ECOACOUSTIC GRADIENTS AND DIRECTIONAL INFORMATION FLOW IN THE SOUNDSCAPE OF AN ALPINE NATIONAL PARK

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This paper is a revised version of the authors' submitted manuscript that was peer-reviewed by at least two anonymous reviewers.

Abstract

High-altitude ecosystems are characterized by strong environmental gradients and increasing seasonal anthropogenic pressure, yet their acoustic structure remains comparatively understudied. In this work, the soundscape of an Alpine National Park was investigated during the peak summer period using passive acoustic monitoring across thirteen recording sites on the Nivolet plateau (Gran Paradiso National Park, Italy). A set of ecoacoustic indices was computed from the recordings and summarized through Principal Component Analysis to identify the dominant acoustic gradients. The indices with the highest loadings on the first two components, Acoustic Entropy (H) and the Normalized Difference Soundscape Heterogeneity Index (NDSHI), were retained as representative descriptors of the July soundscape. Spatial and diel patterns revealed marked heterogeneity among sites, with consistently higher nocturnal values of H and site-dependent variations of NDSHI. To investigate directional relationships among recording locations, Transfer Entropy was applied to the selected ecoacoustic descriptors. Only interactions exceeding the 95th percentile of the |ΔTE| distribution were retained, revealing a sparse but spatially structured network of directional information exchanges. These results highlight the potential of combining ecoacoustic indices with information-theoretic metrics to explore the spatial organization of soundscapes in fragile mountain environments.

Keywords: *ecoacoustics, passive acoustic monitoring, alpine ecosystems, transfer entropy, soundscape*

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1. Introduction

Sound is a fundamental yet often underappreciated component of ecological systems. Acoustic signals mediate biological interactions, influence spatial distribution, and contribute to habitat organization. However, the global expansion of anthropogenic noise is increasingly altering natural acoustic environments, with documented consequences for biodiversity and ecosystem functioning. In response, soundscape ecology has emerged as a framework for investigating the interactions among biophony, geophony, and anthropophony across spatial and temporal scales [1,2]. Passive Acoustic Monitoring (PAM) provides a continuous and non-invasive approach for characterizing environmental conditions through quantitative descriptors derived from acoustic recordings [3, 4]. Compared to traditional field surveys, PAM enables high temporal resolution and facilitates the detection of anthropogenic disturbances, making it particularly suitable for monitoring ecosystems characterized by strong temporal variability.

Despite the rapid expansion of ecoacoustic methodologies, high-altitude mountain ecosystems remain comparatively underrepresented [5]. Alpine environments are characterized by low resilience, steep climatic gradients, and pronounced seasonal variability. During summer months, accessible high-elevation areas often experience intensified tourism and recreational activities, leading to increased anthropogenic acoustic inputs. These fragile systems provide an important context for examining how concentrated seasonal pressures may influence soundscape structure.

Recent conceptual developments suggest that environmental sound should be examined not only through species-level detection but also as a structured acoustic system. The sonotope hypothesis proposes that acoustic heterogeneity emerges from the spatial and temporal configuration of sound patches ("sonotopes"), forming a broader soundscape that can be described independently of explicit biological interpretation [5]. Within this perspective, soundscapes may be treated as dynamic systems whose structural organization and informational exchanges can be quantified using system-level metrics. To date, few studies have explored directional information dynamics within environmental soundscapes, particularly in high-altitude ecosystems.

In this study, we investigate a high-altitude Alpine area during the peak summer period, when anthropogenic pressure has been previously documented to reach its maximum [6]. Multiple ecoacoustic indices are first summarized using Principal Component Analysis (PCA) to derive reduced acoustic descriptors of July soundscape. The indices with the highest loadings on the first two principal components are retained as representative descriptors of the dominant acoustic gradients, defined here as the main axes of variation in ecoacoustic structure across the monitoring sites. We then assess whether directional information dynamics emerge among spatial recording nodes by applying Transfer Entropy to the selected ecoacoustic descriptors. This approach tests whether the reduction of ecoacoustic information can reveal patterns of directional coupling within a fragile Alpine soundscape subjected to concentrated seasonal pressure.

2. Materials and Methods

2.1 Study Area

The study was conducted in the Colle del Nivolet area, located in the Graian Alps, on the watershed between the Orco Valley (Piedmont) and the Valsavarenche (Aosta Valley), within the Gran Paradiso National Park (PNGP), the first protected area established in Italy in 1922. The site extends across a high-altitude plateau at approximately 2,612 m above sea level, characterized by alpine meadows, wetlands, peat bogs, small lakes, and rocky outcrops shaped by the upper reaches of the Dora Baltea River basin. These habitats are home to numerous alpine species of conservation interest, including endemic and rare high-altitude flora associated with wetland environments, as well as migratory and resident bird species. Due to its ecological value, the area is included in the Natura 2000 network as both a Special Area of Conservation (SAC) and a Special Protection Area (SPA) [7, 8].

The plateau is accessible from the SP50 provincial road, which connects the Orco Valley with the Valsavarenche Valley. Due to snow and ice conditions, the road remains closed during the winter and autumn seasons. Once access is restored, the area becomes a popular destination for tourism and outdoor recreation, resulting in a high seasonal concentration of visitors during the summer months, particularly in July and August. Indeed, previous monitoring activities conducted in the study area during the summer of 2024 documented a substantial increase in traffic flows on weekends, reaching values two to five times higher than those observed on weekdays [9]. Although the measured sound pressure levels remained within the legal limits for secondary roads outside urban areas, they were consistently higher than those typically associated with quiet rural environments [6]. Average daytime levels ranged between approximately 49 and 55 dBA on weekdays and 57-60 dBA on weekends, compared to background conditions of approximately 35-40 dBA when the road was closed to traffic. These results indicate that vehicular access constitutes a significant source of anthropogenic noise input in an otherwise quiet Alpine environment.

2.1.1 Monitoring campaign

During the July monitoring campaign, thirteen recording sites were deployed across the Nivolet plateau, spanning an elevation range from approximately 2230 to 2680 m a.s.l., to capture environmental heterogeneity and different levels of exposure to anthropogenic activity (Fig. 1). Several stations were located in proximity to road infrastructure and parking areas (sites 1, 3, 4 and 8), where vehicle traffic and tourist presence are more frequent. A second group of sites was positioned near water bodies such as small alpine lakes and streams (sites 6, 7, 10 and 13), representing wetland habitats characterized by geophonic contributions from flowing water. Additional recorders were deployed in open alpine grasslands and remote plateau areas with limited direct anthropogenic influence (sites 5, 9 and 12). Finally, some stations were located along frequently used hiking routes or grazing areas (sites 2, 10 and 11), representing intermediate conditions between natural and anthropogenic acoustic inputs.

Recordings were collected between 17 and 29 July 2024 using a duty cycle consisting of 1 minute of recording followed by 5 minutes of pause, continuously repeated throughout the monitoring period. This sampling design allowed the characterization of acoustic conditions across a range of habitats and levels of anthropogenic exposure within the study area.

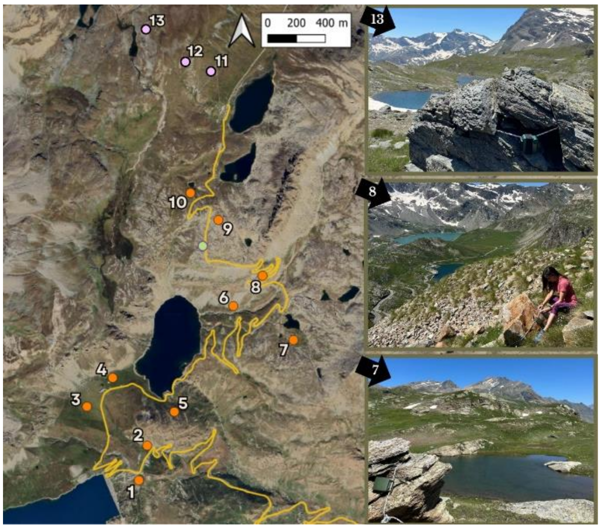

Figure 1. Study area and spatial distribution of the thirteen acoustic monitoring sites across the Nivolet plateau (PNGP, Italy). Sites equipped with AudioMoth recorders are shown in pink, while sites equipped with Wildlife Acoustics recorders are shown in orange.

2.2 Recording devices and signal equalization

Recordings were collected using thirteen autonomous acoustic recorders: seven Song Meter Micro units, three Song Meter Mini 2 AA devices (Wildlife Acoustics, USA), and three AudioMoth recorders. The Song Meter Micro units have a full-system sensitivity of approximately 2 ± 4 dBV re 1 Pa at 1 kHz at a +18 dB gain setting. Song Meter Mini 2 AA devices exhibit an on-axis microphone sensitivity of 12 ± 4 dB FS re 1 Pa at 1 kHz under the same gain configuration. AudioMoth recorders were configured according to the manufacturer specifications for environmental acoustic monitoring.

Because recordings were obtained using different types of acoustic recorders, a signal equalization procedure was applied to obtain a frequency response comparable to that of a reference sound level meter, ensuring the comparability of sound levels and ecoacoustic indices derived from the recordings [10].

The equalization procedure consisted of three main steps. First, a broadband white-noise signal was simultaneously recorded using the reference sound level meter and the acoustic recorders under investigation. Second, a correction filter was generated in the frequency domain by computing the ratio between the Power Spectral Density (PSD) of the signal acquired by the sound level meter and that recorded by each device. Third, the resulting filter was applied to all field recordings. Calibration measurements were conducted both in controlled acoustic conditions (anechoic chamber) and in open-field conditions. The anechoic environment allowed accurate characterization of device frequency responses, while open-field measurements were used to verify the reproducibility of the equalization procedure under realistic propagation conditions. During the open-field calibration, broadband white noise (80 dB(Z)) was emitted by a loudspeaker positioned 3 m from the reference sound level meter and the acoustic recorders. Measurements were performed under no-wind conditions and in the absence of extraneous sound events, in a site selected to approximate quasi-free-field conditions.

2.3 Ecoacoustic indices and dimensional reduction

After signal equalization and preprocessing, a set of ecoacoustic indices was calculated in the R environment (using the tuneR, seewave, and soundecology packages) to characterize the various structural properties of the recorded soundscape [11]. Spectral analyses were based on the Fast Fourier Transform (FFT) using a 1024-point window, corresponding to a frequency resolution of 46.87 Hz.

A set of complementary ecoacoustic descriptors was selected to capture different dimensions of acoustic structure, including: the Acoustic Complexity Index (ACI, frequency range = 0.5-12 kHz, j=60s) [12], the Acoustic Diversity Index (ADI, dB_threshold= -50 dB) [13], the Bioacoustic Index (BI, frequency range 1-12 kHz) [14], Acoustic Entropy (H) [15], the Dynamic Spectral Centroid (DSC) [12], and the Zero Crossing Rate (ZCR) [16], Weighted Proportion of Occupied Frequencies (wPOF) and the Normalized Difference Sound Heterogeneity Index (NDSHI, low-frequency 129-1981 Hz and mid-high frequency 2003-11025 Hz) [17].

To reduce redundancy among indices and identify dominant acoustic patterns, a PCA (R environment, FactoMineR package) was performed on z-score standardized indices. Although NDSHI is intrinsically normalized, the same preprocessing was applied to all indices to ensure comparability. Based on the PCA loading structure, the ecoacoustic indices showing the highest contributions to the first two principal components (PC1 and PC2) were selected as representative descriptors of soundscape variability. Because these components captured the dominant gradients of ecoacoustic variability, focusing on the associated indices allowed a clearer ecological interpretation of the main soundscape patterns. These indices were subsequently used as proxies to examine temporal variability in acoustic conditions through boxplot distributions comparing daytime and nighttime periods.

2.4 Transfer Entropy analysis

Directional information exchange between monitoring sites was analyzed using Shannon Transfer Entropy (TE), an information-theoretic metric that quantifies the amount of information transferred from a source process to a target process over time [18]. TE was calculated using the time series of the ecoacoustic index selected through the PCA analysis. The statistical significance of directional information transfer between pairs of sites was assessed using a permutation-based surrogate test. For each pair of time series, the source series was randomly permuted 1000 times, thereby destroying its temporal structure while preserving its marginal distribution, and Transfer Entropy was recomputed for each surrogate realization to generate a null distribution. Observed TE values exceeding the 95th percentile of this null distribution were considered statistically significant ($\alpha = 0.05$).

To assess the net direction of information exchange between monitoring sites, the estimated information transfer in two opposite directions was compared for each pair of sites ($|\Delta TE|$). Positive differences indicate a stronger influence from site i to site j, while negative values indicate the opposite direction. Only statistically significant interactions were retained to construct the resulting information-flow network among monitoring sites. To visualize directional asymmetry, cumulative profiles $|\Delta TE|$ were plotted by considering, for each destination site, the absolute difference between the incoming and outgoing Transfer Entropy values from all source sites. This representation was used to highlight the relative intensity and spatial distribution of directional information imbalances within the monitoring network.

3. Results

3.1 Dominant ecoacoustic gradients of the July soundscape

A total of 29,624 observations were available for each ecoacoustic index during the July monitoring period, excluding site 11 where recorder malfunction prevented data collection. Descriptive analysis highlighted substantial differences among indices in terms of scale, variability and distributional shape. For example, BI showed the highest dispersion (SD = 16.85), whereas H and wPOF exhibited much lower variability (SD = 0.09 and 0.03, respectively). Indices also differed markedly in their distributional symmetry: ACI displayed strong positive skewness (skew = 5.07), whereas NDSHI and wPOF showed negatively skewed distributions (skew = -2.19 and -0.95). These patterns indicate that ecoacoustic indices capture different aspects of the acoustic environment and exhibit heterogeneous statistical behaviour. To summarize these complementary dimensions of variability, a PCA was performed to identify the dominant gradients of ecoacoustic structure across monitoring sites.

PCA revealed that the first three components explained 71.3% of the total variance (38.8% for PC1, 19.7% for PC2, and 12.8% for PC3). To facilitate interpretation of the main ecoacoustic gradients, the indices showing the highest contributions to each component were identified: H (27.4%), together with ADI, ZCR, DSC (19.8%, 20.1%, 13.6%); NDSHI (36.8%) and wPOF (26.6%) for PC2; and ACI (55.7%) for PC3. Because PC1 and PC2 together accounted for the largest share of explained variance and represented the dominant gradients of ecoacoustic variability, subsequent interpretation focused on these two components. Focusing on these components allowed a clearer ecological interpretation of the main soundscape gradients while retaining the main variance structure of the dataset. The indices associated with them (H and NDSHI) were therefore used as representative descriptors of the July soundscape. PC3, although explaining additional variability, captured more localized variation and was therefore not retained for the subsequent spatial interpretation.

3.2 Soundscape structure and directional information flow

The spatial and diurnal variability of the indices representing the first two components of the PCA (H and NDSHI) was examined across the monitoring sites (Fig. 2). For H, clear spatial differences emerged. Higher values were consistently observed at sites 2, 3, 4, and 8. Sites 6, 7, 10, and 13 showed similar distributions, but with systematically lower values than the previous group. Sites 1, 5, and 9 showed comparable temporal trends with overall lower values. Site 12 showed distinct behavior during the day, characterized by a wider interquartile range, indicative of greater dynamism. Across all sites, both mean and median H values were consistently higher at night. However, nighttime distributions were generally less variable, as indicated by narrower interquartile ranges, whereas daytime conditions exhibited broader distributions, indicating greater variability across both temporal and frequency domains.

The NDSHI showed a different spatial structure. Positive values, indicating a greater contribution from medium- and high-frequency components, were observed primarily at sites 2-6, 8, and 12. In contrast, sites 1, 9, and 13 showed more balanced distributions, while sites 7 and 10 were characterized by lower values, with site 7 exhibiting the greatest variability, as indicated by wider interquartile ranges. The diurnal pattern of the NDSHI varied across sites: at locations such as sites 2, 3, 4, and 8, daytime values tended to exceed nighttime values, while other sites showed comparable or slightly higher nighttime distributions.

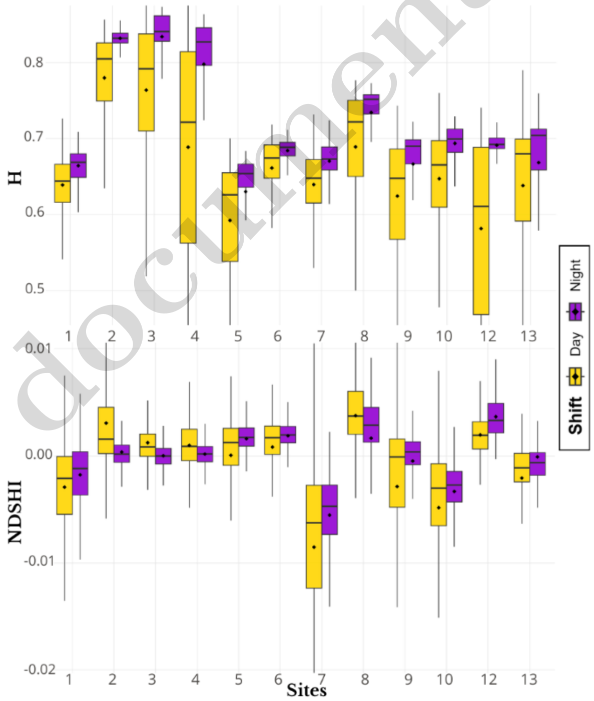

Figure 2. Boxplot distributions of the ecoacoustic indices H and NDSHI across monitoring sites during the July campaign. Daytime (06:00-21:00, yellow) and nighttime (22:00-05:00, violet) conditions are shown separately. Boxes indicate the interquartile range, horizontal lines the median, and black diamonds the mean.

Directional information exchanges among monitoring sites were quantified using TE computed on the indices selected through PCA. Only interactions exceeding the 95th percentile of the $|\Delta TE|$ distribution were retained (Fig. 3). For H, the resulting network identified a limited set of dominant source nodes, mainly sites 2, 3, 4 and 13. The strongest directional transfers were observed from site 13 to site 3 (ΔTE=0.051), from site 2 to site 8 (ΔTE=0.045), and from sites 3 and 4 toward site 1 ($\Delta TE \approx$0.045 and 0.041, respectively). For NDSHI, the directional structure was more restricted. The main interactions involved site 2 toward site 4 (ΔTE=0.029) and site 12 toward sites 8 and 1 ($\Delta TE \approx$0.019 and 0.018), together with a weaker connection between sites 5 and 6 (ΔTE≈0.017). These results indicate a sparse but spatially organized pattern of directional information exchanges within the monitoring network.

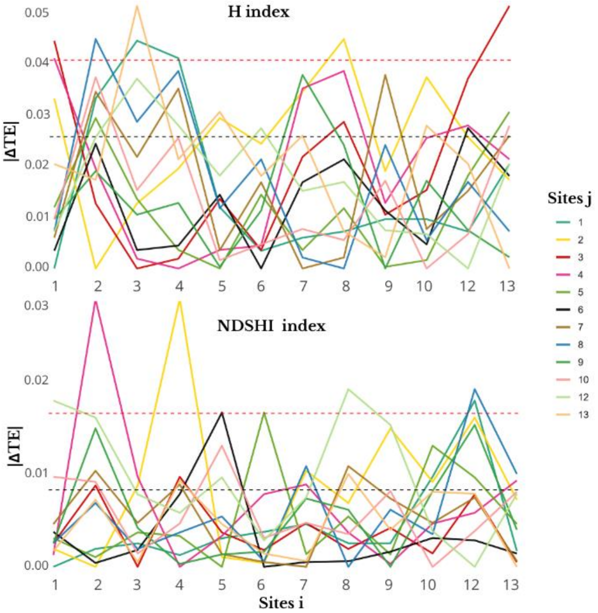

Figure 3. Cumulative directional asymmetry (|ΔTE|) among monitoring sites for the indices H and NDSHI. Each line represents a site j and shows the magnitude of |ΔTE| from all sites i (x axis). Dashed lines indicate the 75th and 95th percentiles of |ΔTE|.

4. Discussion

Alpine ecosystems are highly sensitive to seasonal anthropogenic pressure, making them particularly suitable for investigating how human activities influence environmental soundscapes [1,19].

The analysis of the July soundscape revealed marked spatial heterogeneity across the Nivolet plateau. The ecoacoustic gradients identified through PCA showed that the indices H and NDSHI captured complementary aspects of the acoustic environment. Acoustic entropy (H) describes the distribution of acoustic energy across the frequency spectrum, and higher values generally reflect soundscapes composed of multiple simultaneous sound sources distributed over time and frequency [15, 20]. In this study, the highest H values were observed particularly at sites 2, 3, 4 and 8, which also exhibited positive NDSHI values (Fig. 2). These locations correspond to areas where biological acoustic activity is expected to be higher, including avian vocalizations and marmot whistles, together with grazing-related sounds such as cowbells reported by park management. more evenly distributed acoustic spectrum at these sites (as indicated by the boxplot distributions and interquartile ranges in Fig. 2), a pattern commonly observed in ecosystems characterized by active biological communities [14, 21]. In contrast, sites 6, 7 and 10 showed comparatively lower H values and reduced NDSHI levels (Fig. 2). Lower entropy values are typically associated with soundscapes dominated by a limited number of acoustic sources, resulting in less homogeneous spectral distributions [20]. In the present case, these locations are likely influenced by stronger geophonic components, including wind exposure and water movement from nearby lakes and streams, together with intermittent human presence. In particular, site 7 corresponds to a frequently used resting area for hikers where anthropogenic acoustic activity is commonly observed. Anthropogenic noise sources often concentrate acoustic energy within specific frequency bands, which can reduce spectral heterogeneity and consequently lower entropy values in disturbed environments [13, 21]. These spatial differences highlight how the acoustic structure of alpine environments reflects the interaction between biological activity, geophysical processes and localized human use of the landscape [1, 19].

TE analysis revealed a sparse but structured pattern of directional information exchange among monitoring sites (Fig. 3). Notably, several dominant source nodes corresponded to locations characterized by higher NDSHI values, suggesting that areas with stronger biological acoustic activity may act as drivers of information transfer within the soundscape network. For H, directional exchanges tended to propagate from sites with higher spectral complexity toward sites characterized by lower values, indicating that locations with richer acoustic structure may influence the temporal dynamics of neighbouring sites.

The application of TE to ecoacoustic indices therefore provides a promising framework for investigating directional dependencies within environmental soundscapes, complementing traditional descriptive metrics. Information-theoretic approaches have been increasingly applied to complex ecological systems to investigate directional relationships and information flows among interacting components [22]. Similar applications have recently been proposed for the analysis of acoustic information dynamics in urban and natural parks [18], highlighting the potential of these methods for advancing soundscape ecology.

5. Conclusions

This study demonstrates that complementary ecoacoustic indices combined with information-theoretic metrics can reveal spatial heterogeneity and directional information exchanges in a high-altitude alpine soundscape. These approaches can support the monitoring and management of mountain protected areas, where traditional noise level measurements are often insufficient to describe the ecological structure of the soundscape, helping identify acoustically distinct areas and assess the effects of anthropogenic pressure over time. Future research will extend the analysis to additional monitoring campaigns to assess seasonal variability and long-term soundscape dynamics, integrating ecoacoustic indicators with species-level information, such as avian richness and marmot vocalizations, to investigate whether soundscape structure reflects potential wildlife responses to anthropogenic noise pressure.

6. Acknowledgments

The authors would like to thank Daniele Sartore, Danilo Corgnati (ARPA Piemonte) and Fabio Angelini (University of Milano -Bicocca) for their support in the deployment of acoustic sensors and the collection of sound pressure level data. We also thank the Gran Paradiso National Park for hosting the monitoring activities, in particular Ramona Viterbi and Sonia Calderola for their valuable collaboration.

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