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AN EXPLORATION OF ACOUSTIC DIVERSITY ACROSS AREAS WITH VARYING LEVELS OF TOURISM INTENSITY ON A MEDITERRANEAN ISLAND

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Abstract

This study investigates the acoustic diversity observed on the Naxos island in Greece, through the combined use of eco-acoustic indices and manual sound-source annotations. Recordings from 84 locations were grouped into six regions based on tourism intensity. Sound events were organized and statistically analyzed according to a proposed taxonomy, and Acoustic Entropy (H), Normalized Difference Soundscape Index (NDSI), and Dynamic Spectral Centroid (DSC) data were used to characterize soundscape structure. Results show coherent patterns across regions: high-tourism areas exhibit increased anthropogenic acoustic presence, while low-tourism ones maintain strong biophonic content. The complexity of effective soundscape interpretation and the benefits of using combined analysis approaches which work in a complementary manner is also discussed.

Keywords: *Soundscape Analysis, Ecoacoustic indices, Acoustic Entropy (H), Normalized Difference Soundscape Index (NDSI), Dynamic Spectral Centroid (DSC)*

1. Introduction

The concept of "Soundscapes" has transformed Acoustic Ecology by shifting focus from acoustic measurements to the perceptual and ecological dimensions of auditory environments. Rapid environmental and economic changes around the world often alter the original soundscapes, revealing shifts in the balance between natural and anthropogenic sounds [1]. Studies in regions experiencing such changes highlight the importance of preserving acoustic heritage while offering insights into the complex interdependencies between ecological processes and the human factor [2], [3].

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In recent years, researchers in the field of eco-acoustics have explored a wide range of acoustic indices that are capable of summarizing complex acoustical data into straightforward numerical representations [4]. These specialized metrics offer valuable insights into the complexity and dynamics of soundscapes, revealing ecological changes and aiding in the evaluation of environmental quality [5], [6]. Nowadays, more than 74% of the relevant studies use such metrics for analysis, prevailing over methods of manual audio annotation (23%) [7]. Yet, it should be noted that with more than 60 suggested indices used in relevant research, standardization of methodologies becomes necessary, in order to resolve and even avoid misapplication and misinterpretation issues. For that matter, careful selection and combination of acoustic indices is essential for optimized soundscape representation [4].

This study builds upon previous work on the soundscapes of the Greek island Naxos [8], further analyzing a dataset of soundscape recordings collected from 84 locations around the island. Sound events from these recordings are extracted and correlations between the auditory content and anthropogenic activities are explored. These sounds were organized into categories, following an adaptation of the taxonomy suggested in [9]. Acoustic indices are also employed in an attempt to identify the spectro-temporal patterns that reflect processes related to biodiversity, human activity, or other soundscape contributors, and explore whether these patterns correlate with our previous findings on the regional distribution of sound sources around the island, providing further insights into the components of Naxos' soundscapes and the impact of human activity on them.

2. Data Collection

Naxos is the largest island in the Cyclades. It is situated in the central Aegean Sea, south-east of mainland Greece and near the islands of Paros and Mykonos. It has an area of roughly 429 km^2 and a population of ap-

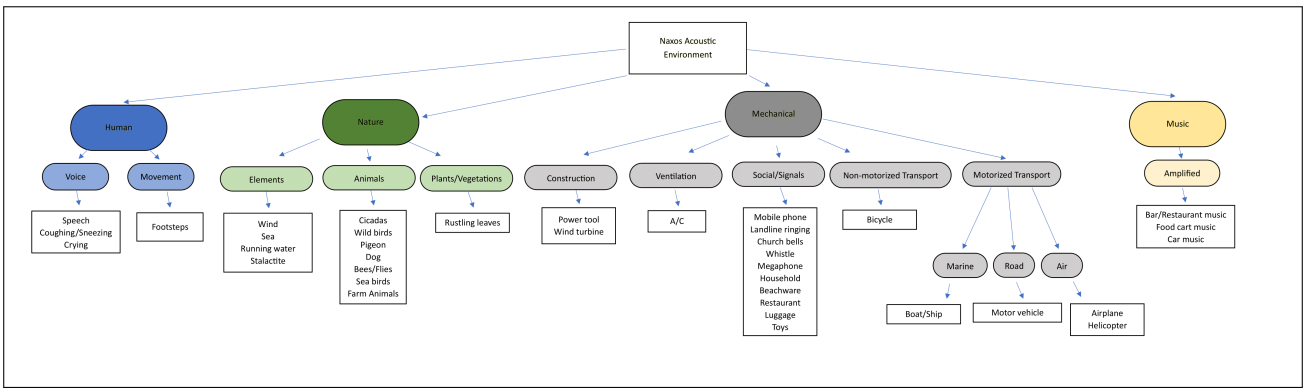

Figure 1: Sound-source classification taxonomy

proximately 18,000 permanent residents. The island is characterized by its diverse landscape, featuring mountains, valleys, and an extensive coastline, making it a popular tourist destination over the summer.
In order to best capture the varied soundscape of Naxos, which includes smaller and larger residential areas, beaches, archaeological sites, infrastructural zones, and nature, data collection was conducted at 84 selected sites across the island. Sites were grouped into six clusters based on geographic location, accessibility, and tourism intensity, in order to facilitate the analysis of the impact of tourism on soundscape authenticity. The said regions are defined as follows:

- High Tourism: i) *Chora* (sites 1-6, red) is the island's capital; it is the most populated area and attracts the highest number of visitors during the summer. ii) *Southwest Naxos* (sites 72-84, orange) is another region attracting a very high number of visitors.
- Moderate Tourism: i) *Central Naxos* (sites 7-20, yellow) and ii) *Northeast Naxos* (sites 55-71, purple) both attract moderate tourist activity.
- Low Tourism: i) *Southeast Naxos* (sites 34-54, green) and ii) *Northwest Naxos* (sites 21-33, blue) both are the least visited areas by tourists on the island.

Recordings took place from July 7^{th} to August 21^{st}, 2023, between 12:00 PM and 6:30 PM, with sessions lasting 5 to 20 minutes. The duration varied according to the sonic complexity of each soundscape; those with more Soundscapes were captured at 96 kHz / 24 bit in First Order Ambisonics (FOA) using a Zoom H3-VR field-recorder with a Zoom WSU-1 windscreen. A-weighted dB levels were also collected using an INGCO HETSL01 digital sound level meter. Gain levels were manually adjusted in each recording location to account for local ambient sound levels, while in-ear headphones were used for real-time monitoring. This monitoring process enabled detailed documentation of individual sound sources present within each soundscape, which took place in the time of data capture, and verified upon second inspection during data post-processing. Each session was paired with landscape photographs and GPS coordinates.

3. Data Analysis

In order to gain insight into the distribution of the observed sound-sources and facilitate soundscape content comparisons across the island, data from each of the six regions was organized and analyzed according to an adapted version of the taxonomy suggested by Salamon et al. [9]. Acoustic indices were also used to reveal signal characteristics linked to biodiversity and human activity, and to evaluate correspondence with the aforementioned analysis, thereby providing a deeper understanding of the Naxos soundscape structure and the human influence on it.

3.1. Taxonomy Analysis

Sounds identified through manual annotations of each soundscape recording were systematically organized into categories, which were then grouped into broader classifications, creating the employed hierarchical structure. As suggested in [9] the top-level of the taxonomy consisted of four groups: *Human*, *Nature*, *Mechanical*, and *Music*, as the most prevailing classes in urban environments. High-level classes maintained the same tags as the referenced taxonomy, and leaves were sufficiently low-level to be unambiguous. Results can be seen in Figure 1.
An analysis of the distribution of sound sources across Naxos, which was based on event counts from full recordings, led to the following observations. In the Chora of Naxos, the Mechanical sound category was prevailing, accounting for 46.34% of the auditory content, with Motor Vehicle sounds alone contributing 31.58% to it. Human sounds, including Footsteps and Voices, made up 29.27% and Nature sounds accounted for 17.07% of the content. Music was the least represented category accounting for 7.32% of the soundscape. At Southwest Naxos, which is popular for its coastline, Mechanical sounds remained a prominent category, constituting 30.19% of the soundscape, followed by Human sounds (27.36%) and Music (3.77%). Nevertheless, unlike Chora, Nature sounds,

including the Sea, Rustling Leaves, Wind, and Wild Birds, were the dominant category, comprising 36.86% of the soundscape.

In Southeast Naxos, a region with low tourism activity, Nature sounds dominated the soundscape, accounting for 63.24% of the recorded data. Characteristic sound sources included Cicadas, Bees/Flies, and Farm Animals. Human sounds, such as Voices and Footsteps, accounted for 26.47%, while Mechanical sounds, primarily from Motor Vehicles, were minimal, making up just 10.29% of the auditory content. Similarly, in Northwest Naxos, Nature sounds, featuring Cicadas, Bees/Flies, Dogs, Farm Animals, Running Water, and Sea Birds, prevailed at 74.55%, while Human and Mechanical sounds made up 10.91% and 14.55% of the auditory content, respectively. The absence of Music and the predominance of Nature sound sources in these regions emphasize the minimal tourist impact on the soundscape of those areas.

Lastly, in regions with moderate tourism activity, specifically Central Naxos and Northeast Naxos, the soundscape was balanced between natural and anthropogenic sources. In Central Naxos, Nature sounds dominated accounting for 62.83% of the auditory content, while Human and Mechanical sounds accounted for 14.16% and 21.24%, respectively. Music was the least represented category, making up only 1.77% of the soundscape. Likewise, in Northeast Naxos, Nature sounds made up 58.78% of the soundscape content, Human sounds 19.65%, Mechanical sounds 19.61% and Music 1.96%.

Overall, according to the above as well as to preliminary analysis of this dataset presented in [8], one may observe that apart from Naxos Chora, where Nature sounds make up less than 20% of the observed soundscape, Nature content remains a significant auditory component across the island. This indicates that while human activity has a notable impact on the soundscape of specific regions, particularly in Chora and Southwest Naxos, Nature sounds continue to play a defining role in the island's overall acoustic environment.

3.2. Acoustic Index Analysis

Acoustic Indices were also used as a means for further shining light into the acoustic properties and characteristics of the soundscapes across the Naxos island. The following post-processing steps were applied to the data prior to analysis: i) All Ambisonics A-format files were converted to B-format (AmbiX) and subsequently the W omnidirectional mono channel was extracted and downsampled from 96kHz/24bit to 44.1kHz/24 bit, ii) Each recording was high-pass filtered at 170 Hz in order to minimize the impact of wind noises on the data [10], iii) Recordings were split into successive 60 s segments, with no overlap, and iv) Each segment was peak-normalized at -12 dBFS. Data processing, analysis, and visualization were conducted via custom Python scripts utilizing libraries such as Librosa, Pydub, Matplotlib, and Pandas, integrated with the FFMPEG framework.

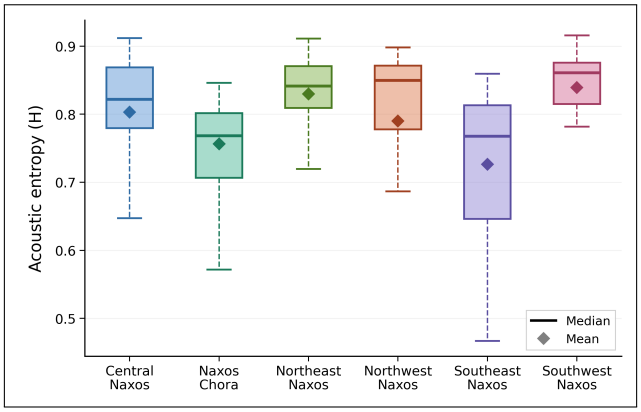

Figure 2: Distribution of Acoustic Entropy Index values per region

Acoustic Indices were applied to the post-processed segmented data, grouped according to the six previously defined regions on the island. The following 3 indices were selected to complement the sound-source distribution per-region analysis described in Section 3.1: Acoustic Entropy (H), Normalized Difference Soundscape Index (NDSI), and Dynamic Spectral Centroid (DSC). When the three are viewed collectively, they offer a comprehensive overview of the soundscape characteristics. H describes how evenly sound energy is spread across time and frequencies, giving an overall idea of how complex a soundscape is. NDSI measures the balance between biophony and anthrophony, detecting whether a soundscape is influenced by nature or by human activity. DSC reveals the frequencies that dominate a soundscape over time, indicating how dominating sounds in an environment change.

3.2.1. Acoustic Entropy Index

The Acoustic Entropy (H) Index [10] quantifies the evenness in the amplitude of a signal across both the temporal and frequency domains and is calculated as the product of Temporal Entropy (Ht), and Spectral Entropy (Hs). Acoustic Entropy values range between 0 and 1, with 0 representing the simplicity of a single pure tone and 1 the randomness of noise or complete silence [11]. Lower H values, closer to 0, correlate with simpler soundscapes, often caused by habitat degradation or the presence of fewer species in a given location. Higher H values, approaching 1, are an indication of higher complexity and hence biodiversity in a given location. It should be noted, though, that the variability of entropy decreases as species richness increases, suggesting that communities with very few species may suffer a higher degree of error [10].

The distributions of the calculated H values per region in Naxos (see Figure 2) show that all six regions fall within the high-end of the scale range, indicating overall complex soundscapes. Nevertheless, closer inspection of the data reveals clear differences between geographic areas. More specifically, high median H val-

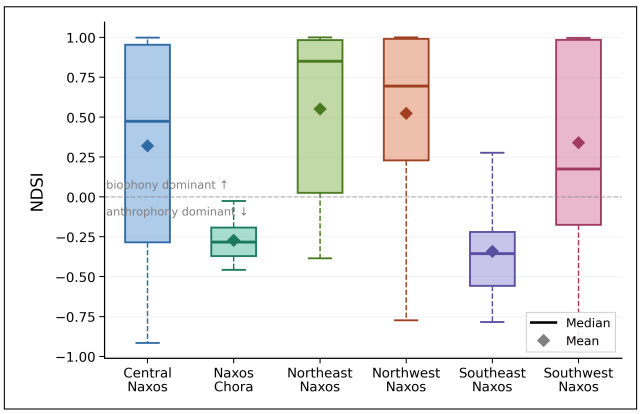

Figure 3: Distribution of Normalized Difference Soundscape Index values per region

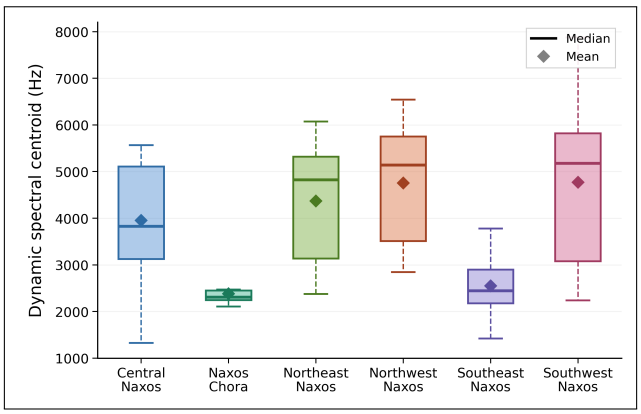

Figure 4: Distribution of Dynamic Spectral Centroid values per region

ues are observed in Southwest (0.86), Northwest (0.85), Northeast(0.84), and Central Naxos (0.82), suggesting more complex and evenly distributed soundscapes, possibly influenced by both anthrophony and biophony. The lowest median values are observed in Chora (0.77) and Southeast Naxos (0.77), indicating simpler or less evenly distributed acoustic environments.

Naxos Chora and Central Naxos, both regions of high and moderate tourism levels, exhibit relative wide H spreads, reflecting more heterogeneous soundscapes that are quite typical of human-dominated environments. On the contrary, the Southwest and Northeast Naxos regions, also locations of high and moderate tourism levels, exhibit much narrower data distributions, implying more consistent soundscape conditions. In Northwest and Southeast Naxos, regions of very low tourist activity, the means of the distributions lie considerable lower than the median. This Negative skewness indicates the occasional presence of low-entropy events such as silence or a dominant noise (e.g. the sound of a vehicle passing by). This interpretation is further supported by the very low minimum (0.47) observed in the Southeast Naxos region, capturing instances of acoustic simplification, which could be caused by anthropogenic noise dominance or low biological activity.

3.2.2. Normalized Difference Soundscape Index

The Normalized Difference Soundscape Index (NDSI) [12] analyzes the spectral content of a soundscape and quantifies the balance between anthrophony, evident in the frequency range from 1 kHz to 2 kHz and biophony, 2 kHz to 8 kHz. The metric output is normalized ranging between -1 and 1, with values approaching the lower-end indicating anthrophony dominance and hence stronger human impact in a soundscape, and values approaching the upper-end indicating biophony dominance [5], [11]. As NDSI serves as an estimation of anthropogenic disturbance in soundscapes, it is often used to assess habitat health in diverse environments [6], [13].

The distribution of NDSI values, depicted in Figure 3, reflects the heterogeneity in the soundscapes across the six regions on the island. The highest values are observed in Northeast (0.85) and Northwest (0.69) Naxos, regions of moderate and low tourism activity respectively, indicating strong biophonic dominance. On the contrary, the Chora (-0.28) and Southeast(-0.36) Naxos showed persistently negative NDSI values, reflecting the dominance of human-related activities in the auditory content. Central and Southwest Naxos hold the widest distributions, ranging from ≈ -0.9 to 1, followed by Northwest Naxos ≈ -0.76 to 1. These ranges imply shifts between natural and human-derived acoustic activity over time in these areas. It should be noted however that, the observed median NDSI value of Southwest Naxos (0.17), a region of high tourism activity, is closer to 0, than that of Central Naxos (0.47), a region of medium tourism activity, and Northwest Naxos (0.69), a region of low tourism activity, indicating that the first is a more balanced soundscape of mixed anthropogenic and natural influences, whereas the other two have biophony-dominated auditory content.

3.2.3. Dynamic Spectral Centroid

The Dynamic Spectral-Center analysis indicator [14] or Dynamic Spectral Centroid (DSC) [6] quantifies the central point of spectral energy distribution over time, revealing the spectral composition of sound events and background sounds in a soundscape. Most of biophonic activity is evident between 2 kHz and 8 kHz, while noise from Mechanical sources is generally evident within the 0.1 kHz to 2 kHz frequency range. Hence, this metric reveals the prevalence of natural or anthropogenic sound-sources in a soundscape over time, by highlighting shifts in dominant frequency bands.

DSC analysis of Naxos' soundscapes (see Figure 4) revealed variations in the dominant frequencies characterizing each region. More specifically, Southwest (5176 Hz), Northwest (5138 Hz), Northeast (4820 Hz), and Central (3826 Hz) Naxos exhibit high median spectral centroid values, indicating the predominance of a high-frequency acoustic energy field, often associated with biophonic activity (e.g. birds, insects,

animals). The data distributions of Central and Southwest Naxos, areas of moderate and high tourism activity, are considerably broader in range than those of the remaining regions, corresponding to predominantly biophonic environments with persistent anthrophonic influences. Finally, Chora (2308 Hz) and Southeast (2446 Hz) Naxos are characterized by substantially lower median DSC values, reflecting persistent dominance of anthropogenic sounds. Nevertheless, it should be noted that while the distribution of the former is highly concentrated around the median, that of the latter is considerably wider, ranging from ≈1420 Hz to ≈3800 Hz, hinting a more mixed auditory environment with temporal shifts in dominant sound-sources.

Northwest Naxos, a region of low tourism activity, is a clear example of ecologically intact soundscape, where biophony dominates. According to annotation statistics, Nature sounds account for 74.55% of the soundscape content, with Human and Mechanical sounds contributing only to the remaining 25.45%. This interpretation is strongly supported by the index analysis. The region features a high H (0.85), a concentration of DSC energy in a high frequency region (5138 Hz), and a high positive NDSI (0.69), all hinting a complex rich auditory environment with dominant biophony content. On the contrary, the soundscape of Southeast Naxos, a region characterized by low tourism infrastructure, presents a contradicting pattern. Manual annotations indicate the strong dominance of nature-related sounds (63.24%) over Mechanical (10.29%). Nevertheless, the acoustic indices present an alternative picture characterized by a low H value (0.77), negative NDSI (-0.36), and low DSC (2446 Hz) relative to the more clearly biophonic Northwest region. This discrepancy likely arises from the presence of human activity in the area. Although Southeast Naxos lacks tourist infrastructure (such as hotels, restaurants etc.) it includes some of the island's most popular beaches. As a result, soundscapes recorded near the coastline and along major access roads are influenced by the human presence and mechanical noises, which reduce acoustic complexity and shift spectral balance despite the overall prevalence of natural sound sources.

4. Discussion

Building upon ongoing research [8], this work discussed a more effective organization of the collected data based on an adaptation of the taxonomy suggested in [9], and presented an updated statistical analysis of the corresponding manually annotated sound-source data, grouped per geographical region across the island. In high-tourism activity regions (Naxos Chora and Southwest Naxos), anthropogenic sounds (i.e., Mechanical, Human, and Music) were dominating the soundscape. Areas with low tourism activity (Southeast and Northwest Naxos) were characterized by Nature sounds with minimal presence of Mechanical and Music sounds. Moderate tourism activity regions (Central and Northeast Naxos) exhibited a mixed soundscape, with Nature sounds prevailing over anthropogenic sounds, though by a narrow margin. These results highlight the uneven distribution of sound sources across different regions of Naxos, suggesting that human presence and activity influence the composition of the island's soundscape.

Statistical analysis using eco-acoustic indices on the soundscape recordings from 84 locations around the island, was also employed in order to identify spectro-temporal patterns associated with biodiversity and human presence in the soundscapes. The analysis aimed to determine whether the soundscape characteristics, objectively extracted from the audio signal could complement the original statistical analysis, thus providing deeper insights into the influence of human activity on the Naxos' acoustic environment. For this purpose three acoustic indices commonly utilized in eco-acoustic research were employed, namely the Acoustic Entropy Index (H), the Normalized Difference Soundscape Index (NDSI), and the Dynamic Spectral Centroid (DSC). H captures the overall acoustic complexity in a soundscape, NDSI reflects the balance between biophony and anthrophony, and DSC tracks the dominant frequency range of acoustic energy. When viewed in parallel with the statistical analysis of the manual annotations, they reveal a detailed overview of the soundscape qualities, characteristics, and properties across Naxos.

Naxos Chora, a region of high tourism activity, is the clearest example of a soundscape with human-activity prevalence. It is characterized by relatively low H (0.77), consistently negative NDSI values (-0.28), and low frequency DSCs (2308 Hz), implying a relatively simple and lower-frequency soundscape, shaped mainly by human and mechanical activity. This interpretation in line with the annotation results, which reported mechanical sounds accounting for 46.34% of the identified sound-sources, far exceeding nature-related sounds (17.07%). Southwest Naxos, another region with high tourism activity, has a mixed soundscape. It is characterized by the highest H value (0.86), a positive but variable NDSI (0.17), and one of the highest DSC values (5176 Hz), implying a rich soundscape with shifting balances between natural and human-driven sound-sources. This observation is supported by the annotation results, according to which Nature sounds were the most populated sound class (36.86%), followed by Mechanical (30.19%) and Human generated sounds (27.36%). Both Chora and Southwest Naxos are examples of regions where the impact of anthrophony due to high concentration of population and tourism is evident in the acoustic characteristics of their corresponding soundscapes. In the case of the Southwest Naxos, though, soundscape appears to be more heterogeneous, with both anthrophony and biophony-related components present.

Northeast Naxos, a region of moderate tourism activity, is characterized by a high H (0.84), positive NDSI (0.85), and high DSC (4820 Hz) indicating a complex soundscape dominated by biophony. The annotation statistics support this conclusion, as Nature sounds

account for 58.78% of the observed sources while Human and Mechanical sounds reach 39.26%, pointing to a mixed but still nature-heavy acoustic environment. Similarly, Central Naxos, another region with moderate tourism activity, has a moderately impacted soundscape. Its moderate H (0.82), positive NDSI (0.47) with high variability, and DSC values at an intermediate range (3826 Hz) imply an acoustic environment in which neither human-driven nor biophonic sounds are dominant. The annotation statistics support this interpretation as Nature sounds dominate at 62.83%, but Mechanical and Human-driven sounds account for 35.4% . Overall, both regions are characterised by soundscapes of high biophony, while also experience a noticeable impact by human activity.

5. Conclusions and Future Work

This work attempted a comprehensive regional analysis of the acoustic characteristics of the Naxos' soundscapes in the summertime. The combined analysis of sound-source annotations with the Acoustic Entropy, Normalized Difference Soundscape Index, and Dynamic Spectral Centroid highlighted variations in the structure of soundscapes across the island, as a function of human activity. It should be noted, that with the exception of Chora, the remaining regions, despite their variability, maintain a lively biophonic component, whose prevalence depends on the impact of human-driven actions.

Future work will extend data collection to cover seasonal and inter-annual variations, for a more understanding of soundscape dynamics. In addition, further analysis of the interplay between natural and anthropogenic sound sources will help refine these eco-acoustic metrics for more effective environmental monitoring and sustainable tourism management.

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