants can also emit distinctive 'oral bursts' by momentarily obstructing and then releasing air within the oral chamber, causing the soft palate to vibrate (Stoeger et al., 2021). These sounds are new creations that over time were encouraged through positive feedback training and reinforcement. Vocal plasticity reflects the elephants' ability to produce a wide range of sounds and adapt them to various contexts. These sounds demonstrate the species' remarkable motor control and social feedback-driven learning (Stoeger et al., 2021).

It has been noted that elephants use around 8–10 call categories (Berg, 1983; Leong et al., 2002; Stoeger-Horwath et al., 2007). While this repertoire is not particularly extensive compared to other mammals, what makes elephants so special is their vocal plasticity and creativity (Nair et al., 2009; Poole, 2011b; Stoeger & Manger, 2014). To accommodate such a creativity and flexibility, elephants must have control over various vocal systems. For instance, they can manipulate the larynx as well as the supra-laryngeal nasal and oral vocal tract structures during low-frequency rumbles (De Silva, 2010; Stoeger, Heilmann, et al., 2012; Stoeger & Manger, 2014). This vocal learning ability highlights the distinctiveness of the elephant vocal system among non-human terrestrial mammals and places them within a small group of species capable of this complex behaviour (Martins & Boeckx, 2020; Tyack, 2020). An example of vocal learning is the Asian elephant (*Elephas maximus*), Koshik, who demonstrated the ability to imitate human words (Stoeger, Mietchen, et al., 2012). Similarly, Mlaika, a young African elephant in Kenya, imitated truck sounds from a nearby highway, producing calls which match the vehicles acoustic features. Another example, Calimero, an African elephant in a Swiss zoo, who was raised among Asian elephants, who then imitated their high-frequency and repetitive sounds, which are typical for Asian elephants. Research also highlights elephants like Jabu and Sawu, who learned new sounds like high-pitched calls by manipulating their trunk or low-frequency throbs by contracting specific muscles (Poole et al., 2005; Stoeger et al., 2021). And another instance for socially guided vocal learning in non-human mammals are killer whales (*Orcinus orca*), who were cross-socialised with bottlenose dolphins (Musser et al., 2014).

Overall, the interplay of cognitive abilities such as memory, imitation, problem-solving, and social understanding, along with social interactions and anatomical flexibility, positions elephants as exceptionally creative and adaptable vocalists. Like humans, elephants are long-lived, highly social and interact in complex fission–fusion societies (Fishlock & Lee, 2013; Pinter-Wollman et al., 2009). Their vocal learning and communication skills are therefore likely driven by this complex social structure, coupled with strong social bonds and feedback mechanisms (Stoeger et al., 2021).

Understanding the diversity and complexity of elephant vocalizations not only enriches our knowledge of their communication systems but also offers crucial insights into the evolution of vocal learning, a trait vital to human speech and language. Furthermore, distinguishing and identifying vocalizations like 'croaking' enhances our comprehension of their vocal repertoire and has significant impacts for future monitoring and conservation efforts (Stoeger et al., 2021).

4.3 Acoustic differences in Males and Females

In addition to providing a general description of the vocal behaviour of the Marataba elephants this thesis aimed to build on previous work of Baotic & Stoeger (2017) by examining whether male and female elephants in Marataba produce acoustically different rumbles. The study of Baotic & Stoeger (2017) presented the first comparative analysis of adult female and male African elephant vocalizations. In the following chapter the similarities and differences in their findings and this thesis will be discussed. Both studies concluded that there are significant differences between male and female rumbles and therefore contribute to our understanding of sexual dimorphism in elephant vocalizations (Baotic & Stoeger 2017).

While Baotic & Stoeger's (2017) study examined data from semi-captive African savannah elephants, this research focused on wild African savannah elephants. Both studies started their statistical analysis with a MANOVA. However, whereas Baotic & Stoeger (2017) utilized all 16 parameters, this thesis selected the eight parameters that their study identified as significantly discriminating between sexes. The MANOVA, followed by a post hoc ANOVA, identified six acoustic parameters (Formant 1, Formant 2, COFM, Jitter Factor, Mean Frequency, and Mid Frequency) as key contributors to these differences. These findings align with prior research, supporting the presence of sex-based vocal dimorphism in elephants. This highlights the critical role of acoustic signals in communication and sexual selection (Baotic & Stoeger, 2017).

The main difference between these studies was that Baotic & Stoeger (2017) used a pDFA (permuted Discriminant Function Analysis) for their analysis whereas this research utilized a

DFA/LDA (Discriminant Function Analysis/ Linear Discriminant Function Analysis) due to an insufficient number of cases for pDFA. Despite this difference, both approaches yielded high classification accuracies. The DFA/LDA approach of this thesis achieved an 83% classification accuracy, with Mean Frequency and Mid Frequency being the most significant contributors to sex differentiation. In comparison, Baotic & Stoeger's (2017) pDFA attained a slightly higher cross-validated accuracy of 85.6%. The mentioned Mean Frequency, in particular, was strongly associated with female vocalizations, reflecting higher values likely due to differences in vocal tract morphology between sexes. These results underscore the robustness of the selected acoustic features in distinguishing male and female vocalizations and provide valuable insights into how anatomical differences manifest in vocal outputs (Baotic & Stoeger, 2017).

Baotic & Stoeger (2017) identified source- and filter-related features as key differentiators, finding significant differences in fundamental frequency (f0) and formant structures. In contrast, this analysis focused on the first harmonic (f1), due to more datapoints, but also revealed significant distinctions in filter-related features, i.e. Formant 1 and Formant 2. The results of this study show males have lower mean values for both formants, aligning with Baotic & Stoegers findings that males exhibit lower frequencies (Baotic & Stoeger, 2017).

Baotic & Stoeger (2017) explored the role of both source-related and filter-related features in sex classification, attributing observed differences partly to size dimorphism and hormonal influences, such as testosterone. Testosterone has been shown to alter vocal folds in males, leading to a lower fundamental frequency (f0) (Beckford et al., 1985; Fouquet et al., 2016). Elephant vocal folds are described as “voluminous and long,” reaching approximately 10 cm in adult females (Herbst et al., 2013), and their size significantly influences vibration patterns during sound production, which in turn affects f0 (Charlton & Reby, 2016; Titze, 2011).Baotic & Stoeger (2017) also found that source-related features showed significant classification success between sexes when controlling for age but not for size. This could be attributed to the pronounced size dimorphism in elephants, where individuals of similar age may differ significantly in shoulder height, resulting in overlapping size categories. Similar findings have been reported in other species, such as baboons (Pfefferle & Fischer, 2006), goats (Briefer & McElligott, 2011), and domestic dogs (Taylor et al., 2008), where source-related vocal characteristics revealed size-related variations across age groups and sexes.

Additionally, Baotic & Stoeger (2017) emphasized the importance of filter-related features, such as Formant 1 (F1) and Formant 2 (F2), which encode reliable information about the sex of African elephants. These formant frequencies reflect the resonance characteristics of the vocal tract (VT) and are strongly associated with body size and shape. Male elephants, due to their larger vocal tract dimensions, produce lower and more closely spaced formants compared to females. This highlights how anatomical differences, such as vocal tract morphology, and hormonal factors, including testosterone, jointly influence acoustic outputs. Such differences play a crucial role in communication and sexual selection, as they provide valuable cues for social and reproductive interactions (Baotic & Stoeger, 2017).

Although this study does not explore hormonal effects, it highlights the relevance of formants in vocal dimorphism. Future research should integrate hormonal data to better understand how testosterone and other factors influence vocalizations, as suggested by Baotic & Stoeger (2017). Such investigations could provide deeper insights into the interplay between morphology, hormones, and acoustic features in vocal communication.

Furthermore, despite the successful classification in this thesis, violations of normality and homoscedasticity assumptions in the dataset highlight methodological challenges. While the robustness of LDA mitigates these concerns, future studies could explore advanced machine learning approaches, which may better handle such data distributions. Additionally, the sample imbalance (66.4% female vs. 33.6% male recordings) may influence classification accuracy, suggesting the need for more balanced datasets in future research.

In summary, the results of this study confirm those of Baotic & Stoeger (2017), showing significant acoustic differences between sexes in wild African savannah elephants. While this study successfully identifies these differences, it should be mentioned that there is a need for larger and more balanced sample sizes to improve classification accuracy and enhance the robustness of future acoustic monitoring systems that should be able to discriminate sex based on vocal cues. Therefore, future research should focus on increasing sample sizes, exploring additional components, refining methods to enhance accuracy and maybe integrate hormonal data.

4.4 Musth Rumbles

During musth, a periodic state of heightened sexual and aggressive behaviour caused by increased androgen levels in mature male elephants, they produce a specific type of rumble known as the musth-rumble (Ganswindt et al., 2005b; Poole, 1987, 2011b). This rumble is a distinct elephant vocalizations, characterised by repeated pulsations resonating in the nasal passages and overlaid on harmonic frequencies (Ganswindt et al., 2005b; Poole, 1987, 2011b).

One focus of this study was the investigation, whether males in musth also produce normal rumbles in addition musth-rumbles (which are part of a display), or whether it is possible to distinguish the hormonal state (musth/no musth) of an individual based on acoustic cues. This thesis analyzed the differences between rumbles from males not in musth, rumbles from males in musth, and musth-specific rumbles. Due to the limited sample size in terms of individuals as well as number of calls in two out of the three categories, the analysis focused only on means and standard deviations to compare the three categories of rumbles.

The findings carefully suggest that rumbles from males not in musth and males in musth exhibit similar values in their acoustic parameters. For instance, the filter-related parameter Formant 1 shows comparable values between these two categories, with means of 26.65 Hz and 24.84 Hz for males not in musth and males in musth. In contrast, the musth rumbles from males in musth exhibited a significantly lower mean frequency of 15.18 Hz. This trend was consistent across other frequency-related parameters such as 'Min Frequency,' 'Max Frequency,' 'Mean Frequency,' and 'Median Frequency,' where the musth rumbles consistently displayed lower frequencies. Despite these observed trends, the small sample size prevents me to make definitive conclusions.

In her chapter on “Behavioural Contexts of Elephant Acoustic Communication”, Poole (2011) stated, that musth-rumbles start with a low fundamental frequency, typically around 12 Hz, rises to around 17 Hz, and then falls back to about 11 Hz. The duration of the musth rumble averages around 4.4 seconds. During musth, males are also associated with behaviours like urine dribbling, temporal gland discretion and a specific ear posture called the Ear-Wave (LaDue et al., 2021; Moss et al., 2011; Poole, 1987, 1999, 2011b; Stoeger & Baotic, 2016).

Poole (2011) further conducted a discriminant function analysis (DFA), demonstrating that these specific rumbles can accurately differentiate between individual males, even with a small sample size. However, direct comparisons with other types of rumbles were not possible, because the musth-specific rumbles are exclusively produced by males during musth, making them fundamentally distinct and unavailable for comparison with rumbles produced outside of this context (Moss et al., 2011; Poole, 2011b).

The musth-rumbles are a reliable indicator for the presence of a musth male, with lone musth males emitting these rumbles more frequently than those guarding an oestrous female. When females hear musth rumbles, they sometimes respond with behaviours such as vocalizing in unison, secreting from temporal glands, or urinating and defecating (Moss et al., 2011; Poole, 1999, 2011b).

This subtype of rumbles occurs in various contexts, such as during aggressive and sexual interactions, while marking territory, drinking, wallowing, or when feeling challenged. They serve to advertise the elephant's aggressive, territorial, and sexual state to rivals and potential mates. This aggression is directed not only at other elephants but can also extend to humans and other animals (Ganswindt et al., 2005b, 2010; Poole, 1999, 2011b). During our data collection, we also observed musth males displaying aggressive and dominant behaviour toward us and our car as well as other animals, such as giraffes and warthogs.

The paper of Poole, (1999) highlights that males in musth are less tolerant of disturbances and particularly sensitive to the presence of other males, leading them to respond more aggressively to potential rivals. This increased aggression heightens the risk of fatal encounters with humans, especially if the elephants perceive them as threats or obstacles. Additionally, other studies by Ganswindt et al. (2010) and Keil (2023) noted that musth males have been documented attacking humans, particularly when they feel cornered or challenged. Therefore, during musth, male elephants are more unpredictable and potentially even more dangerous (Ganswindt et al., 2005b; Graham et al., 2010; Keil, 2023; Moss et al., 2011; Poole, 1999, 2011b).

Another important aspect of the human-elephant conflict is that R. E. Hoare (1999) found male elephants are more frequently involved in problematic behaviours, such as approaching human settlements and engaging in crop raiding, compared to females. This male bias has been observed in both African and Asian elephants, although it has not always been quantified (R. Hoare, 1995; Naughton-Treves, 1998; Sukumar, 1991; Thouless, 1994). However, in some areas, crop-raiding is also associated with family groups led by mature bulls, especially along migration routes (Smith & Kasiki, 1999). Males are believed to be more attracted to food crops due to their higher nutritional value and palatability, which aligns with their risk-taking strategy to maximize reproductive success. This behaviour is consistent with optimal foraging theory, suggesting that males prioritise better nutrition despite the risks involved (Nelson et al., 2003; Sukumar, 1990, 1991; Thouless, 1994; Thouless & Sakwa, 1995).

In conclusion, more research is required to validate the preliminary findings of this thesis and explore whether it is possible to determine an individual's hormonal state based on acoustic cues of calls, even when only a single rumble is available. For future research, enhancing data collection could involve equipping male elephants with collars fitted with microphones. This approach would facilitate the gathering of extensive acoustic data from both males in musth and those not in musth, allowing for a more comprehensive analysis. Additionally, it has to be noted that our understanding of male vocal behaviour is still limited compared to that of females, necessitating further investigation into their behaviour and communication (Baotic & Stoeger, 2017, 2017; Poole JH., 1994; Zeppelzauer & Stoeger, 2015)

Lastly, for the development of an effective early-warning system, it is crucial to distinguish between males in musth and those not in musth based on acoustic cues. Males in musth are known to exhibit increased aggression towards humans and pose a greater risk to local people and communities. It is essential for humans to accurately identify which animals are approaching, as responses may differ significantly between a calm male or an aggressive male in musth. This study hints at the possibility that males in musth can selectively choose their vocalizations, which could have significant implications for human-elephant conflict mitigation strategies. Developing an acoustic monitoring system capable of accurately identifying a male elephant's hormonal state through its rumbles could greatly enhance the effectiveness of warning systems and help reduce conflicts between humans and elephants (Ganswindt et al., 2005b; Poole, 1999, 2011b; Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

4.5 Acoustic Monitoring System

The main goal of this thesis was to contribute recorded, annotated, and analyzed data to the early-warning system (Zeppelzauer et al., 2013, 2015; Zeppelzauer & Stoeger, 2015) and supporting its further development. The proposed method outperforms previous approaches, such as those by Venter & Hanekom (2010), in both detection rate and false-positive rate, representing a step toward an autonomous early-warning system for elephants. However, the system still requires improvements, such as reducing the false-positive rate and refining the system before it can be tested and used in the field.

A significant focus of the project was on acoustic detection, particularly the detection of elephant rumbles. The research underscored that signal enhancement is crucial for robust detection, especially when recordings are made in uncontrolled environments with lower signal-to-noise ratios. Previous studies often overlooked this because they relied on controlled conditions where such enhancement was unnecessary. The project also highlighted the need for the detection system to adapt to different environments and elephant populations. Therefore, it was crucial that we collected data from a new population in Marataba, were we gained insights in the vocal behaviour and the different noise sources of another elephant population Zeppelzauer et al., 2013, 2015; Zeppelzauer & Stoeger, 2015).

As mentioned in the chapters '4.1.1 Identification of individuals', '4.1.2 Noise' and '4.2.2 Vocal creativity' and also emphasised by Zeppelzauer et al. (2015) acoustic characteristics can vary significantly depending on the surroundings, for example nearby roads or railways, airplanes, wind turbines and also different elephant species or populations can have distinct vocal repertoires. Machine learning techniques are employed to model both the elephant calls and the background soundscape, which is critical for adapting the detection system to different settings.

To ensure this, a lot of data has to be collected and provided to the system (Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

A prototype acoustic detector was developed and tested in the laboratory with field data by Zeppelzauer & Stoeger (2015). However, several challenges remain. Firstly, the team explored the limitations of using template matching for detecting elephant rumbles in noisy wildlife recordings. Template matching often fails due to its inability to model noise and the variability in rumble duration and fundamental frequency, resulting in a high false-positive rate of 24.4%. The proposed solution, which involves spectro-temporal signal enhancement, significantly reduces this rate to 13.7% by improving the signal-to-noise ratio. Another suggested approach is to incorporate multiscale analysis to differentiate sounds based on their temporal structure (Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

Secondly, the research by Zeppelzauer et al. (2015) and Zeppelzauer & Stoeger (2015) highlight that engine noises, which have similar frequencies in the infrasonic range and harmonic structures with rumbles, cannot be reliably distinguished using short-time acoustic analysis. The authors propose that longer-time analysis is necessary, as it allows for differentiation between rumbles and engine sounds based on their duration. Future improvements could include combining the detector with long-time acoustic analysis. Additionally, the detector could assist in semi-automatic annotation by identifying rumbles that were missed during manual annotation, potentially becoming a valuable tool for annotating large volumes of monitoring data in the future (Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

The project also suggests that the detector should not be limited to rumbles alone but should recognise other elephant calls like trumpets, snorts, and roars. This would involve training individual detectors for each call type and combining them into an ensemble, potentially improving detection performance (Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

As shown in chapter 1.3 in figure 3., the project of Zeppelzauer & Stoeger (2015) addressed the necessities and complexities of visual detection of elephants. Often it is not possible to rely on acoustic cues, therefore a visual component of the early-warning system is planned too. Nevertheless, there are some challenging environmental factors as occlusions, low contrast, and poor lighting. Despite these difficulties, the project showed that elephants could be reliably detected at short distances. A key to robust detection was developing an adaptive colour model of elephant skin, tailored to different sites and lighting conditions, along with using temporal processing to track elephants over time for tasks like estimating group sizes and identifying behaviours (Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

However, the computational demands for visual detection, especially in image segmentation and motion analysis, are high. To address this, their project suggests speeding up these algorithms for real-time processing and using background models to reduce the load in fixed-camera setups. For environments with limited processing power, the project proposes developing image-based detectors as a simpler alternative to video-based systems, which could run on affordable hardware like Raspberry Pi (Gay, 2014; Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

The project concluded that combining acoustic and visual detectors could create a more reliable system, compensating for the weaknesses of each method. As for example some elephants do not rumble when approaching human settlements or some elephants cannot be seen visually because of dense forest or other environmental factors. To further enhance detection capabilities, the project also recommends incorporating thermal cameras, which could improve visual detection both at night and during the day (Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

In summary, the project has made significant progress in establishing the scientific foundation for an elephant detection and early-warning system. However, further research, development, and funding are required to refine the detectors, evaluate them in real-world conditions, and ultimately implement them in the field. Such a system holds great potential for mitigating the ongoing human-elephant conflict, which is a pressing issue in many regions (Zeppelzauer et al., 2015; Zeppelzauer & Stoeger, 2015).

4.6 Conclusion and Research Outlook

In this thesis, I have delved into the human-elephant conflict, focusing on how we can mitigate this issue using acoustic detection and monitoring systems. Specifically, I explored how we can further enhance the early-warning system of (Zeppelzauer et al., 2015 and Zeppelzauer & Stoeger, 2015). The data collected, annotated, and analyzed throughout this research will contribute to the further development of this system. This may involve improving the system's ability to reliably distinguish between male and female rumbles, identifying different types of recorded noises for system learning, differentiating between rumble and musth rumbles, understanding various behavioural contexts, or incorporating new ideas and approaches identified in this study.

For my first research question, I focused on whether we can distinguish the males and females of Marataba using rumbles. Following the methods of Baotic & Stoeger (2017), I was able to determine with significant results that we can indeed distinguish the sexes based on acoustic cues. These results not only showed that this statistical analysis is well-suited to this question, but also that it is now possible to reliably distinguish between females and males from two different populations, which is crucial information for the early-warning system.

Furthermore, to understand not only the differences between females and males but also within a sex, I formulated my second research question, in which I wanted to find out whether the hormonal state of a male can be identified through a rumble. Since we observed that males in musth not only produced typical musth rumbles, the question arose as to whether a normal rumble could be used to determine if a male was in musth or not. As a control group, the typical musth rumbles, which differ significantly from normal rumbles in their frequency and structure were used. Due to unbalanced groups and too few data points in two of the three groups, only the means and standard deviations could be calculated. The preliminary results showed that musth rumbles differed from the other two categories 'rumble male not in musth' and 'rumble male in musth', while the two rumble categories did not show any clear differences. It will be necessary to collect more data and explore this question further.

Therefore, more studies are needed to explore whether it is possible to determine an individual elephant's hormonal state based on acoustic cues. This could significantly enhance the accuracy of monitoring systems, particularly if we can identify specific vocal patterns associated with different emotional states, such as nervousness or fear. Understanding these emotional cues is vital for improving the effectiveness of anti-poaching measures. For instance, if a conservation team detects vocalizations indicative of stress or anxiety in male elephants, such as a rise in fundamental frequency (f0), this could serve as a cue potential poaching activity. The ability to detect these signs would allow for effective action to protect the elephants. In addition, since male elephants, particularly those in musth, are often involved in destroying fences and aggressive behaviour towards humans, it is essential to focus more research on these individuals. Understanding the vocal communication and behaviour of males, especially during musth, could provide critical insights into mitigating conflicts and improving coexistence strategies (Nelson et al., 2003; Osborn, F.V. & Parker, G.E., 2002; Shaffer et al., 2019).

The results of this work show several promising approaches for future research that could significantly advance our understanding of elephant behaviour and enhance conservation efforts through acoustic monitoring systems. Further research, development, and funding are required to refine acoustic detectors and evaluate them in real-world conditions. Implementing these detectors in the field will be crucial for their effective use in monitoring and mitigating human-elephant conflicts (Zeppelzauer et al., 2015 and Zeppelzauer & Stoeger, 2015). Future studies should also focus on improving data collection methods. One potential approach involves equipping male elephants with collars, fitted with recording devices or microphones. This would simplify the gathering of extensive acoustic data from both males in musth and those not in musth, providing a more comprehensive analysis of their vocalizations. Additionally, it would be helpful, to investigate how elephants behave when they approach crops or human settlements, for example if they remain quiet or vocalise and whether collars can help capture this behaviour.

In conclusion, further investigation into elephant vocal communication is not only important for advancing scientific knowledge but also for developing practical applications in conservation. By refining our understanding of how elephants communicate their emotional states, we can improve the accuracy and effectiveness of acoustic monitoring systems, ultimately leading to better protection of these magnificent animals.

I believe that conducting area-wide monitoring in the future is crucial. Detecting when elephants are approaching human settlements is important, as it allows people to take timely precautions. This can help prevent human-elephant conflicts. For the future development of the acoustic monitoring system, securing additional funding for further research and data collection is essential. Additionally, incorporating visual components will be important, necessitating further data collection in this area. The potential of machine learning and AI in enhancing animal monitoring systems will also be a promising approach for the future. Ideally with future projects, we can further research about elephants, their complex behaviour and unique communication system and hopefully help saving this exceptional species.

References

Adams, W. M., & Hulme, D. (2001). If community conservation is the answer in Africa, what is the question? *Oryx*, *35*(3), 193–200. https://doi.org/10.1046/j.1365-3008.2001.00183.x

Alex. (2017, Juli 13). *Modern and Historical range of the elephants*. Vivid Maps. https://vividmaps.com/elephants/

Armbruster, P., & Lande, R. (1993). A Population Viability Analysis for African Elephant (*Loxodonta africana*): How Big Should Reserves Be? *Conservation Biology*, *7*(3), 602–610. https://doi.org/10.1046/j.1523-1739.1993.07030602.x

Au, W. W. L., & Hastings, M. C. (2008). *Principles of Marine Bioacoustics*. Springer US. https://doi.org/10.1007/978-0-387-78365-9

Balasz P., & Noll A. (2000). *Concept of the integrated signal analysis software system STx*. Jahrestagung der Österreichischen Physikalischen Gesellschaf 2000, ÖPG.

Baotic, A., & Stoeger, A. S. (2017). Sexual dimorphism in African elephant social rumbles. *PLOS ONE*, *12*(5), e0177411. https://doi.org/10.1371/journal.pone.0177411

Barnes, R. F. W. (1999). Is there a future for elephants in West Africa? *Mammal Review*, *29*(3), 175–200. https://doi.org/10.1046/j.1365-2907.1999.00044.x

Barnes, R. F. W., Craig, G. C., Dublin, H. T., Overton, G., Simons, W., & Thouless, C. R. (1998). *African Elephant Database 1998*.

Bates, L. (2020). Cognitive Abilities in Elephants. In L. Workman, W. Reader, & J. H. Barkow (Hrsg.), *The Cambridge Handbook of Evolutionary Perspectives on Human Behavior* (1. Aufl., S. 14–22). Cambridge University Press. https://doi.org/10.1017/9781108131797.003

Beckford, N. S., Schaid, D., Rood, S. R., & Schanbacher, B. (1985). Androgen Stimulation and Laryngeal Development. *Annals of Otology, Rhinology & Laryngology*, *94*(6), 634–640. https://doi.org/10.1177/000348948509400622

Beranek LL. (1988). *Acoustics—Acoustical measurements.* American Institute of Physics.

Berg, J. K. (1983). Vocalizations and Associated Behaviors of the African Elephant (*Loxodonta africana*) in Captivity. *Zeitschrift Für Tierpsychologie*, *63*(1), 63–79. https://doi.org/10.1111/j.1439-0310.1983.tb00741.x

Blake, S., Deem, S. L., Strindberg, S., Maisels, F., Momont, L., Isia, I.-B., Douglas-Hamilton, I., Karesh, W. B., & Kock, M. D. (2008). Roadless Wilderness Area Determines Forest Elephant Movements in the Congo Basin. *PLoS ONE*, *3*(10), e3546. https://doi.org/10.1371/journal.pone.0003546

Blanc, J. J., Barnes, R. F. W., Craig, G. C., Dublin, H. T., Thouless, C. R., Douglas-Hamilton, I., & Hart, J. A. (2007). *African elephant status report 2007: An update from the African elephant database*. IUCN. https://doi.org/10.2305/IUCN.CH.2007.SSC-OP.33.en

Borden, J. B., & Flory, S. L. (2021). Urban evolution of invasive species. *Frontiers in Ecology and the Environment*, *19*(3), 184–191. https://doi.org/10.1002/fee.2295

Briefer, E., & McElligott, A. G. (2011). Indicators of age, body size and sex in goat kid calls revealed using the source–filter theory. *Applied Animal Behaviour Science*, *133*(3–4), 175–185. https://doi.org/10.1016/j.applanim.2011.05.012

Calabrese, A., Calabrese, J. M., Songer, M., Wegmann, M., Hedges, S., Rose, R., & Leimgruber, P. (2017). Conservation status of Asian elephants: The influence of habitat and governance. *Biodiversity and Conservation*, *26*(9), 2067–2081. https://doi.org/10.1007/s10531-017-1345-5

Caughley, G., Dublin, H., & Parker, I. (1990). Projected decline of the African elephant. *Biological Conservation*, *54*(2), 157–164. https://doi.org/10.1016/0006-3207(90)90140-K

Charlton, B. D., & Reby, D. (2016). The evolution of acoustic size exaggeration in terrestrial mammals. *Nature Communications*, *7*(1), 12739. https://doi.org/10.1038/ncomms12739

Chase, M. J., Schlossberg, S., Griffin, C. R., Bouché, P. J. C., Djene, S. W., Elkan, P. W., Ferreira, S., Grossman, F., Kohi, E. M., Landen, K., Omondi, P., Peltier, A., Selier, S. A. J., &

Sutcliffe, R. (2016). Continent-wide survey reveals massive decline in African savannah elephants. *PeerJ*, *4*, e2354. https://doi.org/10.7717/peerj.2354

Coverdale, T. C., Kartzinel, T. R., Grabowski, K. L., Shriver, R. K., Hassan, A. A., Goheen, J. R., Palmer, T. M., & Pringle, R. M. (2016). Elephants in the understory: Opposing direct and indirect effects of consumption and ecosystem engineering by megaherbivores. *Ecology*, *97*(11), 3219–3230. https://doi.org/10.1002/ecy.1557

De Boer, W. F., & Baquete, D. S. (1998). Natural resource use, crop damage and attitudes of rural people in the vicinity of the Maputo Elephant Reserve, Mozambique. *Environmental Conservation*, *25*(3), 208–218. https://doi.org/10.1017/S0376892998000265

De Silva, S. (2010). Acoustic communication in the Asian elephant, Elephas maximus maximus. *Behaviour*, *147*(7), 825–852. https://doi.org/10.1163/000579510X495762

Digby, A., Towsey, M., Bell, B. D., & Teal, P. D. (2013). A practical comparison of manual and autonomous methods for acoustic monitoring. *Methods in Ecology and Evolution*, *4*(7), 675–683. https://doi.org/10.1111/2041-210X.12060

Don Ho. (2003). *Author | Notepad++*. https://notepad-plus-plus.org/author/

Douglas-Hamilton, I. (1987). African elephants: Population trends and their causes. *Oryx*, *21*(1), 11–24. https://doi.org/10.1017/S0030605300020433

Drakshayini, S.T, M., M., S., Assistant Professor, Atria Institute of Technology, Bengaluru., Nanjundeshwara, K., & Assistant Professor, East West school of Business Management Bengaluru. (2023). LEVERAGING MACHINE LEARNING AND REMOTE SENSING FOR WILDLIFE CONSERVATION: A COMPREHENSIVE REVIEW. *International Journal of Advanced Research*, *11*(06), 636–647. https://doi.org/10.21474/IJAR01/17110

Dudley, J. P. (2000). Seed Dispersal by Elephants in Semiarid Woodland Habitats of Hwange National Park, Zimbabwe [1]. *Biotropica*, *32*(3), 556–561. https://doi.org/10.1111/j.1744-7429.2000.tb00503.x

Eleuteri, V. (o. J.). *Gestural communication in African savannah elephants (in preparation)*.

Eleuteri, V., Bates, L., Rendle-Worthington, J., Hobaiter, C., & Stoeger, A. (2024). Multimodal communication and audience directedness in the greeting behaviour of semi-captive African savannah elephants. *Communications Biology*, *7*(1), 472. https://doi.org/10.1038/s42003-024-06133-5

Fernando, P., Wikramanayake, E., Weerakoon, D., Jayasinghe, L. K. A., Gunawardene, M., & Janaka, H. K. (2005). Perceptions and Patterns of Human–elephant Conflict in Old and New Settlements in Sri Lanka: Insights for Mitigation and Management. *Biodiversity and Conservation*, *14*(10), 2465–2481. https://doi.org/10.1007/s10531-004-0216-z

Fishlock, V., & Lee, P. C. (2013). Forest elephants: Fission–fusion and social arenas. *Animal Behaviour*, *85*(2), 357–363. https://doi.org/10.1016/j.anbehav.2012.11.004

Fitch, W. T. (2004). *Fitch_Die Stimme aus biologischer Sicht.pdf* (S. 85-102.). : Matthes & Seitz.

Fitch, W. T., & Hauser, M. D. (2003). Unpacking "Honesty": Vertebrate Vocal Production and the Evolution of Acoustic Signals. In A. M. Simmons, R. R. Fay, & A. N. Popper (Hrsg.), *Acoustic Communication* (Bd. 16, S. 65–137). Springer-Verlag. https://doi.org/10.1007/0-387-22762-8_3

Fouquet, M., Pisanski, K., Mathevon, N., & Reby, D. (2016). Seven and up: Individual differences in male voice fundamental frequency emerge before puberty and remain stable throughout adulthood. *Royal Society Open Science*, *3*(10), 160395. https://doi.org/10.1098/rsos.160395

Fritz, H. (2017). Long-term field studies of elephants: Understanding the ecology and conservation of a long-lived ecosystem engineer. *Journal of Mammalogy*, *98*(3), 603–611. https://doi.org/10.1093/jmammal/gyx023

Frommolt, K.-H. (2013). *Akustische Mustererkennung von Tierstimmen und deren Nutzung für Monitoringaufgaben im Interesse des Naturschutzes*.

Ganswindt, A., Muenscher, S., Henley, M., Henley, S., Heistermann, M., Palme, R., Thompson, P., & Bertschinger, H. (2010). Endocrine correlates of musth and the impact of ecological and social factors in free-ranging African elephants (Loxodonta africana). *Hormones and Behavior*, *57*(4–5), 506–514. https://doi.org/10.1016/j.yhbeh.2010.02.009

Ganswindt, A., Rasmussen, H. B., Heistermann, M., & Hodges, J. K. (2005a). The sexually active states of free-ranging male African elephants (Loxodonta africana): Defining musth and non-musth using endocrinology, physical signals, and behavior. *Hormones and Behavior*, *47*(1), 83–91. https://doi.org/10.1016/j.yhbeh.2004.09.002

Ganswindt, A., Rasmussen, H. B., Heistermann, M., & Hodges, J. K. (2005b). The sexually active states of free-ranging male African elephants (Loxodonta africana): Defining musth and non-musth using endocrinology, physical signals, and behavior. *Hormones and Behavior*, *47*(1), 83–91. https://doi.org/10.1016/j.yhbeh.2004.09.002

Garstang, M. (2004). Long-distance, low-frequency elephant communication. *Journal of Comparative Physiology A*, *190*(10), 791–805. https://doi.org/10.1007/s00359-004-0553-0

Gay, W. W. (2014). *Raspberry Pi Hardware Reference*. Apress. https://doi.org/10.1007/978-1-4842-0799-4

Graham, M. D., Notter, B., Adams, W. M., Lee, P. C., & Ochieng, T. N. (2010). Patterns of crop-raiding by elephants, *Loxodonta africana* , in Laikipia, Kenya, and the management of human–elephant conflict. *Systematics and Biodiversity*, *8*(4), 435–445. https://doi.org/10.1080/14772000.2010.533716

Gubbi, S. (2012). Patterns and correlates of human–elephant conflict around a south Indian reserve. *Biological Conservation*, *148*(1), 88–95. https://doi.org/10.1016/j.biocon.2012.01.046

Hao, Z., Zhang, C., Li, L., Gao, B., Wu, R., Pei, N., & Liu, Y. (2024). Anthropogenic noise and habitat structure shaping dominant frequency of bird sounds along urban gradients. *iScience*, *27*(2), 109056. https://doi.org/10.1016/j.isci.2024.109056

Haynes, G. (1991). *Mammoths, mastodonts, and elephants: Biology, behavior, and the fossil record*. Cambridge University Press.

Haynes, G. (2012). Elephants (and extinct relatives) as earth-movers and ecosystem engineers. *Geomorphology*, *157–158*, 99–107. https://doi.org/10.1016/j.geomorph.2011.04.045

Herbst, C. T., Stoeger, A. S., Frey, R., Lohscheller, J., Titze, I. R., Gumpenberger, M., & Fitch, W. T. (2012). How Low Can You Go? Physical Production Mechanism of Elephant Infrasonic Vocalizations. *Science*, *337*(6094), 595–599. https://doi.org/10.1126/science.1219712

Herbst, C. T., Švec, J. G., Lohscheller, J., Frey, R., Gumpenberger, M., Stoeger, A. S., & Fitch, W. T. (2013). Complex vibratory patterns in an elephant larynx. *Journal of Experimental Biology*, *216*(21), 4054–4064. https://doi.org/10.1242/jeb.091009

Hoare, R. (1995). *OPTIONS FOR THE CONTROL OF ELEPHANTS IN CONFLICT WITH PEOPLE*. *19*.

Hoare, R. (2015). Lessons From 20 Years of Human–Elephant Conflict Mitigation in Africa. *Human Dimensions of Wildlife*, *20*(4), 289–295. https://doi.org/10.1080/10871209.2015.1005855

Hoare, R. E. (1999). Determinants of human–elephant conflict in a land-use mosaic. *Journal of Applied Ecology*, *36*(5), 689–700. https://doi.org/10.1046/j.1365-2664.1999.00437.x

Höft, R., & Höft, M. (1995). The differential effects of elephants on rain forest communities in the Shimba Hills, Kenya. *Biological Conservation*, *73*(1), 67–79. https://doi.org/10.1016/0006-3207(95)90067-5

Holmes, S. B., McIlwrick, K. A., & Venier, L. A. (2014). Using automated sound recording and analysis to detect bird species-at-risk in southwestern Ontario woodlands. *Wildlife Society Bulletin*, *38*(3), 591–598. https://doi.org/10.1002/wsb.421

IUCN SSC African Elephant Specialist Group | IUCN. (2023). https://iucn.org/our-union/commissions/group/iucn-ssc-african-elephant-specialist-group

Keil, P. G. (2023). Chapter 12. Musth as a biosocial event. In N. Lainé, P. G. Keil, & K. Rahmat (Hrsg.), *Composing Worlds with Elephants* (S. 233–252). IRD Éditions. https://doi.org/10.4000/books.irdeditions.47375

Kenya Wildlife Service, & Kenya Wildlife Service. (1994). *Wildlife-human conflicts in Kenya*. (Kenya Wildlife Service, Hrsg.).

Knight, E. C., Hannah, K. C., Foley, G. J., Scott, C. D., Brigham, R. M., & Bayne, E. (2017). Recommendations for acoustic recognizer performance assessment with application to five common automated signal recognition programs. *Avian Conservation and Ecology*, *12*(2), art14. https://doi.org/10.5751/ACE-01114-120214

Kohi, E. M., De Boer, W. F., Peel, M. J. S., Slotow, R., Van Der Waal, C., Heitkönig, I. M. A., Skidmore, A., & Prins, H. H. T. (2011). African Elephants *Loxodonta africana* Amplify Browse Heterogeneity in African Savanna. *Biotropica*, *43*(6), 711–721. https://doi.org/10.1111/j.1744-7429.2010.00724.x

LaDue, C. A., Schulte, B. A., Kiso, W. K., & Freeman, E. W. (2021). Musth and sexual selection in elephants: A review of signalling properties and potential fitness consequences. *Behaviour*, *159*(3–4), 207–242. https://doi.org/10.1163/1568539X-bja10120

Langbauer, W. R. (2000). Elephant communication. *Zoo Biology*, *19*(5), 425–445. https://doi.org/10.1002/1098-2361(2000)19:5<425::AID-ZOO11>3.0.CO;2-A

Langbauer, W. R., Payne, K. B., Charif, R. A., Rapaport, L., & Osborn, F. (1991). African Elephants Respond to Distant Playbacks of Low-Frequency Conspecific Calls. *Journal of Experimental Biology*, *157*(1), 35–46. https://doi.org/10.1242/jeb.157.1.35

Larom, D., Garstang, M., Payne, K., & Raspet, R. (1997). Surface meteorology and animal communication. *The Journal of the Acoustical Society of America*, *102*(5_Supplement), 3124–3124. https://doi.org/10.1121/1.420598

Leimgruber, P., Gagnon, J. B., Wemmer, C., Kelly, D. S., Songer, M. A., & Selig, E. R. (2003). Fragmentation of Asia’s remaining wildlands: Implications for Asian elephant conservation. *Animal Conservation*, *6*(4), 347–359. https://doi.org/10.1017/S1367943003003421

Leong, K. M., Ortolani, A., Burks, K. D., Mellen, J. D., & Savage, A. (2003). QUANTIFYING ACOUSTIC AND TEMPORAL CHARACTERISTICS OF VOCALIZATIONS FOR A GROUP OF CAPTIVE AFRICAN ELEPHANTS *LOXODONTA AFRICANA*. *Bioacoustics*, *13*(3), 213–231. https://doi.org/10.1080/09524622.2003.9753499

Leong, K. M., Ortolani, A., Graham, L. H., & Savage, A. (2002). The use of low-frequency vocalizations in African elephant(Loxodonta africana) reproductive strategies. *Hormones and Behavior*, *43*(4), 433–443. https://doi.org/10.1016/s0018-506x(03)00025-4

MacFadden, B. J. (1997). Origin and evolution of the grazing guild in new world terrestrial mammals. *Trends in Ecology & Evolution*, *12*(5), 182–187. https://doi.org/10.1016/S0169-5347(97)01049-5

Marataba. (2020). Marataba. https://www.marataba.co.za/

Martins, P. T., & Boeckx, C. (2020). Vocal learning: Beyond the continuum. *PLOS Biology*, *18*(3), e3000672. https://doi.org/10.1371/journal.pbio.3000672

McComb, K., Moss, C., Durant, S. M., Baker, L., & Sayialel, S. (2001a). Matriarchs As Repositories of Social Knowledge in African Elephants. *Science*, *292*(5516), 491–494. https://doi.org/10.1126/science.1057895

McComb, K., Moss, C., Durant, S. M., Baker, L., & Sayialel, S. (2001b). Matriarchs As Repositories of Social Knowledge in African Elephants. *Science*, *292*(5516), 491–494. https://doi.org/10.1126/science.1057895

McComb, K., & Reby, D. (2009). Communication in Terrestrial Animals. In *Encyclopedia of Neuroscience* (S. 1167–1171). Elsevier. https://doi.org/10.1016/B978-008045046-9.01863-5

McComb, K., Reby, D., Baker, L., Moss, C., & Sayialel, S. (2003). Long-distance communication of acoustic cues to social identity in African elephants. *Animal Behaviour*, *65*(2), 317–329. https://doi.org/10.1006/anbe.2003.2047

Menton, M., Larrea, C., Latorre, S., Martinez-Alier, J., Peck, M., Temper, L., & Walter, M. (2020). Environmental justice and the SDGs: From synergies to gaps and contradictions. *Sustainability Science*, *15*(6), 1621–1636. https://doi.org/10.1007/s11625-020-00789-8

Moss, C. J., Croze, H., & Lee, P. C. (2011). *The Amboseli Elephants: A Long-Term Perspective on a Long-Lived Mammal*. University of Chicago Press. https://doi.org/10.7208/chicago/9780226542263.001.0001

Musser, W. B., Bowles, A. E., Grebner, D. M., & Crance, J. L. (2014). Differences in acoustic features of vocalizations produced by killer whales cross-socialized with bottlenose dolphins. *The Journal of the Acoustical Society of America*, *136*(4), 1990–2002. https://doi.org/10.1121/1.4893906

Nair, S., Balakrishnan, R., Seelamantula, C. S., & Sukumar, R. (2009). Vocalizations of wild Asian elephants (*Elephas maximus*): Structural classification and social context. *The Journal of the Acoustical Society of America*, *126*(5), 2768–2778. https://doi.org/10.1121/1.3224717

Naughton-Treves, L. (1998). Predicting Patterns of Crop Damage by Wildlife around Kibale National Park, Uganda. *Conservation Biology*, *12*(1), 156–168. https://doi.org/10.1111/j.1523-1739.1998.96346.x

Nelson, A., Bidwell, P., & Sillero-Zubiri, C. (2003). *A review of human-elephant conflict management strategies*.

Niskanen, L. (2006). Managing Human Elephant Conflict − Lessons Learned. *Proceedings of the Vertebrate Pest Conference*, *22*. https://doi.org/10.5070/V422110141

NOAA Ocean Exploration. (2024). https://oceanexplorer.noaa.gov/

Nyhus, P. J., Tilson, R., & Sumianto. (2000). Crop-raiding elephants and conservation implications at Way Kambas National Park, Sumatra, Indonesia. *Oryx*, *34*(4), 262–274. https://doi.org/10.1046/j.1365-3008.2000.00132.x

O'Connell-Rodwell, C. E., Berezin, J. L., Pignatelli, A., & Rodwell, T. C. (2024). The use of vocal coordination in male African elephant group departures: Evidence of active leadership and consensus. *PeerJ*, *12*, e17767. https://doi.org/10.7717/peerj.17767

O'Connell-Rodwell, C. E., Berezin, J. L., Shambaugh, K., & Stewart, E. (2023). Who is calling: Proof of concept for the use of laser Doppler vibrometry in identifying individual callers within African elephant vocalization bouts. *The European Physical Journal Special Topics*, *232*(2), 253–259. https://doi.org/10.1140/epjs/s11734-022-00704-5

O'Connell-Rodwell, C. E., Rodwell, T., Rice, M., & Hart, L. A. (2000). Living with the modern conservation paradigm: Can agricultural communities co-exist with elephants? A five-year case study in East Caprivi, Namibia. *Biological Conservation*, *93*(3), 381–391. https://doi.org/10.1016/S0006-3207(99)00108-1

O'Connell-Rodwell, C. E., Wood, J. D., Kinzley, C., Rodwell, T. C., Alarcon, C., Wasser, S. K., & Sapolsky, R. (2011). Male African elephants (*Loxodonta africana*) queue when the stakes are high. *Ethology Ecology & Evolution*, *23*(4), 388–397. https://doi.org/10.1080/03949370.2011.598569

Osborn, F.V. & Parker, G.E. (2002). *Community-based methods to reduce crop loss to elephants: Experiments in the communal lands of Zimbabwe.*

Otero, I., Farrell, K. N., Pueyo, S., Kallis, G., Kehoe, L., Haberl, H., Plutzar, C., Hobson, P., García-Márquez, J., Rodríguez-Labajos, B., Martin, J., Erb, K., Schindler, S., Nielsen, J., Skorin, T., Settele, J., Essl, F., Gómez-Baggethun, E., Brotons, L., … Pe'er, G. (2020). Biodiversity policy beyond economic growth. *Conservation Letters*, *13*(4), e12713. https://doi.org/10.1111/conl.12713

Palminteri, S. (2015, September 6). *Call of the Wild Tiger: Using acoustics software to identify individual tigers by their calls*. Wildtech. https://wildtech.mongabay.com/2015/09/call-of-the-wild-tiger-using-acoustics-software-to-identify-individual-tigers-by-their-calls/

Panda, B. P., Purohit, S., Parida, S. P., Dash, A. K., Mohapatra, R. K., & Pradhan, A. (2022). Noise pollution effect on composition of avian structure in different urban gradients. *Materials Today: Proceedings*, *67*, 1123–1128. https://doi.org/10.1016/j.matpr.2022.07.282

Pardo, M. A., Fristrup, K., Lolchuragi, D. S., Poole, J. H., Granli, P., Moss, C., Douglas-Hamilton, I., & Wittemyer, G. (2024). African elephants address one another with individually specific name-like calls. *Nature Ecology & Evolution*, *8*(7), 1353–1364. https://doi.org/10.1038/s41559-024-02420-w

Pardo, M. A., Lolchuragi, D. S., Poole, J., Granli, P., Moss, C., Douglas-Hamilton, I., & Wittemyer, G. (2024). Female African elephant rumbles differ between populations and sympatric social groups. *Royal Society Open Science*, *11*(9), 241264. https://doi.org/10.1098/rsos.241264

Pardo, M. A., Poole, J. H., Stoeger, A. S., Wrege, P. H., O'Connell-Rodwell, C. E., Padmalal, U. K., & De Silva, S. (2019). Differences in combinatorial calls among the 3 elephant species cannot be explained by phylogeny. *Behavioral Ecology*, *30*(3), 809–820. https://doi.org/10.1093/beheco/arz018

Parker, I. S. C., & Graham, A. D. (1989). Elephant decline: Downward trends in African elephant distribution and numbers (part ii). *International Journal of Environmental Studies*, *35*(1–2), 13–26. https://doi.org/10.1080/00207238908710546

Payne, K. B., Langbauer, W. R., & Thomas, E. M. (1986). Infrasonic calls of the Asian elephant (Elephas maximus). *Behavioral Ecology and Sociobiology*, *18*(4), 297–301. https://doi.org/10.1007/BF00300007

Payne, K. B., Thompson, M., & Kramer, L. (2003). Elephant calling patterns as indicators of group size and composition: The basis for an acoustic monitoring system. *African Journal of Ecology*, *41*(1), 99–107. https://doi.org/10.1046/j.1365-2028.2003.00421.x

Pfefferle, D., & Fischer, J. (2006). Sounds and size: Identification of acoustic variables that reflect body size in hamadryas baboons, Papio hamadryas. *Animal Behaviour*, *72*(1), 43–51. https://doi.org/10.1016/j.anbehav.2005.08.021

Pinter-Wollman, N., Isbell, L. A., & Hart, L. A. (2009). The relationship between social behaviour and habitat familiarity in African elephants (*Loxodonta africana*). *Proceedings of the Royal Society B: Biological Sciences*, *276*(1659), 1009–1014. https://doi.org/10.1098/rspb.2008.1538

Plotnik, J. M., & Jacobson, S. L. (2022). A “thinking animal” in conflict: Studying wild elephant cognition in the shadow of anthropogenic change. *Current Opinion in Behavioral Sciences*, *46*, 101148. https://doi.org/10.1016/j.cobeha.2022.101148

Poole, J. H. (1987). Rutting Behavior in African Elephants: The Phenomenon of Musth. *Behaviour*, *102*(3–4), 283–316. https://doi.org/10.1163/156853986X00171

Poole, J. H. (1999). Signals and assessment in African elephants: Evidence from playback experiments. *Animal Behaviour*, *58*(1), 185–193. https://doi.org/10.1006/anbe.1999.1117

Poole, J. H. (2011a). *Chapter 9 Behavioral Contexts of Elephant*.

Poole, J. H. (2011b). *The Amboseli Elephants. Chapter 9 Behavioral Contexts of Elephant*. The University of Chicago Press.

Poole, J. H., & Granli P. K. (2004). *The visual, tactile and acoustic signals of play in African savanna elephants*.

Poole, J. H., Payne, K., Langbauer, W. R., & Moss, C. J. (1988a). The social contexts of some very low frequency calls of African elephants. *Behavioral Ecology and Sociobiology*, *22*(6), 385–392. https://doi.org/10.1007/BF00294975

Poole, J. H., Payne, K., Langbauer, W. R., & Moss, C. J. (1988b). The social contexts of some very low frequency calls of African elephants. *Behavioral Ecology and Sociobiology*, *22*(6), 385–392. https://doi.org/10.1007/BF00294975

Poole, J. H., Tyack, P. L., Stoeger-Horwath, A. S., & Watwood, S. (2005). Elephants are capable of vocal learning. *Nature*, *434*(7032), 455–456. https://doi.org/10.1038/434455a

Poole JH. (1994). Sex differences In The Behviour of African elephants. In *In: Short RV, Balaban Editors. The differences between the sexes.* (S. 331-246.). Cambridge, U.K.: Cambridge University Press.

Richardson, W. J., Greene, C. R., Malme, C. I., & Thomson, D. H. (1995). MEASUREMENT PROCEDURES. In *Marine Mammals and Noise* (S. 33–58). Elsevier. https://doi.org/10.1016/B978-0-08-057303-8.50006-9

Santiapillai, C., Wijeyamohan, S., Bandara, G., Athurupana, R., Dissanayake, N., & Read, B. (2010). An assessment of the human-elephant conflict in Sri Lanka. *Ceylon Journal of Science (Biological Sciences)*, *39*(1), 21–33. https://doi.org/10.4038/cjsbs.v39i1.2350

Sekar, N., Lee, C., & Sukumar, R. (2017). Functional nonredundancy of elephants in a disturbed tropical forest. *Conservation Biology*, *31*(5), 1152–1162. https://doi.org/10.1111/cobi.12907

Shaffer, L. J., Khadka, K. K., Van Den Hoek, J., & Naithani, K. J. (2019). Human-Elephant Conflict: A Review of Current Management Strategies and Future Directions. *Frontiers in Ecology and Evolution*, *6*, 235. https://doi.org/10.3389/fevo.2018.00235

Shannon, G., Page, B., Slotow, R., & Duffy, K. (2006). African elephant home range and habitat selection in Pongola Game Reserve, South Africa. *African Zoology*, *41*(1), 37–44. https://doi.org/10.1080/15627020.2006.11407333

Shannon, G., Slotow, R., Durant, S. M., Sayialel, K. N., Poole, J., Moss, C., & McComb, K. (2013). Effects of social disruption in elephants persist decades after culling. *Frontiers in Zoology*, *10*(1), 62. https://doi.org/10.1186/1742-9994-10-62

Sharma, S., Sato, K., & Gautam, B. P. (2023). A Methodological Literature Review of Acoustic Wildlife Monitoring Using Artificial Intelligence Tools and Techniques. *Sustainability*, *15*(9), 7128. https://doi.org/10.3390/su15097128

Shoshani, J. (1993). Elephants: The super keystone species. *Swara*, *16*(2), 25–28.

Shoshani, J. (1998). Understanding proboscidean evolution: A formidable task. *Trends in Ecology & Evolution*, *13*(12), 480–487. https://doi.org/10.1016/S0169-5347(98)01491-8

Smith, R. J., & Kasiki, S. M. (1999). *A spatial analysis of human-elephant conflict in the Tsavo ecosystem, Kenya*.

Soltis, J. (2010). Vocal communication in African Elephants (*Loxodonta africana*). *Zoo Biology*, *29*(2), 192–209. https://doi.org/10.1002/zoo.20251

Soltis, J. (2013). Emotional communication in African elephants (*Loxodonta africana*). In E. Altenmüller, S. Schmidt, & E. Zimmermann (Hrsg.), *Evolution of Emotional Communication* (1. Aufl., S. 105–115). Oxford University PressOxford. https://doi.org/10.1093/acprof:oso/9780199583560.003.0007

Soltis, J., King, L. E., Douglas-Hamilton, I., Vollrath, F., & Savage, A. (2014). African Elephant Alarm Calls Distinguish between Threats from Humans and Bees. *PLoS ONE*, *9*(2), e89403. https://doi.org/10.1371/journal.pone.0089403

Soltis, J., Leighty, K. A., Wesolek, C. M., & Savage, A. (2009). The expression of affect in African elephant (Loxodonta africana) rumble vocalizations. *Journal of Comparative Psychology*, *123*(2), 222–225. https://doi.org/10.1037/a0015223

Soltis, J., Leong, K., & Savage, A. (2005). African elephant vocal communication I: Antiphonal calling behaviour among affiliated females. *Animal Behaviour*, *70*(3), 579–587. https://doi.org/10.1016/j.anbehav.2004.11.015

Spierenburg, M. (2002). African Wildlife and Livelihoods: The promise and performance of community conservation edited by D AVID H ULME and M ARSHALL M URPHREE Oxford: James Currey; Cape Town: David Philips; Harare: Weaver; Zomba: Kachere; Nairobi:

E.A.E.P.; Kampala: Fountain; Portsmouth, NH: Heinemann, 2001. Pp. 336. US$29.95 (pbk.). *The Journal of Modern African Studies*, *40*(3), 499–518. https://doi.org/10.1017/S0022278X02274091

Staufer, V. (2021). *Kommunikation Afrikanischer Elefanten (Loxodonta africana) im Tiergarten Schönbrunn*. Universität Wien.

Stoeger, A. (Hrsg.). (2020). *Neuroendocrine regulation of animal vocalization: Mechanisms and anthropogenic factors in animal communication*. Amsterdam. https://doi.org/10.1016/C2017-0-02810-0

Stoeger, A. S., & Baotic, A. (2016a). Information content and acoustic structure of male African elephant social rumbles. *Scientific Reports*, *6*(1), 27585. https://doi.org/10.1038/srep27585

Stoeger, A. S., & Baotic, A. (2016b). Information content and acoustic structure of male African elephant social rumbles. *Scientific Reports*, *6*(1), 27585. https://doi.org/10.1038/srep27585

Stoeger, A. S., Baotic, A., & Heilmann, G. (2021). Vocal Creativity in Elephant Sound Production. *Biology*, *10*(8), 750. https://doi.org/10.3390/biology10080750

Stoeger, A. S., Charlton, B. D., Kratochvil, H., & Fitch, W. T. (2011). Vocal cues indicate level of arousal in infant African elephant roars. *The Journal of the Acoustical Society of America*, *130*(3), 1700–1710. https://doi.org/10.1121/1.3605538

Stoeger, A. S., Heilmann, G., Zeppelzauer, M., Ganswindt, A., Hensman, S., & Charlton, B. D. (2012). Visualizing Sound Emission of Elephant Vocalizations: Evidence for Two Rumble Production Types. *PLoS ONE*, *7*(11), e48907. https://doi.org/10.1371/journal.pone.0048907

Stoeger, A. S., & Manger, P. (2014). Vocal learning in elephants: Neural bases and adaptive context. *Current Opinion in Neurobiology*, *28*, 101–107. https://doi.org/10.1016/j.conb.2014.07.001

Stoeger, A. S., Mietchen, D., Oh, S., de Silva, S., Herbst, C. T., Kwon, S., & Fitch, W. T. (2012). An Asian Elephant Imitates Human Speech. *Current Biology*, *22*(22), 2144–2148. https://doi.org/10.1016/j.cub.2012.09.022

Stoeger, A. S., Zeppelzauer, M., & Baotic, A. (2014). Age-group estimation in free-ranging African elephants based on acoustic cues of low-frequency rumbles. *Bioacoustics*, *23*(3), 231–246. https://doi.org/10.1080/09524622.2014.888375

Stoeger-Horwath, A. S., Stoeger, S., Schwammer, H. M., & Kratochvil, H. (2007). Call repertoire of infant African elephants: First insights into the early vocal ontogeny. *The Journal of the Acoustical Society of America*, *121*(6), 3922–3931. https://doi.org/10.1121/1.2722216

Sukumar, R. (1990). Ecology of the Asian elephant in southern India. II. Feeding habits and crop raiding patterns. *Journal of Tropical Ecology*, *6*(1), 33–53. https://doi.org/10.1017/S0266467400004004

Sukumar, R. (1991). The management of large mammals in relation to male strategies and conflict with people. *Biological Conservation*, *55*(1), 93–102. https://doi.org/10.1016/0006-3207(91)90007-V

Swanepoel, C. M. (1993). Baobab damage in Mana Pools National Park, Zimbabwe. *African Journal of Ecology*, *31*(3), 220–225. https://doi.org/10.1111/j.1365-2028.1993.tb00535.x

Taylor, A. M., Reby, D., & McComb, K. (2008). Human listeners attend to size information in domestic dog growls. *The Journal of the Acoustical Society of America*, *123*(5), 2903–2909. https://doi.org/10.1121/1.2896962

Tchamba, M. N. (1995). The impact of elephant browsing on the vegetation in Waza National Park, Cameroon. *African Journal of Ecology*, *33*(3), 184–193. https://doi.org/10.1111/j.1365-2028.1995.tb00796.x

Tchamba, M. N. (1996). History and present status of the human/elephant conflict in the Waza-Logone region, Cameroon, West Africa. *Biological Conservation*, *75*(1), 35–41. https://doi.org/10.1016/0006-3207(95)00040-2

Teixeira, D., Maron, M., & Van Rensburg, B. J. (2019). Bioacoustic monitoring of animal vocal behavior for conservation. *Conservation Science and Practice*, *1*(8), e72. https://doi.org/10.1111/csp2.72

The IUCN Red List of Threatened Species. (2021). IUCN Red List of Threatened Species. https://www.iucnredlist.org/en

Thomas, B., Holland, J. D., & Minot, E. O. (2008). Elephant (Loxodonta africana) Home Ranges in Sabi Sand Reserve and Kruger National Park: A Five-Year Satellite Tracking Study. *PLoS ONE*, *3*(12), e3902. https://doi.org/10.1371/journal.pone.0003902

Thompson, M. E. (2010). Heard but not seen: An acoustic survey of the African forest elephant population at Kakum Conservation Area, Ghana. *African Journal of Ecology*, *48*(1), 224–231. https://doi.org/10.1111/j.1365-2028.2009.01106.x

Thompson, M. E., Schwager, S. J., Payne, K. B., & Turkalo, A. K. (2010). Acoustic estimation of wildlife abundance: Methodology for vocal mammals in forested habitats. *African Journal of Ecology*, *48*(3), 654–661. https://doi.org/10.1111/j.1365-2028.2009.01161.x

Thouless, C. R. (1994). Conflict between humans and elephants on private land in northern Kenya. *Oryx*, *28*(2), 119–127. https://doi.org/10.1017/S0030605300028428

Thouless, C. R., & Sakwa, J. (1995). Shocking elephants: Fences and crop raiders in Laikipia District, Kenya. *Biological Conservation*, *72*(1), 99–107. https://doi.org/10.1016/0006-3207(94)00071-W

Titze, I. R. (1994). *Principles of voice production*. Prentice Hall.

Titze, I. R. (Hrsg.). (2011). Vocal Fold Mass Is Not A Useful Quantity for Describing F_0 in Vocalization. *Journal of Speech, Language, and Hearing Research*, *54*(2), 520–522. https://doi.org/10.1044/1092-4388(2010/09-0284)

Tyack, P. L. (2020). A taxonomy for vocal learning. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1789), 20180406. https://doi.org/10.1098/rstb.2018.0406

Van De Water, A., Garaï, M., Burnett, M., Henley, M., Di Minin, E., Streicher, J., Bates, L., & Slotow, R. (2024). Integrating a “One Well-being” approach in elephant conservation: Evaluating consequences of management interventions. *Ecology and Society*, *29*(3), art15. https://doi.org/10.5751/ES-15193-290315

Vancuylenberg, B. W. B. (1977). Feeding behaviour of the asiatic elephant in South-East Sri Lanka in relation to conservation. *Biological Conservation*, *12*(1), 33–54. https://doi.org/10.1016/0006-3207(77)90056-8

Venter, P. J., & Hanekom, J. J. (2010). Automatic detection of African elephant (Loxodonta africana) infrasonic vocalisations from recordings. *Biosystems Engineering*, *106*(3), 286–294. https://doi.org/10.1016/j.biosystemseng.2010.04.001

Wall, J., Wittemyer, G., Klinkenberg, B., & Douglas-Hamilton, I. (2014). Novel opportunities for wildlife conservation and research with real-time monitoring. *Ecological Applications*, *24*(4), 593–601. https://doi.org/10.1890/13-1971.1

Walsh, E. J., Armstrong, D. L., Smith, A. B., & McGee, J. (2010). The acoustic features of the long distance advertisement call produced by *Panthera tigris altaica* , the Amur (Siberian) tiger. *The Journal of the Acoustical Society of America*, *128*(4_Supplement), 2485–2485. https://doi.org/10.1121/1.3508918

Wemmer, C. (2008). *Elephants and Ethics*. Johns Hopkins University Press. https://doi.org/10.56021/9780801888182

Western, D., Russell, S., & Cuthill, I. (2009). The Status of Wildlife in Protected Areas Compared to Non-Protected Areas of Kenya. *PLoS ONE*, *4*(7), e6140. https://doi.org/10.1371/journal.pone.0006140

White, P. C. L., & Ward, A. I. (2010). Interdisciplinary approaches for the management of existing and emerging human—Wildlife conflicts. *Wildlife Research*, *37*(8), 623. https://doi.org/10.1071/WR10191

Wrege, P. H., Rowland, E. D., Keen, S., & Shiu, Y. (2017). Acoustic monitoring for conservation in tropical forests: Examples from forest elephants. *Methods in Ecology and Evolution*, *8*(10), 1292–1301. https://doi.org/10.1111/2041-210X.12730

Wynyard, J. (2019). *In 2019, the situation for elephants has slowly improved in most of southern and eastern Africa, but they are still imperiled in other parts of their range, especially in the troubled regions of central and western Africa*.

Young, K. D., & Van Aarde, R. J. (2011). Science and elephant management decisions in South Africa. *Biological Conservation*, *144*(2), 876–885. https://doi.org/10.1016/j.biocon.2010.11.023

Zeppelzauer, M., Hensman, S., & Stoeger, A. S. (2015). Towards an automated acoustic detection system for free-ranging elephants. *Bioacoustics*, *24*(1), 13–29. https://doi.org/10.1080/09524622.2014.906321

Zeppelzauer, M., & Stoeger, A. S. (2015). Establishing the fundamentals for an elephant early warning and monitoring system. *BMC Research Notes*, *8*(1), 409. https://doi.org/10.1186/s13104-015-1370-y

Zeppelzauer, M., Stöger, A. S., & Breiteneder, C. (2013). Acoustic detection of elephant presence in noisy environments. *Proceedings of the 2nd ACM International Workshop on Multimedia Analysis for Ecological Data*, 3–8. https://doi.org/10.1145/2509896.2509900

Zimmer, W. M. X. (2011). *Passive Acoustic Monitoring of Cetaceans* (1. Aufl.). Cambridge University Press. https://doi.org/10.1017/CBO9780511977107

Appendix

Female	Male

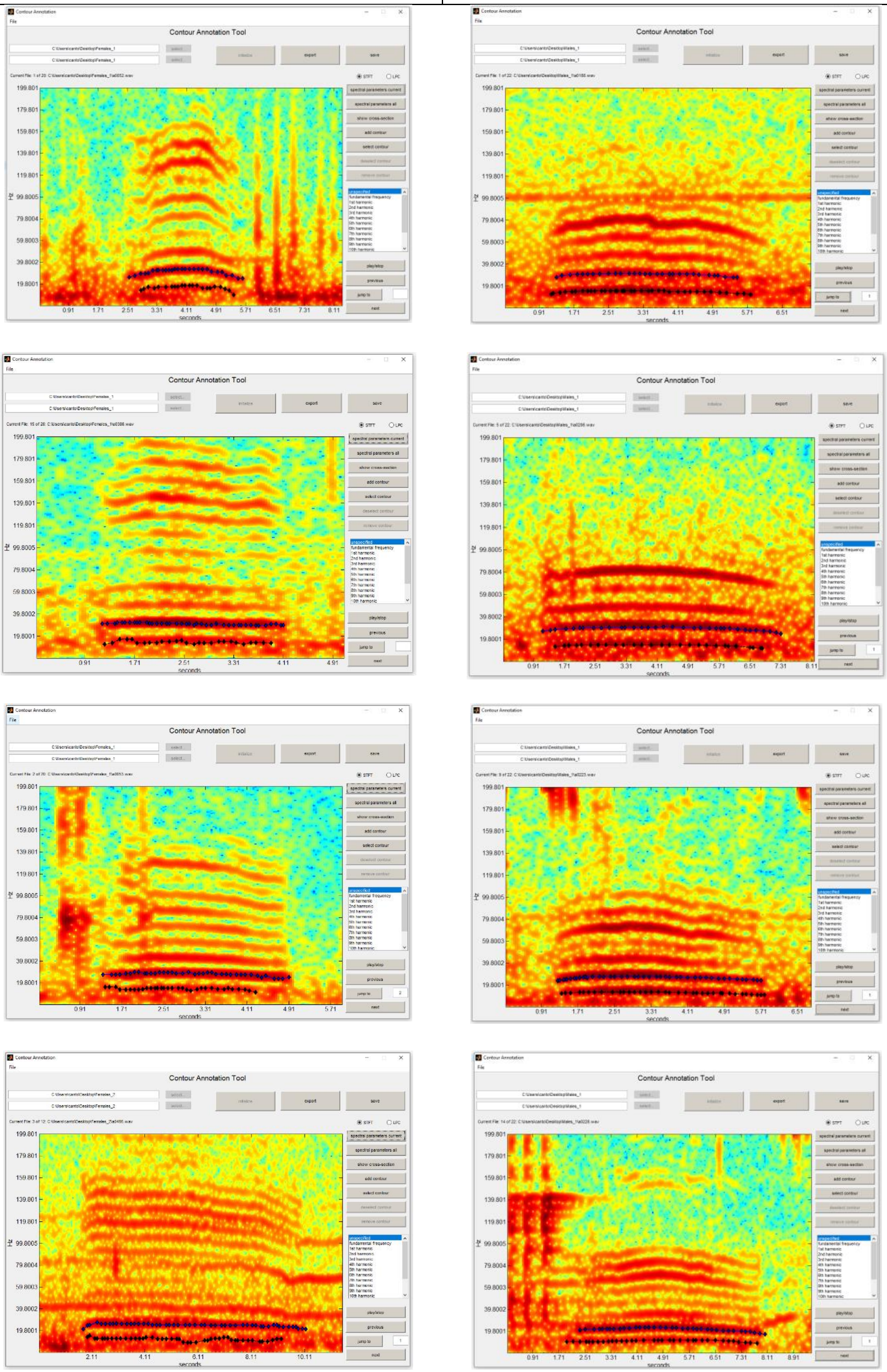

Figure 16: Visual comparison of female (left) and male (right) African elephant rumbles, showing show the f0 (fundamental frequency) and f1(first harmonic) plotted in Matlab.