



## Research Article

# The acoustic ecology of Karstic caves: a spectrogram approach to ecomusicology

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### Article Info

Received: 23 September 2024

Accepted: 26 December 2024

Online: 30 December 2024

### Keywords

Acoustic ecology

Ecomusicology

Karstic caves

Soundscapes

Spectrogram analysis

### Abstract

This study investigates the acoustic environments of Karstic caves through spectrogram analysis, emphasizing their significance in Ecomusicology. These unique subterranean soundscapes are shaped by two primary dimensions: the natural ambience generated by ecological processes and the anthropomorphic influence of human-induced sounds. The interplay between these elements forms the foundation of this research, highlighting the gradual interrelations and ecological processes that define cave acoustics. Using spectrogram analysis, this study provides a detailed representation of the temporal and spectral characteristics of these soundscapes. This approach allows for the identification of patterns, contrasts, and interactions between natural and anthropogenic sound sources within cave environments. By examining these dynamics, the research uncovers insights into how ecological processes are influenced by and respond to sound, both naturally occurring and human-induced. The findings contribute to ecomusicology by demonstrating the ecological and cultural relevance of sound in understanding and interpreting Karstic caves. Through this dual lens, the study bridges scientific acoustic analysis with cultural and artistic perspectives, advancing the understanding of how sound mediates the relationship between humans and natural environments. The research underscores the role of sound as a critical tool in both ecological inquiry and cultural reflection. It highlights the necessity of preserving these fragile ecosystems, not only as natural wonders but also as resonant spaces where ecological and human narratives converge. By situating cave acoustics within an ecomusicological framework, this study offers a novel perspective on the ecological and artistic dimensions of subterranean soundscapes, enriching the broader discourse on the intersection of sound, environment, and culture.

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### To cite this article

Chokhonelidze, A. (2024). The acoustic ecology of Karstic caves: a spectrogram approach to ecomusicology. *Journal of Music Theory and Transcultural Music Studies*, 2(2), 131-142. DOI: <https://doi.org/10.5281/zenodo.15031848>

### Introduction

Ecomusicology, an interdisciplinary field bridging ecological and musical studies, examines the relationships between sound, culture, and environment. Ecomusicology is “the study of music, culture, and nature in all the complexities of those terms. Ecomusicology considers musical and sonic issues, both textual and performative, related to ecology and the natural environment” (Aaron, 2013). This field highlights the importance of acoustic environments as both ecological phenomena and cultural artefacts. By investigating how sound reflects and shapes interactions between humans and their surroundings, ecomusicology provides critical insights into the dynamic interplay between nature and

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culture. Its significance lies not only in understanding sound as a medium of ecological communication but also in advocating for the preservation of delicate ecosystems through an auditory lens.

Karstic caves, with their unique geological and acoustic properties, represent a remarkable natural phenomenon. These caves, formed by the dissolution of soluble rock, create complex subterranean landscapes that serve as reservoirs of ecological and cultural significance. Beyond their aesthetic and geological value, caves function as natural acoustic chambers where sounds resonate in ways distinct from open environments. This research conceptualizes the cave itself as a “tool,” a dynamic system that captures and reflects both natural and anthropogenic sounds. Understanding these interactions within cave soundscapes provides a unique perspective on how ecological and human processes interrelate.

## Theoretical Framework

Ecomusicology offers an interdisciplinary perspective that connects ecology and music, examining sound as both an ecological and cultural phenomenon. This theoretical lens emphasizes the role of soundscapes—composite auditory environments composed of biophony (natural sounds), geophony (non-biological natural sounds), and anthropophony (human-made sounds)—in understanding the relationship between sound, environment, and culture (Schafer, 1977). Within this framework, three key concepts shape this study:

**Soundscape Ecology:** Originating from R. Murray Schafer's seminal work *The Soundscape: Our Sonic Environment and the Tuning of the World*, soundscape ecology explores sound as a critical element of ecosystems. By analyzing soundscapes, we can discern ecological health, cultural practices, and anthropogenic impacts, offering a foundation for investigating Karstic caves as acoustic environments (Schafer, 1977).

**Sonic Ecology:** This concept extends the idea of soundscapes to include the interaction between sound and ecosystems. It emphasizes sound's dual role as both an influencer and indicator of ecological processes, providing a critical lens for understanding the dynamic interplay between human-induced and natural sounds in subterranean environments (Allen & Dawe, 2016).

**Cultural Acoustics:** Cultural acoustics examines how sound embodies cultural values and identities. It highlights how auditory environments—like caves—serve as cultural archives that reflect historical and contemporary human-nature interactions (Pediely, 2016).

**Spectrogram analysis:** Grounded in sound physics, provides a scientific method to visualize and analyze the acoustic properties of environments. This research leverages its quantitative approach to complement the qualitative insights offered by ecomusicology.

**Fourier Analysis:** Central to spectrogram analysis, Fourier analysis decomposes sound signals into their constituent frequencies, enabling the identification of dominant frequencies and harmonics within cave soundscapes (Oppenheim et al., 1999).

**Spectrograms:** Spectrograms, which visually represent the frequency spectrum of sounds over time, facilitate the detection of temporal patterns and tonal structures, offering insights into the interaction between natural and anthropogenic sounds (Dunn, 2007).

**Acoustic Parameters:** Parameters like sound pressure level and frequency spectrum are extracted to characterize the acoustic environments of Karstic caves. These metrics provide objective data to assess the impact of human activity on natural soundscapes (Krause, 2013).

This research integrates Ecomusicological perspectives with spectrogram analysis to explore the acoustic ecology of Karstic caves. The ecomusicological framework offers a cultural and ecological interpretation of soundscapes, while the spectrogram-based framework provides the quantitative tools necessary for detailed analysis. Together, these frameworks facilitate a comprehensive understanding of the relationship between human and natural sounds in these subterranean environments.

## Literature Review

Ecomusicology is an interdisciplinary field that examines the intricate relationships between music, soundscapes, culture, and ecological systems. This burgeoning area of study goes beyond traditional musicology to include environmental and cultural dimensions, presenting sound as a phenomenon central to ecological and cultural identity.

At its core, Ecomusicology explores how human and non-human sounds interact with natural and built environments, framing these interactions within broader ecological and sociocultural contexts. Allen and Dawe (2016) highlight the field's dual focus on sustainability and cultural heritage, emphasizing the need to preserve not only musical traditions but also the natural soundscapes that inspire them. For instance, natural soundscapes like bird songs and cave acoustics serve as both artistic inspiration and ecological indicators.

The foundational work of R. Murray Schafer (1977) introduced the concept of soundscapes as ecological entities, comprised of biophony, geophony, and anthropophony. This tripartite division provides a framework for studying how sound reflects ecological health and human influence. Schafer's *The Soundscape* underscores the importance of critical listening and contextual awareness, arguing that sound is both an aesthetic experience and an ecological signal.

Ecomusicology builds on this framework by analyzing soundscapes concerning cultural practices and environmental challenges. For instance, Titon (2014) underscores the role of sound in fostering sustainability, advocating for preserving soundscapes as cultural and ecological resources. Similarly, Pedelty (2016) demonstrates how music can serve as environmental advocacy, using sound to inspire ecological awareness and action.

Ecomusicology also delves into the interplay between music and cultural identity. A study of Kaluli soundscapes in Papua New Guinea (Feld, 2012) illustrates how ecological sounds are integral to cultural expression and identity. Cultural acoustics, as a subfield, examines how specific environments influence the creation and perception of sound, linking ecological and sociocultural factors. For example, caves have historically been used as resonant spaces for rituals and performances, making them a focal point for Ecomusicological inquiry. Recent studies emphasize the practical applications of ecomusicology, particularly in education and advocacy (Gambirasio, 2022). Such approaches align with the ecomusicology goal of bridging academic research with community engagement, ensuring that soundscapes are not only studied but also valued and protected. In conclusion, ecomusicology offers a comprehensive framework for understanding the ecological and cultural significance of soundscapes. By integrating ecological science, cultural studies, and sound physics, this field provides a nuanced perspective on the interconnections between nature, music, and human experience, making it particularly relevant to studies of unique environments like Karstic caves.

Karstic caves, formed by the dissolution of soluble rocks such as limestone, gypsum, and dolomite, are extraordinary natural phenomena that combine geological, ecological, and cultural significance. These subterranean landscapes exhibit unique acoustic and ecological properties that make them ideal subjects for interdisciplinary research, including studies in ecomusicology and acoustic ecology. Karstic caves are created through a natural process of chemical weathering, where acidic water dissolves rock over millions of years, resulting in complex networks of underground chambers, tunnels, and sinkholes. The unique morphology of these caves—marked by stalactites, stalagmites, and other mineral formations—provides exceptional acoustic environments, with surfaces that reflect, absorb, and diffuse sound in complex ways (Ford & Williams, 2007).

The microclimates within these caves are also significant, offering stable temperatures, high humidity, and a natural isolation from external noise. These characteristics create an environment where natural and anthropogenic sounds can be studied in detail, making them valuable for ecomusicological inquiries.

The acoustic properties of karstic caves are shaped by their unique geological features. The irregular surfaces and mineral compositions influence sound propagation, resulting in rich reverberations and echoes. These acoustic qualities have been utilized historically in cultural practices, such as ritualistic music and communication. Recent studies in bioacoustics and sound physics have leveraged these properties to explore the interaction between human and natural soundscapes within caves (Daugherty, 2010).

Caves act as natural amplifiers and filters of sound, making them critical sites for studying the relationship between sound and the environment. Spectrogram analysis of cave acoustics can reveal patterns in biophonic and geophonic elements, such as the movement of water or the calls of cave-dwelling species. Karstic caves serve as habitats for specialized ecosystems, including unique fauna like bats, cave crickets, and troglobites. These environments are sensitive to disturbances, including noise pollution caused by human activity, which can alter natural soundscapes and disrupt

ecological balance (Gillieson, 1996). The interplay between biophony and anthrophony in such fragile ecosystems is a critical area of study, highlighting the need for sustainable practices in cave tourism and research.

In ecomusicology, spectrograms can be employed to explore the relationship between sound, culture, and ecology. Spectrograms facilitate a deeper understanding of sound as a cultural and ecological phenomenon by allowing scholars to quantify and compare natural and human-induced sound patterns Dunn (2007). For instance, spectrogram analysis of ritualistic music or cave acoustics helps interpret the acoustic properties that influence human interactions with these environments, contributing to a broader understanding of cultural acoustics (Titon, 2014).

Spectrograms also play a critical role in assessing the impact of human activity on natural soundscapes. For example, studies have used spectrograms to assess the effects of noise pollution on wildlife and habitats (Gillieson, 1996). In the context of Karstic caves, spectrogram analysis could provide vital data on how human exploration and tourism alter the natural acoustic environment, potentially disrupting the delicate balance between natural sounds and human activities.

Spectrogram analysis, with its ability to provide a detailed and quantitative representation of sound, offers invaluable insights into the acoustic properties of environments such as Karstic caves. By integrating spectrogram analysis into Ecomusicology, researchers can better understand the complex interactions between natural and anthropogenic soundscapes, furthering the interdisciplinary study of sound, culture, and ecology. This tool's application in the study of caves and other ecological environments helps illuminate the broader implications of sound on cultural practices and environmental sustainability.

In Georgia, eco-music and ecomusicology are currently emerging as novel fields, primarily connected with the Georgian composer Eka Chabashvili.<sup>2</sup> As musicologist, Gvantsa Ghvinjilia notes: "The representative of Georgian post-avant-garde music—Eka Chabashvili, is a composer who is known for implementing scientific ideas in music and for the first examples of Eco-music" (Ghvinjilia, 2024, 27). Eka Chabashvili is the creator of a new musical instrument—the modified eco-piano, Modekal, whose tuning system and construction involve a modification of the traditional piano (Jvania, Chabashvili, & Zhvania, 2022). Eka Chabashvili's name is closely associated with the exploration of Georgian caves as sites for eco-music experiments. Her innovative work integrates the natural acoustics of these caves, showcasing their unique resonance and environmental significance through musical expression. In the scientific study *Soundscape in Music and Music in Soundscape*, conducted with a team of research-composers from the Vano Sarajishvili Tbilisi State Conservatoire—Maka Virsaladze, Alexander Chokhonelidze, and Joni Asitashvili—the soundscape of a specific Sound Oasis was thoroughly examined. The research explored compositional techniques for integrating the oasis's unique acoustic characteristics and environmental sounds into the texture of a piece specifically composed for this setting. Maka Virsaladze, a notable representative of the Post-Avantgarde composition school, along with Eka Chabashvili also explores acoustic ecology in both urban and rural landscapes, including the karstic caves of Georgia (Virsaladze & Chokhonelidze, 2023).

### **Importance of Study**

This study, which explores the acoustics of Karstic caves through spectrogram analysis within the framework of ecomusicology, aims to offer significant interdisciplinary value. By bridging ecology, musicology, and acoustics, it provides a novel perspective on the relationship between natural soundscapes and human-induced changes in delicate ecosystems. The implications of this research are far-reaching, contributing to both the scientific understanding of cave environments and the emerging field of Ecomusicology.

Ecomusicology, a field that integrates environmental sound with musical practices and cultural contexts, provides a crucial framework for this research. As (Krause, 2013) argued, sound is a fundamental aspect of ecosystems, shaping both ecological processes and cultural experiences. This study addresses a gap in ecomusicology by focusing on the acoustic characteristics of subterranean environments, particularly Karstic caves, which are often overlooked in

<sup>2</sup> Eka Chabashvili is an artistic researcher, doctor of musical art, associate professor of Tbilisi State Conservatoire, director of Contemporary Music Development Centre, and creator of the multi-topophone composition technique and atomic-nuclear music system. In addition to ecology, she studies problems of genetics and syncretism of visuals and music. Her compositions *Symphony-Exhibition "Khma"*, Nano opera—“*Pandora*”, Nano Eco-Cantata—“*Silkworm Butterfly's Wisdom*” and the music project—“*Experimental interactive sound performance "Let's Listen to the Caves": Eco-music and sound oases*” organized in the caves of Georgia, are important examples of Georgian Eco-music (Ghvinjilia, 2024).

environmental studies. By employing spectrogram analysis, the research will provide detailed, quantitative insights into the natural and anthropogenic elements of cave soundscapes. This knowledge is essential for understanding how soundscapes influence both ecological processes and cultural heritage, especially in spaces with cultural significance, such as caves used in rituals and art.

The findings of this study have practical implications for the conservation and management of Karstic caves. Caves are highly sensitive environments where human activity, such as tourism, can disrupt both natural soundscapes and delicate ecosystems by applying spectrogram analysis, this research provides a tool for monitoring and assessing the impact of human-induced noise on cave acoustics, aiding in the development of sustainable cave exploration guidelines. This is crucial for preserving the ecological and cultural integrity of these spaces. Furthermore, understanding the acoustic properties of caves may lead to improved practices in cave conservation, balancing human interest with ecological protection.

This study contributes to the methodological development of ecomusicology, particularly in its use of spectrogram analysis as a robust tool for sound studies. Spectrograms offer a visual and quantitative method to examine complex sound environments, surpassing traditional auditory analysis. The use of technology like spectrograms allows for more precise and objective studies of soundscapes (Sueur et al., 2008). This is especially beneficial in environments where subjective auditory perception may be inadequate or inconsistent. The ability to capture detailed acoustic data over time enables the detection of subtle changes in sound patterns indicative of ecological shifts or human impacts, making spectrograms an invaluable tool for both researchers and environmental managers.

The theoretical contributions of this study extend beyond the specifics of cave acoustics. By integrating sound physics and ecomusicology, the research offers a holistic understanding of how natural and anthropogenic sounds interact in shared environments. This approach encourages a more nuanced interpretation of sound as both an ecological and cultural phenomenon. The practical implications of this research are equally significant. By highlighting the role of sound in ecological processes and human culture, the study may inspire more sustainable practices in managing natural spaces, promoting a deeper appreciation for the acoustic dimensions of environmental conservation.

### **Problem of Study**

Spectrogram analysis emerges as a "super tool" for this investigation, offering precise visual and quantitative representations of sound. By mapping the frequency, intensity, and temporal characteristics of acoustic events, spectrograms allow researchers to dissect the intricate soundscapes of Karstic caves. This method bridges scientific rigour with artistic inquiry, enabling an in-depth exploration of how natural and human-induced sounds coexist and interact within these environments.

The study seeks to address key questions:

- How do human and natural soundscapes interact within Karstic caves from an ecomusicological perspective?
- What impact does human activity have on the delicate balance of natural cave ambiances?
- Can spectrogram analysis adequately support the theoretical and practical goals of understanding these interactions?

The answers to these questions promise not only to advance theoretical knowledge in ecomusicology but also to underscore the practical implications of preserving the acoustic integrity of Karstic caves. Through this research, the field gains valuable insights into the intersections of sound, ecology, and culture, contributing to a broader understanding of environmental soundscapes and their importance.

### **Method**

The research uses Sonic Visualizer – musical tool for analyzing audio files. It allows for a detailed examination of sound signals, including spectrograms, waveforms, and other visual representations. For this study, we will primarily utilize the Spectrogram Layer to analyze the acoustic characteristics of Karstic cave recordings.

A spectrogram is a visual representation of the frequency content of a sound signal over time. It is a two-dimensional (2D) plot with time on the horizontal axis and frequency on the vertical axis. The colour or intensity of each point on the spectrogram represents the amplitude of the sound at that specific time and frequency.

Key Components of the spectrogram layer: 1) Waveform Layer: This layer displays the amplitude of the sound signal over time, providing a visual representation of the overall shape of the waveform. 2) Time Axis Sub-layer: This sub-layer indicates the time scale of the spectrogram, allowing for precise measurements of time intervals. Frequency Axis Sub-layer: This sub-layer indicates the frequency range of the spectrogram, typically measured in Hertz (Hz).

Spectrograms are often represented in 2D or 3D visual forms: 2D Spectrograms: These are the standard spectrograms used in this study. They provide a clear visual representation of the frequency content of a sound signal over time. 3D Spectrograms: While 3D spectrograms can offer additional insights, they can be more complex to interpret. They add a third dimension, often representing the amplitude of the sound. 3D spectrograms can be useful for visualizing complex sound patterns, but for this study, 2D spectrograms will be sufficient.

Frequency-Spectrogram Interrelation: The frequency axis of a spectrogram represents the range of frequencies present in the sound signal. Higher frequencies are located at the top of the spectrogram, while lower frequencies are at the bottom. The intensity of the colour at a particular point on the spectrogram indicates the amplitude of the sound at that specific frequency and time.

Audio data was collected from the Prometheus Cave in West Georgia. To capture the diverse acoustic characteristics of the cave, recordings were made at various times of the day. Zoom H6 and Roland R26 were used to record high-quality audio directly within the cave. The recordings were conducted at specific locations within the cave, chosen to represent a range of acoustic environments, such as large chambers, narrow passages, and areas with water features. The recorded audio was then transferred to digital format and stored on external hard drives for subsequent analysis. By analyzing the frequency content of cave recordings, we can identify patterns in the sound, such as the presence of specific frequency bands associated with natural or anthropogenic sources. For example, the presence of high-frequency noise may indicate human activity, while low-frequency sounds may be associated with natural processes like water dripping or wind.

## Document Analysis

Document analysis was employed to supplement the literature review and gain a deeper understanding of the ongoing discourse in ecomusicology. This involved a detailed examination of written materials, such as academic articles, conference papers, and reports, to identify key concepts, methodologies, and case studies relevant to the research. Document analysis provided valuable contextual information and helped to shape the research questions and methodology.

The literature review involved a systematic search of academic databases such as JSTOR, Google Scholar, and ProQuest to identify relevant scholarly articles, books, and theses. Keywords such as "ecomusicology," "soundscape ecology," "acoustic ecology," "cave acoustics," and "spectrogram analysis" were used to refine the search. The collected literature was critically analyzed to identify key themes, theoretical frameworks, and empirical findings related to the study of sound in natural environments, particularly in Karstic caves.

## Ethic

Ethical considerations were paramount throughout this research. All sources used during the literature review and document analysis were accurately referenced, ensuring intellectual honesty and academic integrity. The copyright of the sources was respected, and proper citations were provided to acknowledge the original authors and their contributions. Additionally, the collection of audio data in the Prometheus Cave was conducted with sensitivity to the cave's fragile ecosystem and cultural significance. Care was taken to minimize any disturbance to the natural environment and to adhere to any specific regulations or guidelines related to cave exploration and research.

## Results

This section presents the findings from our study, structured around a systematic analysis of soundscapes recorded within Karstic caves (Prometheus, Navenakhevi) located in West Georgia. By utilizing spectrograms to visualize and quantify sound characteristics, the results are organized into four key categories: cave entrance ambient sounds, inner hall ambient sounds, human-induced sounds, and musical improvisations performed within the cave. This structure allows for a comprehensive examination of the dynamic interplay between natural and anthropogenic acoustic elements, offering a detailed exploration of how these unique environments function as both ecological systems and cultural spaces.

Audio recordings were conducted in a sequential order to capture distinct environmental scenarios: ambient sounds at the cave entrance, inner hall soundscapes, human-induced noises, and improvised musical performances. This order was chosen to provide a progressive understanding of how sound characteristics evolve from external to internal spaces and under varying conditions of human interaction. The recorded audio files were analysed using Sonic Visualizer, a software tool that creates spectrograms to visually represent the frequency, amplitude, and temporal characteristics of sounds. Spectrogram analysis was used to identify and compare patterns, such as resonance, tonal variations, and noise levels, across the different scenarios. This approach enabled an objective evaluation of the acoustic properties of the cave environment, providing insights that align with Ecomusicological perspectives on sound ecology and human-environment interactions.

The cave entrance area serves as a powerful transitional zone between external ecosystems and the internal environment of a cave. It represents a vital ecological and acoustic threshold, where the external world meets the unique subterranean system. This zone, often located at the cave entrance, functions as an interface where natural soundscapes from the surrounding environment—such as wind, rainfall, and biophonic elements like bird songs or insect sounds—gradually give way to the muted and resonant acoustics of the cave interior.

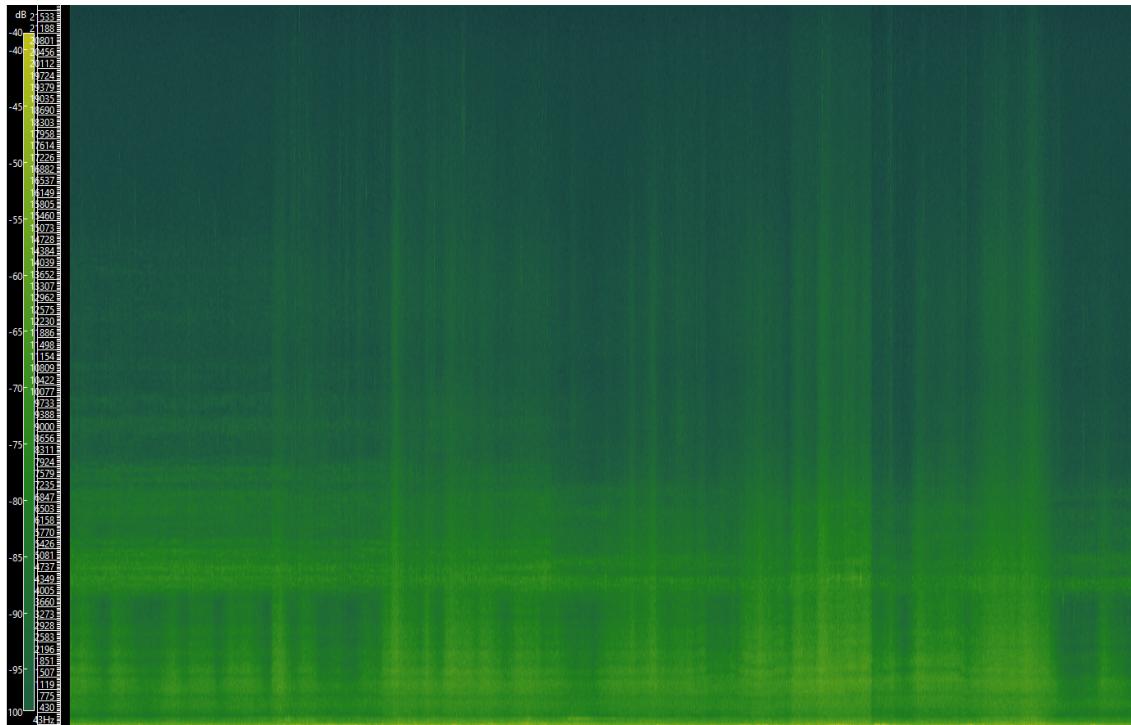
The significance of this zone lies in its role as a mediator between two distinct ecological realms. In every ecosystem, transitional zones, such as forest edges, wetland margins, or estuaries, play crucial roles in biodiversity and ecological processes. These areas often exhibit heightened ecological activity due to the convergence of environmental influences and resources. Similarly, the transitional zone of a cave serves as a bridge, introducing external energy, sounds, and even organisms into the subterranean ecosystem.

Acoustically, the transitional zone is equally important. It captures a blend of external and internal soundscapes, providing a unique auditory experience where external noise attenuates and gives way to the resonance and dampened reverberations characteristic of the cave interior. This shift not only reflects changes in the physical structure but also offers a metaphorical boundary—where the familiar open soundscape transitions into the mysterious and enclosed acoustic world of the cave. In ecomusicological terms, this zone is rich with meaning. It embodies the interaction between natural and anthropogenic elements, often highlighting the effects of human activity as sounds from the external world seep into the cave environment. Understanding this zone is crucial for studying how soundscapes evolve and interact across ecological boundaries, offering insights into the way ecosystems are interconnected through sound, energy, and culture.

This transitional tendency underscores the need to preserve cave entrances as they play critical roles in maintaining the balance between external influences and the internal integrity of the cave ecosystem. The research presents two spectrograms for the transitional zone category to illustrate distinct examples. Here's the breakdown: by including two spectrograms per category, we provide a sufficient basis for analysis while avoiding overwhelming detail. Omitting the other categories helps maintain focus on the natural versus human-induced soundscape dynamics, which are central to the research's ecomusicological framework. The time-frequency analysis is a critical tool for examining the detailed acoustic properties of the cave soundscapes, offering insights into both the temporal and spectral characteristics of the recorded sounds. By analyzing the spectrograms, we can observe how the sound's frequency content evolves, identifying key features such as tonal shifts, resonances, and noise patterns that are integral to understanding the cave's acoustic ecology.

The time axis represents the duration of the sound event, while the frequency axis reveals the range of sounds that occur at different points in time. This dual view allows us to analyze how sound fluctuates, revealing patterns such as periodicity, harmonics, and interference effects.

Key parameters extracted from the spectrograms include frequency distribution (which shows which frequencies dominate the soundscape) and amplitude variation (which reveals the loudness or intensity of these frequencies). These factors are crucial for understanding the dynamic range of the cave's acoustics and how human activity might modify it.



**Figure 1.** Spectrogram. Navenakhevi cave entrance

The Navenakhevi Cave entrance spectrogram (see Figure I) reveals a distinctive and pristine sonic environment largely unaffected by human interference. The soundscape at this location is characterized by low noise levels, primarily shaped by the natural sounds of the external ecosystem. The main parameters are:

**Cicada Song as a Noise Blanket:** The dominant acoustic element is the song of cicadas, which manifests as consistent horizontal lines on the spectrogram. These lines represent a stable, uninterrupted frequency range, functioning as a "noise blanket" that sets a foundation for the ambient soundscape. The evenness and constancy of their sound contribute to the unique timbral quality of this zone.

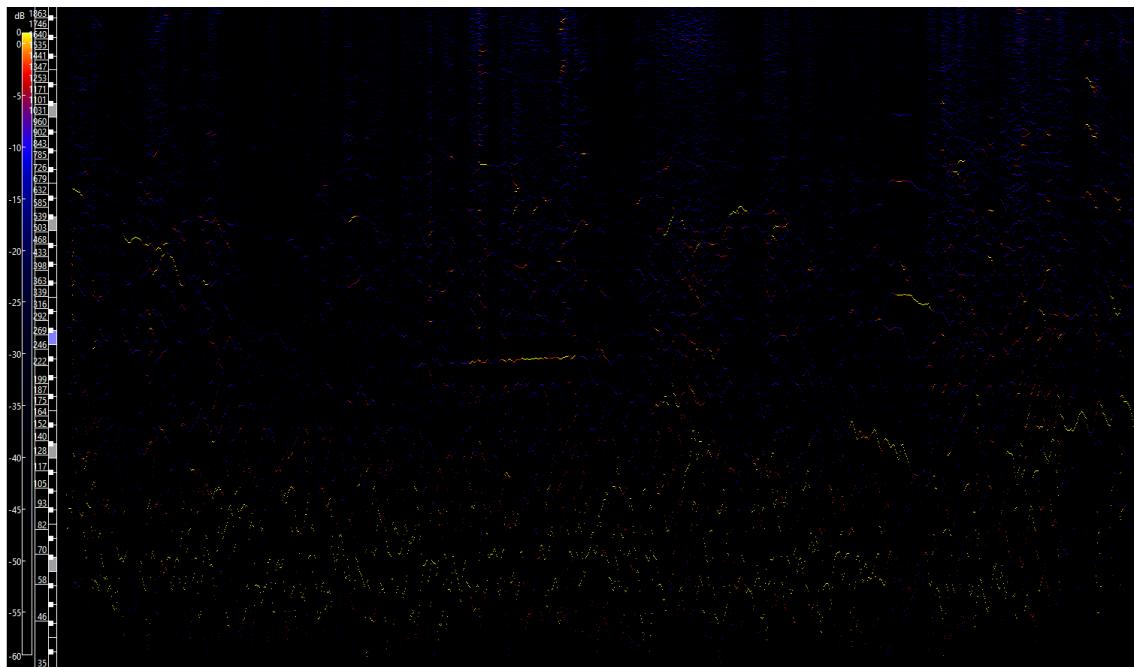
**Wind as vertical spikes:** occasional gusts of wind are captured as vertical spikes on the spectrogram. These spikes vary in intensity and occur irregularly, creating a dynamic contrast to the steady hum of cicadas. This interplay between consistent and transient sound elements is a defining characteristic of the cave entrance soundscape. Additional acoustic layers: the presence of dragonflies adds subtle, intermittent sounds that punctuate the ambient hum, further enriching the acoustic texture. Together, these elements form a complex yet harmonious auditory environment that is visually striking on the spectrogram and captivating to the listener.

**Significance of the entrance zone:** the specific combination of cicada songs, wind patterns, and other natural sounds is unique to the cave entrance. As one moves deeper into the cave, the soundscape transitions dramatically, with external elements fading and being replaced by internal cave sounds, such as the rhythmic dripping of water from stalactites and the overall muted resonance typical of subterranean environments. This analysis underscores the ecological and acoustic importance of transitional zones like the cave entrance, where the external environment and cave dynamics intersect, creating a rich and temporally dynamic soundscape. Similar analysis was made in other caves with varying results depending on human-induced environmental change factors.

Prometheus cave entrance was analyzed by peak frequency spectrogram. Peak frequency refers to the dominant frequency within a sound signal, representing the point of highest amplitude in the frequency spectrum at any given

moment. This measure is particularly useful for identifying prominent elements in complex soundscapes, as it highlights the most acoustically significant components over time.

A peak frequency spectrogram is a specialized visualization that focuses on capturing and displaying these dominant frequencies while filtering out less prominent data. By isolating peaks, this type of spectrogram provides a cleaner and more streamlined representation of the audio signal, making it easier to detect patterns or disturbances within a sound environment. In ecological and acoustic studies, peak frequency spectrograms are particularly valuable for analyzing soundscapes impacted by noise pollution. They emphasize key sound events, allowing researchers to assess how human-induced noise disrupts natural acoustic layers, such as the song of cicadas or wind patterns. This method offers clarity and precision in understanding the interactions between natural and anthropogenic acoustic elements.



**Figure 2.** Peak frequency Spectrogram. Prometheus cave entrance

The spectrogram analysis of the Prometheus Cave entrance reveals a compromised sonic environment, reflective of its popularity and human activity. Unlike the pristine soundscape of Navenakhevi Cave, the acoustic characteristics here are significantly influenced by anthropogenic noise (See Figure 2).

As in Navenakhevi Cave, the cicada song forms the primary low-noise layer, providing a continuous horizontal frequency band. This consistent hum would typically serve as the "noise blanket" for other natural sounds.

**Absence of wind layer:** unlike the Navenakhevi cave entrance spectrogram, the Prometheus cave case lacks vertical spikes indicative of wind sounds, suggesting reduced natural airflow or masking by other elements in the sonic environment.

**Crowd chatter dominance:** the peak frequency spectrogram highlights the impact of crowd chatter, which occupies a broad frequency range, disrupting the natural acoustic balance. The chatter is low in intensity but pervasive, with frequencies extending across both the low and high ends of the spectrum. This overlapping presence partially obscures the cicada song, diminishing its clarity and resonance. The result is a degraded auditory experience where the unique timbral qualities of the natural soundscape are overshadowed.

The spectrogram and corresponding acoustic data illustrate how even low-intensity anthropogenic noise can devastate a soundscape's integrity. The intrusion of human chatter obliterates the pristine sound environment, replacing the ecological harmony with an uneven and polluted acoustic structure.

This analysis underscores the fragility of natural soundscapes in the face of human activity, highlighting the need for conservation efforts, especially in popular and frequently visited ecological sites. The degraded acoustic environment at the Prometheus Cave entrance serves as a stark contrast to the untouched soundscape of Navenakhevi, offering a compelling case study in the interplay between natural and anthropogenic acoustic dynamics.

In the natural ambient conditions (cave entrance and inner hall), the spectrograms reveal distinctive low-frequency patterns with occasional high-frequency peaks, often associated with environmental features such as water drips or air movement.

These low-frequency elements are typically indicative of the cave's natural resonance properties. In contrast, the human-induced sounds introduce broader frequency spectra, with sharper peaks and a wider amplitude range, demonstrating the disturbance or alteration caused by human presence. This alteration often results in a higher temporal variability in the sound signal, marked by sudden spikes or irregular oscillations.

Additionally, temporal resolution in spectrogram analysis allows us to track transient events such as footsteps or voices, which disrupt the continuous sound profile of the cave's natural ambience. These disruptions are typically more erratic, affecting both the high-frequency and low-frequency bands, and they create unique sonic signatures that distinguish human sounds from those produced by the natural cave environment.

By analyzing the time-frequency data across the different recording categories, we can gain deeper insights into the acoustic dynamics of the cave and how both natural and anthropogenic sounds interact with the environment. This analysis is essential for understanding how the cave acts as both a resonant space for natural sounds and a medium that is susceptible to alteration through human influence.

## Conclusion

The findings reveal the acoustic damage caused by human-induced changes, showing how pervasive noise pollution affects both ecological and cultural dimensions of soundscapes. From an ecomusicological viewpoint, caves represent unique "instruments" where natural and human-generated sounds resonate within their physical structures. The degradation of these soundscapes through human interference risks losing their eco-cultural significance, where the intersection of sound, nature, and human expression fosters deeper environmental awareness and connection.

The research further validates spectrogram analysis as an indispensable tool for this interdisciplinary exploration. By visualizing acoustic patterns, spectrograms allow precise measurement of the impacts of noise pollution, offering insights into the delicate balance of natural and cultural sounds. The method aligns with ecomusicology's focus on the interrelationship between ecology and music, providing both theoretical and practical means to analyze how sound operates as a critical element of ecological and cultural systems.

From an ecomusicological lens, these findings illustrate not just the auditory disruption but also a loss of cultural essence. Each cave is a natural instrument, its walls reverberating with the echoes of life, history, and ecological interplay. The intrusion of anthropogenic noise is more than an auditory blemish; it disrupts the delicate song of nature, robbing these spaces of their unique resonance—a vital bridge between ecology and human expression.

In safeguarding these sonic worlds, we protect more than sound; we preserve the intangible beauty of a shared ecological and cultural heritage. Caves, with their deep echoes and ethereal hums, offer more than shelter—they invite us into an ancient dialogue between nature and humanity, urging us to listen, understand, and act.

## Recommendations

### Recommendations for cultural policy and practical applications

Cultural policymakers should prioritize the protection of natural soundscapes in ecologically sensitive areas, such as caves, by introducing noise management regulations. This could include limiting visitor group sizes, scheduling "silent hours," and creating designated quiet zones to minimize anthropogenic noise pollution.

Natural soundscapes should be recognized as intangible cultural heritage. Caves, with their unique acoustic properties, can serve as sites for cultural and ecological education, promoting awareness of the interplay between nature, culture, and sound. Incorporating soundscape conservation into cultural heritage frameworks would underscore their ecological and cultural importance.

Spectrogram analysis should be integrated into environmental monitoring practices for caves and other sensitive ecosystems. By regularly analyzing soundscapes, managers can detect and address disruptions caused by human activity or ecological shifts, ensuring ongoing protection of these environments.

Managers of popular caves, like Prometheus, should employ evidence-based guidelines derived from this research. Measures could include installing sound-absorbing materials in high-traffic areas, training guides to manage noise levels, and conducting periodic acoustic assessments to maintain the integrity of the cave's soundscape.

### Limitations of Study

The study presented here is part of a broader, ongoing investigation into the ecomusicological aspects of various natural soundscapes. As such, the findings and analyses have been selectively narrowed to focus on key examples, leaving other relevant aspects of the research outside the scope of this article. This limitation, while necessary for clarity and space, means that the study does not fully represent the entirety of the research effort.

While spectrogram analysis offers invaluable insights into acoustic environments, it is a highly technical method that requires specialized knowledge to interpret and present effectively. The space constraints of this article restrict the comprehensive display of findings, necessitating the omission of numerous spectrograms and their corresponding analyses. This limits the reader's ability to fully grasp the depth and variability of the acoustic data collected.

The results presented in this study are specific to the soundscapes of Navenakhevi and Prometheus caves. While these findings offer valuable insights into the interplay of natural and human-induced ambiances, they cannot be assumed to generalize across all ecomusicological landscapes. Each soundscape is unique, shaped by its distinct ecological and cultural context, and future studies may reveal different patterns or dynamics in other environments.

These limitations underscore the complexity of studying soundscapes within an ecomusicological framework and highlight the need for further research to expand and validate the findings across a wider range of contexts and methods.

### Acknowledgement

This article is part of the fundamental research project "Implementation of Ecomusicology Research Methodology for the Study of the Musical Ecosystem of Georgia". The project, as well as this work, is supported by the Shota Rustaveli National Science Foundation of Georgia (SRNSFG) [grant number FR-22-8174].

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